ATTACHMENT 2

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ABB COMBUSTION ENGINEERING

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Series 44 & 51 Design Steam Generator Tube Repair Using A Tube ReRolling Technique

FINAL REPORT

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ABSTRACT

A technique is presented for repairing degraded steam generator tubes in Westinghouse pressurized water reactors with Series 44 and 51 design steam generators. The technique alleviates the need for plugging or sleeving those steam generator tubes with defects in the tubesheet region.

Instead of traditional repair techniques (plugging and sleeving), the degraded tubes will be rerolled above the original tubesheet hard roll to form a new leaktight joint above the initial tubesheet roll transition zone. This technique will re-establish the pressure boundary between the primary and secondary side systems and provide the necessary structural capability for operational and upset conditions.

This report details analyses and testing performed to verify the adequacy of the roll transition zone reroll process for returning nuclear steam generator tubes back to service. It demonstrates that rerolling tubes, with defects in the tubesheet region, is an acceptable repair technique.

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1.0 INTRODUCTION

1.1 Purpose

The purpose of this report is to provide information sufficient to back licensed F*, EF* and L* analyses in support of a 10CFR50.59 safety evaluation allowing installation of reroll joints in Westinghouse-designed Series 44 and 51 steam generators with degraded tubes in the tubesheet region. This report demonstrates that reactor operation with a tube reroll joint in the steam generator tubes will not increase the probability or consequence of a postulated accident condition previously evaluated. Also it will not create the possibility of a new or different kind of accident and will not reduce the existing margin of safety.

ABB Combustion Engineering (ABB-CE) provides two types of leaktight reroll joints for Westinghouse Series 44 and 51 steam generator tube repair. The first joint type can be located anywhere in the [

].

[ ]. This joint type was designed to be located anywhere in the [

].

The steam generator tube with the reroll joints meets the [ ] of tubes which are not degraded.

Design criteria for the reroll joints were prepared to ensure that all design and licensing requirements are considered. Analyses and testing have been performed on the tube reroll joints to demonstrate that the design criteria are met.

The effect of reroll joints on steam generator heat removal capability and system flow rate are discussed in Section 10 of this report.

After the reroll joints are installed, an examination is performed using eddy current (ET) techniques. The ET examination serves as a method to verify that the reroll joint was [ ] in the steam generator tube and to assure that F*, EF* and/or L* criteria are met by the reroll process.

Plugs or sleeves will be installed if the reroll procedure is not successful or if there is unacceptable degradation of steam generator tubes due to the process.

1.2 Background

The operation of Pressurized Water Reactor (PWR) steam generators has, in some instances, resulted in localized corrosive attack at the roll transition zone region and in the tubesheet crevice region of the steam generator tubing. This corrosive attack results in a localized reduction in steam generator tube wall thickness. Steam generator tubing has been designed with considerable margin between the actual wall thickness and the wall thickness required to meet structural requirements. Thus it has not been necessary to take corrective action unless structural limits are being approached.

Historically, the corrective action taken where steam generator tube wall degradation has been severe has been to install plugs at the inlet and outlet of the steam generator tube when the reduction in wall thickness reached a calculated value referred to as a plugging criteria. An additional repair option has been to bridge the defect utilizing a sleeve. Eddy current (ET) examination has been used to measure steam generator tube degradation and the tube plugging criteria accounts for ET measurement uncertainty.

Installation of steam generator tube plugs removes the heat transfer surface of the plugged tube from service and leads to a reduction in the primary coolant flow rate available for core cooling. Installation of steam generator sleeves does not significantly affect the heat transfer removal capability of the tube being sleeved and a large number of sleeves can be installed without significantly affecting primary flow rate. However, there is a minor reduction in flow rate associated with large numbers of sleeves and potential accessibility concerns as well.

The use of a tube reroll process will alleviate these concerns as well as leave the tube in a condition to perform repairs at a later time.

2.0 QUALIFICATION CRITERIA

2.1 Technical Specification

Westinghouse Series 44 and 51 Steam Generators

2.1.1 Design and Operating Ratings

Primary Operating/Design Temperature:	590-611/650^{0}F
Primary Operating/Design Pressure:	2235/2485 psig
Secondary Operating/Design Temperature:	506-521/550^{0}F
Secondary Operating/Design Pressure:	690/1085 psig

2.1.2 Steam Generator Tube Data

Tube Hole Drilling (min./max.):	.888/.893 in.
Tube Nominal O. D.:	.875 in.
Tube Nominal Wall:	.050 in.
Tube Wall Reduction Due to Rolling:	4-6%

2.2 Acceptance Criteria

The following acceptance criteria were used to assess the performance of rerolled joint coupon specimens during testing.

2.2.1 The established torque values shall yield a [ ] percent tube wall reduction. These values were chosen as a means of [ ]. This range of values reflects ABB's experience in plug and sleeve rolling in steam generator tubes. Also, the [ ] accommodates the uncertainties associated with remote field applications.

2.2.2 The rerolled tube joint shall exhibit no movement relative to the tubesheet during simulation of cyclic loading conditions.

2.2.3 The rerolled tube joint shall exhibit no movement relative to the tubesheet at push test forces which represent the maximum load experienced by the tube under operating or accident conditions with the tube unrestrained at the support plates. These loads are [ ].

2.2.4 The rerolled tube joint shall exhibit [ ] when subjected to secondary side pressure levels equal to [ ] the operating or upset condition pressure differential. Section 7.0 defines the basis for the test pressure selection.

2.2.5 The roller expander shall produce consistent rolls of bright metal surface finish. There shall be no measurable signs of wear which could effect the rolled joint over [ ], which is the proposed life of the roller expander, assuming a planned lubrication interval.

2.2.6 Non-destructive examination techniques shall be utilized to verify that the [ ] were properly placed in the tube and that F*, Elevated F* (EF*) and L* criteria were met.

2.2.7 The tube reroll joint shall not adversely affect system flow rate or heat transfer capability of the steam generator tube.

3.0 SUMMARY

A total of [ ] coupons consisting of [ ] for F* qualification and a total of [ ] coupons consisting of [ ] for EF* qualification were subjected to a rigorous qualification program. The program was designed to [ ] that could be experienced during field operations. These variables included the [ ]. Such conditions include the [ ]. The [ ] effective length roll expander (for reroll joints below the tubesheet neutral axis) and the [ ] effective length roll expander (for reroll joints above the tubesheet neutral axis) were conservatively used to prepare all test coupons. The complete test matrices are included as Tables 3.1 and 3.2.

Torque values associated with a [ ] percent tube wall reduction were established using production equipment. The minimum torque value [ ] used in the test program yielded a [ ] percent tube wall reduction, and the maximum torque value [ ] used in the test program yielded a [ ] percent tube wall reduction. The nominal value was established at [ ]. The tooling and control systems used in the test programs represent the present technology for reroll production equipment. As technological advances are made, the updated equipment may be utilized upon completion of laboratory verification.

Adhering to the test matrices, samples were prepared for testing. The samples were [ ].

All samples prepared for F* Cases 1 through 5 were [ ], then [ ] tested. EF* Cases 1 through 3 were [ ], then [ ] tested. The results of these [ ] tests replicated the results obtained prior to [ ] testing. These samples were used to determine the effect on the rolled joint of conditions expected in the steam generators, such as; the [ ].

All samples prepared for F* Case 9 were [ ], then [ ] tested at the above [ ] values. The results of these tests replicated the results obtained prior to [ ] testing. These samples were used to determine the effect on the rolled joint due to the maximum steam generator loading.

All F*samples were [ ], and all EF*samples were [ ]. There was [ ]. Samples were also [ ].

Samples which had been rerolled were [ ] after completion of the rolling operation. There were no [ ] of the tube due to the reroll process.

Table 3-1

F* REROLL TEST MATRIX

CASE	VARIABLES	NO. OF COUPONS	TUBE HOLE	TESTS		
				CYCLE	PUSH	HYDRO
1	NOMINAL	3	MIN - .888"	X	X	X
2	MIN TORQUE	3	MAX - .893"	X	X	X
3	MAX TORQUE	3	MAX - .893"	X	X	X
4	DRY SLUDGE	3	NOM - .890"	X	X	X
5	WET SLUDGE	3	NOM - .890"	X	X	X
6	LIFE TEST	3 (NOTE 1)	NOM - .890"			
7	NOMINAL	3	NOM - .890"		X	X
8	COLLAPSE	3	NOM - .890"			
9	MIN - MAX TORQUE	3	NOM - .890"	X	X	X

Note 1: Test roller expanders at intervals of 50, 100 and 200.

Table 3-2

EF* REROLL TEST MATRIX

CASE	VARIABLES	NO. OF COUPONS	TUBE HOLE	TESTS		
				CYCLE	PUSH	HYDRO
1	NOMINAL	1	NOM - .890"	X	X	X
2	MIN TORQUE	1	MAX - .893"	X	X	X
3	MAX TORQUE	1	MIN - .887"	X	X	X
4	DRY SLUDGE	1	MIN - .887"			X
5	WET SLUDGE	1	NOM - .890"			X
6	COLLAPSE	2	NOM - .890"			

4.0 REFERENCES

4.1 Nuclear Power Business Nuclear Quality Assurance Manual, QAM-100, Fourth Edition, Revision 4.

4.2 Quality Assurance Procedures Manual, QPM-101, Revision 0.

4.3 Quality Plan No. 2004396-QP-94-014, Rev. 00, "Project Quality Plan for the Development and Qualification of a Tube Re-Roll Process for Westinghouse Steam Generator Tubes."

4.4 STD-400-153, Rev.00, "Test Plan for the Development and Qualification of a Steam Generator Tube Re-Roll Process for Westinghouse Series "44" and "51" Steam Generators."

4.5 00000-OSW-007, Rev. 00, "Test Procedure for the Development and Qualification of a Steam Generator Tube Re-Roll Process for Westinghouse Series "44" and "51" Steam Generators."

4.6 Telecopy to Dave Stepnick of ABB-CE from Richard Pearson of Northern States Power, dated December 21, 1994. Design Input on F-Star/L-Star Plugging Criteria.

4.7 TR-ESE-887, Rev. 00, "Test Report for the Qualification of the Roll Transition Zone Sleeve Rolled Joint for Westinghouse "D" Series Steam Generators."

4.8 CENC 1599, "Qualification Testing of Combustion Engineering Mechanical Tube Plug with Addendum A."

4.9 Test Report No. WO-94-205, "Test Report for the Additional Development and Verification of the Transition Zone Sleeve Rolled Joint for 3/4" Steam Generator Tubes."

4.10 Drawing No. C-SGN-217-458, Rev. 04, "ReRoll Joint Configuration."

4.11 Qualification Report, GBRA 014 020, "Steam Generator Tube Repair by Tube Reexpansion." (ABB Reaktor)

4.12 "Doel 2 - Tube Reexpansion, ABB Conclusions about July Demonstration," 08/13/90. (ABB Reaktor)

4.13 "Repair of SG Tubes by Rerolled Expansion - Corrosion Test." (Laborelec Labs)

4.14 Memo No. PENG-95-015, "Testing of Steam Generator Tubesheet Reroll Samples," A. B. Goulet to E. P. Kurdziel, dated January 23, 1995.

4.15 Memo No. WO96186, "Test Results for Re-Roll Qualification Program," D. G. Stepnick to E. P. Kurdziel, dated October 11, 1996.

4.16 00000-OSW-010, Rev 00, "Test Procedure For The Life Testing Of Roll Expanders."

4.17 TR-400-002, Rev. 00, "Test Report For The Life Testing Of Roll Expanders With Decreased Lubrication Frequency."

4.18 Report No. A-ABBCE-9419-1119, Revision 00, "Evaluation of Tube Re-Rolling for Westinghouse Series 44 & 51 Steam Generators."

4.19 Specification No. 00000-OSW-009, Rev. 00, "Design Specification for Re-Rolled Joints in Steam Generator Tubes."

4.20 Telecopy to Dave Stepnick of ABB-CE from Richard Pearson of Northern States Power, dated September 1, 1996. Design Input on EF-Star/L-Star Plugging Criteria.

4.21 Memo No. 96177.DS, "Continuation Of ReRoll Qualification Test Program," D. Stepnick to E. Pohl, dated October1, 1996.

4.22 Memo from D. Proctor to D. G. Stepnick, "Top Of Tubesheet Reroll Collapse Test," dated September 19, 1996.

4.23 Memo No. PENG-96-496, "Testing of Steam Generator Tubesheet Reroll Samples," A. B. Goulet to Dane Proctor, dated December 4, 1996.

5.0 DESIGN DESCRIPTION OF REROLL JOINT AND INSTALLATION EQUIPMENT

5.1 ReRoll Joint Design

Reference 4.19 contains requirements for the reroll joint and its installation. The joint becomes the [ ]. The reroll joint design is based upon the technology previously developed at ABB. Included in this category is the experience of ABB Reaktor in the areas of [ ], and the experience of ABB Combustion Engineering in the areas of]. ABB has installed over [ ] using rolling technology and over [ ] using similar technology.

The reroll joint geometry is shown in the drawing presented in Figure 5-1. Multiple reroll joints may be used in a tube. The critical parameters concerning the joint geometry were developed by the original equipment manufacturer using F*, EF* and L* analyses. Based on these analyses, it was determined that up to [ ] upon completion of the reroll would meet F* criteria. In addition, it was determined that up to [ ] upon completion of the reroll would meet EF* criteria. Per the analyses, up to [ ].

Based upon information provided by utility personnel who owned and operated Series 44 and 51 steam generators, ABB-CE determined that the original hard roll length in steam generator tubes ranged from a minimum of one and one half inches to a maximum of two and three quarter inches. Based upon this information, ABB-CE decided to [ ] from the steam generator tube end. This joint is put in place using a [ ]. This geometry places the bottom edge of the reroll joint a [ ] from the maximum height of the original roll transition.

As part of the reroll joint, a [ ] may be performed prior to the hard roll process step. This [ ] utilizes current steam generator sleeving technology. The [ ] from the tube end and extending past the hard roll region. This process step serves a number of purposes; first, to [ ]; second, to [ ] above the reroll joint; and third, to [ ] upon process completion.

Through the use of [ ], the tube wall reduction from the hard roll will be limited from [ ] percent minimum to [ ] percent maximum. This range of wall reduction ensures an acceptable reroll joint under the variety of conditions tested under this program. This range of roll expansions is [

], as well as industry experience demonstrating this range to provide optimum structural integrity for hard rolled joints.

5.2 Repair Of A Defective ReRolled Tube

If a tube is found to have an unacceptable rerolled joint, the [ ] above the first reroll. When [multiple reroll joints] are unacceptable or not possible, the tube can be sleeved in order to keep it in service or it can be taken out of service with standard mechanical tube plugs at both ends of the tube. In either case, approved methods to perform the processes are in place.

5.3 ReRoll Joint Installation Equipment

The equipment used for the remote installation of rerolled joints in a steam generator is made up of the following basic systems:

1. Remote Controlled Manipulator

2. Rotation Station

3. Tube [ ] Equipment

4. Tube [ ] Equipment

5. Tube Rolling Equipment

6. Tube Eddy Current Equipment

These systems, when used together, allow installation of the reroll joints without entering the steam generator. In this way, personnel exposure to radiation is held to a minimum.

The tooling and methods described in the following sections represent the present technology for rerolled joint installation. As technological advances are made in the installation process, the updated techniques may be utilized upon completion of laboratory verification by ABB-CE.

5.3.1 Remote Controlled Manipulator

The remote controlled manipulator (Figure 5-2) serves as a transport vehicle for repair and inspection inside a steam generator hot leg or cold leg plenum.

The manipulator consists of two major components; the manipulator leg and the manipulator arm. The manipulator leg is installed between the tubesheet and the bottom of the primary head and provides axial (vertical) movement of the arm. The manipulator arm is divided into the head arm, probe arm and swivel arm. Each arm is moved independently with encoder position controlled electric motors. The swivel arm allows motion for tool alignment in various types of tube pitches. Computer control of the manipulator allows the operator to move tools from outside the manway and accurately position them under the proper tube against the tubesheet.

5.3.2 Rotation Station

The rotation station (Figure 5-3) mounts on the end of the manipulator arm through the use of a locking dovetail arrangement. The rotation station delivers the various tools required for the reroll operation to the proper location. Cameras mounted on the rotation station are used to verify location as well as aid in the entry of tools into the tube. Proper elevations for the various tools are obtained through the use of hardstops. The rotation station also provides controlled rotation to some of the tools used in the reroll operation. The station is controlled through the use of a torque monitoring system, which trips the station off when the preset torque value is reached.

5.3.3 Tube [ ] Equipment

The initial step in the reroll process involves [ ] (Figure 5-4), or equivalent. The purpose of this step is to [ ] during power plant operation. The [ ]. Additionally, the [ ]. An air motor rotates the [ ] as it is inserted into the end of the tube. At the appropriate elevation, the tool is [ ]. An interference fit between the tube and the [ ] upon completion of this process step.

5.3.4 Tube [ ] Equipment

When applicable, the [ ] equipment (Figure 5-5) is used to minimize the amount of crevice products between the tube and tubesheet [ ] the steam generator tube. The [ ]. When the [ ]. A tool hardstop is provided for proper tool vertical positioning.

The [ ] prior to use. The [ ] signal is fed back to the display screen's strip chart recorder in order to record the [ ].

An [ ] is utilized to move the [ ] away from the area. This [ ] of the joint and no credit is taken during analysis of the joint.

The [ ] may be used with any of the reroll joints (Figure 5-1). However, due to equipment reachability and tube access concerns, it is typically used only on the lower two reroll elevations.

5.3.5 Tube Rolling Equipment

The tube rolling equipment (Figure 5-6) is used to expand the tube into intimate contact with the tubesheet, forming a strong leaktight joint. The rolling tool is positioned under the proper tube using the manipulator, which is then used to insert the tool into the tube. The rolling tool utilizes a hardstop to position it vertically in the proper location.

The rolling equipment consists of the air motor, tube expander, torque readout and torque calibration unit. The torque readout and settings of the rolling tool are verified on the torque calibration unit prior to rolling of the tube. The tube is expanded to a torque which has been demonstrated by testing to provide a leaktight joint. The torque trace appears on the display screen's strip chart recorder and is used for evaluation of the rolling process on the individual tubes. The torque trace is used as the official record of the process. A second roll is performed to verify the torque level reached on the first reroll. The evaluation of the torque trace is the basis for acceptance or rejection of the reroll joint since the joint integrity is based on percent wall thinning. A rolled joint which fails to meet the acceptance criteria may be rerolled. [ ].

5.3.6 Tube Eddy Current Equipment

After the reroll joints are installed, an examination is performed using eddy current (ET) techniques. The ET examination serves as a method to verify that the reroll joint was [ ] in the steam generator tube and to assure that F*, EF* and/or L* criteria are met by the reroll process.

5.4 ALARA Considerations

The steam generator repair operation is designed to minimize personnel exposure during re-roll operations. The manipulator is installed from the manway without entering the steam generator. It is operated remotely from a control station outside the containment building. The positioning accuracy of the manipulator is such that it can be remotely positioned without having to install templates in the steam generator.

The rotation station is designed so that the dovetail fitting quickly attaches to the manipulator. The rotation station is designed to quickly engage the individual rerolling tools. The tools are simple in design and all operations are performed remotely using tools held by the manipulator. Each tool can be changed at the manway in 10-15 seconds. A tool operation is performed on several tubes rather than performing each tool operation on the same tube before proceeding to the next tube. This reduces the number of tool changes which are required. If tool repair is necessary, the tool is removed and reroll operations continue using a spare tool. Tool repair is completed off the platform in a low radiation area.

Air, water and electrical supply lines for tooling are designed and maintained so that they do not become entangled during operation. This minimizes personnel exposure on the steam generator platform. All equipment is operated from outside the containment building.

In summary, the steam generator operation is designed to minimize personnel exposure to ionizing radiation and is in full compliance with ALARA standards.

Figure 5-1
ReRoll Joint Configuration

Figure 5-2

Figure 5-3

Figure 5-4

Figure 5-5

Figure 5-6

6.0 TEST PROGRAM

6.1 Test Matrix

Two test matrices were developed to test the reroll joint over a range of test conditions. These matrices are shown in Tables 3-1 and 3-2. The matrices represent a range of conditions to which the rerolled joint was tested. A total of [ ] coupons were tested for each test case for the F* program. A total of [ ] coupon was tested for each test case for the EF* program. A description of each of the test conditions and type of tests is given below.

6.1.1 Tube Dimensions

Two heats of Inconel 600 tubing were used in this program. The heat numbers are [ ], purchased from Sandvik Steel Co.(F* program), and [ ], purchased from Valinox N...aire(EF* program). The tubing was purchased to nominal dimension of .875" O.D. x .050" wall, however, the tube wall dimensions were not uniform, varying from a minimum of [ ]. This was accounted for in the measurement step of sample preparation.

6.1.2 Tube [ ] Size

A [ ] sizes was tested in the reroll program. This range of [ ] sizes represents actual tubesheet [ ] sizes per the original equipment manufacturer's specification. The [ ] sizes tested were the [ ]. Changes in [ ] affect the amount of wall thinning the tube will experience and require that the roller expander perform consistently over a [ ].

F* Program

Test Case 1 performed the reroll in a [. Test Cases 2 and 3 performed the reroll in [ ]. The remaining test cases were performed in a nominal size tube hole. [ ] torque was defined as that torque required to produce approximately [ ] percent wall thinning and [ ] torque as that torque required to produce approximately [ ] percent wall thinning.

EF* Program

Test Case 1 performed the reroll in a [ ]. Test Cases 2 and 3 performed the reroll in [ ].

6.1.3 Surface Finish

The tube holes for this program were bored to produce a surface finish of [ ] RMS. The tubes were purchased to a [ ] RMS outside diameter surface finish and were received with a [ ] RMS finish. These variables were constant throughout the test program.

6.1.4 Torque Setting

A [ ] setting was developed as part of this program. As described earlier, these settings are defined as the torque required to produce approximately [ ] percent tube wall thinning. Test Cases 2 and 3 of the F* program performed the reroll using a [ ] percent wall thinning. These rerolls were performed in [ ] in order to force the rollers [ ]. Test Cases 2 and 3 of the EF* program also performed the reroll using [ ] percent wall thinning. However, the [ ] were used to bracket the test results.

6.1.5 [ ] Conditions

The possibility exists that [ ] during rerolling operations. [ ] prior to performing the reroll. Test Cases 4, 5 and 8 of the F* program simulated these conditions. A [ ] for Test Cases 4 and 8. This same [ ] was performed. This extra preparation step assured a [ ]. Test Cases 4, 5 and 8 of the EF* program also simulated these conditions.

[ ].

6.1.6 Roller Expander

Roller expander geometry is a constant with the [ ]. This roller expander geometry is based upon experience gained in plug and sleeve installation programs. The [ ] effective length roll expander was used to prepare all test coupons for the F* program, while the [ ] effective length roll expander was used to prepare all test coupons for the EF* program.

6.2 <u>Tests Required On Coupons</u>

The test procedure requires a [ ] test after rerolling the tube into the block. Upon completion of the [ ] test, the coupons were subjected to [ ] tests, after which the coupons were [ ] tested a second time. The [ ] tests were performed from the [ ] in order to increase the conservatism of the test. A [ ] test was also performed in order to conform to the requirements of Reg. Guide 1.121. Finally, the coupons were subjected to a [ ] at which joint movement occurs.

7.0 TEST RESULTS

7.1 Coupon Preparation

Mock tubesheets were machined with [ ] as defined in the test matrix. Additionally, a split block with a nominal hole size was machined. This block was used to develop the torque range required to meet the acceptance criteria.

7.1.1 Tube Installation

Steam generator tubes were cut to six inch lengths and rolled into the tubesheet blocks at the lower end of the blocks. This was done to anchor the tube in the block and to simulate the original hard roll. If the particular coupons required [ ] conditions, the [ ] onto both the tube outside surface and the tube hole inside surface prior to locking the tube in place. Measurements required for tube wall reduction calculations were taken prior to installing the tube into the block.

7.1.2 Tube [ ]

The tube [ ]. The coupons were placed in a test stand and the rotation station was used to perform the [ ]. The [ ].

7.1.3 Tube [ ]

Where applicable, the tubes were [ ] described earlier. The [ ]. The use of a [ ] for testing will not detrimentally affect the use of a [ ] during the field effort. An [ ] was used to [ ] into the block. A typical [ ] trace, as recorded on the strip chart, is shown in Figure 7-1.

7.1.4 Tube ReRolling

The rerolling operation was performed by fixturing the coupon into a rolling stand. The [ ] roll expander was conservatively used for all rerolling tests. The test matrix defined the [ ] that were required for coupon preparation. A typical torque trace, as recorded on the strip chart (torque is along the Y-axis, while time is along the X-axis), is shown in Figure 7-2 for a coupon prepared with [ ]. The [ ] and there is a smooth, steady increase in torque.

A typical torque trace, as recorded on the strip chart, is shown in Figure 7-3 for a coupon prepared with [ ]. The [

] during the rolling operation. The torque setpoint is reached over a much longer period of time.

7.1.5 Coupon Numbering

The following numbering system was used to identify the coupons.

<u>F* Program</u>

B1, B2, B3	Case 1 [	]
A1, A2, A3	Case 2 [	]
A4, A5, A6	Case 3 [	]
C1, C2, C3	Case 4 [	]
C4, C5, C6	Case 5 [	]
D1, D2, D3	Case 7 [	]
E1, E2, E3	Case 8 [	]
F1, F2, F3	Case 9 [	]

<u>EF* Program</u>

110-3	Case 1 [	]
90-4	Case 2 [	]
140-3	Case 3 [	]
90-5	Case 4 [	]
110-4	Case 5 [	]
130-1, 130-2	Case 6 [	]

7.2 <u>Torque Development</u>

The first step in the program was to develop torque levels associated with tube wall thinning of [ ] percent. This was done by using the split block arrangement. Tubes were placed in the split block, rolled, then measured to determine wall thinning. Tables 7-1 and 7-2 give the values for the various torques using the [ ] effective length roll for the F* program and the [ ] effective length roll for the EF* program.

Based upon this information, maximum and minimum torque values were first chosen for the [ ] effective length rolls. These values were [ ] for the minimum torque setpoint, [ ] for the nominal torque setpoint and [ ] for the maximum torque setpoint. These were the torque settings that were utilized during the testing process.

Additionally, a test coupon was rolled to the system limited (based on supply air) torque value of [ ] This sample, with a wall thinning of [ ], successfully passed [ ] testing.

Table 7-1 - F* Data

Torque (in-lbs)	Wall Thinning (%)	Torque (in-lbs)	Wall Thinning (%)
74	2.43	138	5.59
74	1.61	130	4.66
89	2.21	131	5.83
87	3.21	139	4.60
85	3.81	145	5.12
88	2.84	144	4.54
109	2.53	153	7.58
102	3.25	153	7.41
113	3.82	154	6.67
115	4.03	168	7.68
116	4.82	167	7.28
111	4.50	167	7.68
135	3.85	199	9.39

Table 7-2 - EF* Data

Torque (in-lbs)	Wall Thinning (%)	Torque (in-lbs)	Wall Thinning (%)
95	3.41	136	3.64
97	4.02	137	7.71
100	4.77	153	4.00
102	5.56	161	4.28
112	3.66	166	4.55
112	5.20	173	5.99
120	5.12	174	5.48
126	4.09	175	7.03
129	5.10	177	4.44
135	6.66	185	5.85

7.3 Test Procedure

Reference 4.5 is the detailed procedure describing all step-by-step activity for the test program. This section summarizes the procedure used to conduct the various tests on the coupons. Tables 7-3 and 7-4, at the end of this section summarize all of the test results.

7.3.1 [ ] Tests

Normal operating and postulated accident conditions [ ] on the steam generator tube and tubesheet. The maximum tubesheet loadings result from a flexure pattern where tubesheet ligament stress across the majority of the tubesheet is tensile above the neutral axis and compressive below the neutral axis. For reroll joints below the neutral axis, the compressive stress would tend to close the tubesheet hole during operating conditions, thus increasing the tube to tubesheet joint contact pressure. For reroll joints above the neutral axis, the tensile stress <u>could</u> open the tubesheet hole during operating conditions, thus <u>potentially</u> reducing the tube to tubesheet joint contact pressure. An extensive test and qualification program on the Roll Transition Zone Sleeve rolled joint (Reference 4.7), has shown that the tubesheet flexure has no effect on the joint structural integrity or leak tightness. Therefore, only axial loads were applied to test coupons during the reroll joint cyclic test program.

The rerolled joints were subjected to a cyclic axial load test to demonstrate structural capability of the joint. The loads used for the cyclic tests were based upon the operating loads experienced by a tube [ ], as this was the worst case loading condition on the tubes. These loads are [ ]. Section 8 provides an analysis of this condition. The loading was applied to these rerolled joint at [ ]using an MTS Testing Machine. [ ].

All coupons prepared for F* Cases 1 through 5 were [ ]. The rerolled joints for F* test Case 9 were conservatively loaded between [ ] for a total of [ ] cycles. Coupons prepared for EF* Cases 1 through 3 were [ ]. [ ]. These samples were used to determine the effect on the rolled joint due to conditions expected in the steam generators, such as; the [ ].

7.3.2 [ ] Tests

As described in the previous section, steam generator tubes are subjected to loading conditions while in operation. The maximum loads to which the tube is subjected are [

]. The rerolled coupons were push tested to a load of [ ] for the F* coupons and [ ] for the EF* coupons using an MTS Testing Machine. Coupons from F* Cases 1 through 5 and EF* Cases 1 through 3 exhibited [ ] at this load and the test was terminated. Coupons from F* Cases 7 and 9 were pushed to failure. The failure occurred due to tube buckling at a load of [ ]; the rerolled joint did not [ ].

7.3.3 [ ] Tests

[ ] tests were performed on the coupons before and after [ ] testing. The tests were performed from the secondary side in order to increase the conservatism of the test. The test was performed at [

]. The first pressure level represents a secondary side test.

The ASME Code hydrostatic test pressure of:

1.25 x Primary Design Pressure = 1.25 x 2485 psi = 3106 psi

is the basis for the first primary side pressure level. Rerolled joints passing the test at this pressure are considered acceptable. For added conservatism, ABB-CE increased the pressure [ ] above the acceptance criteria. This represents a factor of safety of over [ ] for the test.

All samples except the samples [ ] exhibited leaktightness. Samples C1,C2 and C3 had an [

].

In order to comply with the guidelines of Regulatory Guide 1.121, which call for a test pressure of three times the operating differential, F* Test Case 7 coupons were pressurized to [ ] from the primary side. [

].

7.3.4 Collapse Tests

The possibility exists that sludge will be present in the annulus between the tube and tubesheet during rerolling operations. The moisture in wet sludge, trapped between two rerolled joints, has the potential of flashing to steam under operating temperatures. The pressure build up during this event will be released either

through the rolled joints or by a collapse of the tube. [
].

7.4 F* Coupon Results

Test Case 1 - [ ]

Coupons B1,B2 and B3 of this test case successfully passed all phases of testing.

[
].

Test Case 2 - [ ]

Coupons A1, A2 and A3 of this test case successfully passed all phases of testing.

[
].

Test Case 3 - [ ]

Coupons A4, A5 and A6 of this test case successfully passed all phases of testing.

[
].

Test Case 4 - [ ]

Coupons C1, C2 and C3 of this test case successfully passed all phase of testing.

[
].

Test Case 5 - [ ]

Coupons C4, C5 and C6 of this test case successfully passed all phases of testing.

[
].

Test Case 6 - [ ]

See Section 7.7 for the results of the roller life test.

Test Case 7 - [ ]

Coupons D1, D2 and D3 of this test case successfully passed the push tests and the primary side hydrostatic leak test.

[ ].

Test Case 8 - [ ]

[ ].

[ ].

[ ].

Test Case 9 - [ ]

Coupons F1, F2 and F3 of this test case successfully passed all phases of testing.

[ ].

7.5 <u>EF* Coupon Results</u>

Test Case 1 - [ ]

Coupon 110-3 of this test case successfully passed all phases of testing.

[ ].

Test Case 2 - [ ]

Coupon 90-4 of this test case successfully passed all phases of testing.

[

].

Test Case 3 - [ ]

Coupon 140-3 of this test case successfully passed all phases of testing.

[

].

Test Case 4 - [ ]

Coupon 90-5 of this test case successfully passed all phases of testing.

[

].

Test Case 5 - [ ]

Coupon 110-4 of this test case successfully passed all phases of testing.

[

].

Test Case 6 - [ ]

[

].

[

].

7.6 Tube Growth Tests

An additional area of concern was the area of steam generator tube growth or contraction during the rerolling operation. Three coupons were prepared and measured prior to the rerolling operation. The samples were then [ ], a length which represents the amount of unrolled tube that will be [ ] in the steam generators. The coupons were then subject to a torque that resulted in [ ] percent wall thinning. The results are shown below.

Tube No.	Initial Length	[ ]	[ ]	Change
1	6.060"	[ ]	[ ]	[ ]
2	6.068"	[ ]	[ ]	[ ]
3	6.069"	[ ]	[ ]	[ ]

The change in length due to the [ ] and the length change due to the [ ], for an overall length change of, on average, [ ].

7.7 Roller Life

ABB-CE has a large volume of experience with rolling operations. References 4.16 and 4.17 document life testing performed on roller expanders during sleeve roll qualification testing. This data is applicable to the current program, since similar roller designs are employed and similar materials are involved. In both of the referenced programs, there was no evidence of detrimental wear beyond burnishing marks and a slight change in color on the mandrel and rolls. [

].

7.8 Discussion

Torque values associated with tube wall thinning of [ ] were established using production rolling equipment. These values were established by rolling tube samples in a split block and recording the torque trace. The tubes were then removed from the block, sectioned and measured to determine wall thinning. Based upon the acceptance criteria established, which bracketed original equipment manufacturing criteria and reflected ABB-CE rolling experience, torque values for the [ ] and [ ] effective length rollers in the range of [ ] were established.

Using the torque values established, the tests called out in the test matrices were performed. All samples were prepared using a production control system and tooling. All [ ] coupons, representing various steam generator conditions, were tested and met the acceptance criteria. The low torque coupon (A1-A3) preparation resulted in torques above the minimum value of [ ]. This occurred due to an overshoot of the intended value by the system. However, it still resulted in a low wall thinning value of approximately [ ] percent.

Cyclic load ranges of [ ] and [ ] were used to test both the F* and EF* coupons for a total of [ ]. The load values were based on the worst case loading that the tube would experience(depending upon location in the tubesheet) and cycling the tube through the total amount of load cycles the tube experiences during operation, regardless of loading conditions. This approach assures a high degree of conservatism. Under these loading conditions, [

].

A push test load of [ ] was applied to all of the reroll joint coupons. This value represents a load greater than the maximum tube loading conditions described earlier. The tests were stopped before joint failure was observed. [ ]. As an additional test, six coupons were pushed to failure. Failure occurred by tube buckling at [ ].

Hydrostatic leak tests were performed on all coupons before and after cyclic loading. The test pressures represented a secondary side hydrostatic test and a primary side hydrostatic test. All tests were performed from the secondary side of the coupons, which represents a high degree of conservatism. The ASME Code hydrostatic test pressure of [ ]. An additional [ ] was then applied to increase the factor of safety further. [ ] coupons were tested from the primary side at a pressure of [ ]. This represents a pressure greater than the three times operating differential pressure set forth in Regulatory Guide 1.121.

All coupons held pressure for a [ ] minimum at each pressure level with no observable leakage except for the coupons with [ ]. These coupons exhibited an [ ]. [ ].

[ ].

Table 7-3
F* Test Results

Table 7-4
EF* Test Results

Figure 7-1
Typical [ ] Trace

Figure 7-2
Typical Torque Trace - [ ] Sample

Figure 7-3
Typical Torque Trace - [ ]Sample

8.0 STRUCTURAL CONSIDERATIONS

An analysis was performed to generate conservatively high loads to be used in the test program discussed in Section 7.0. The "worst" case loading condition was found to be for [

].

The operating and design conditions for all of the Westinghouse Series 44 and 51 plants (Reference 8.3.1) are considered. Only the "worst" case operating/design conditions for each of the Series 44 and 51 steam generators are used in the analysis. This analysis addresses [ ] cases. In the first case the [ ] for the Series 44 and 51 units, respectively. In the second case the [ ] allowed per Reference 8.3.2. A structural evaluation for the re-rolled tube geometry is modeled in Figure 8-1.

8.1 ReRoll Joint Configuration

8.1.1 Axial Loading for the First ReRolled Joint Case with [ ]

The rerolled tube schematics for both the Westinghouse Series 44 and 51 steam generators are shown in Figures 8-2 and 8-3, respectively, for the first location case. The rerolled joint is [ ] for the Series 44 and 51 units, respectively. The structural model is a system of axial members with properties and boundaries as shown in Tables 8-1 and 8-2 for Series 44 and 51 steam generators, respectively. The [ ] come from Reference 8.3.6. The axial load on the rerolled tube is due to the [

].

From Figure 8-1, [

].

Therefore, from Table 2, page 5-70, of Reference 8.3.4; the total spring stiffness for the lower and upper tube in series is:

[ ]

From equation 15.142, page 15-27, of Reference 8.3.5; the [

] are:

[ ]

[ ]

From the model in Figure 8-1, the forced tube displacement, δ_{forced}, due to temperature is:

[ ]

Also, from equation 15.142, page 15-27, of Reference 8.3.5; the axial load, F, is:

[ ]

The calculations from the above equations result in a [

] for the Series 44 and 51 steam generators, respectively, due to [

]. The results are tabulated in Tables 8-3 and 8-4.

[ ]

Figure 8-1
ReRolled Tube Model and Environment

Figure 8-2
Tube Schematic - Series "44" Steam Generators for the
First ReRolled Joint Location Case

Figure 8-3
Tube Schematic - Series "51" Steam Generators for the
First ReRolled Joint Location Case

Table 8-1

Axial Member Physical Properties - Westinghouse Series "44" Steam Generators
for
the First ReRolled Joint Location Case with Tube Lock-up

Table 8-2

Axial Member Physical Properties - Westinghouse Series "51" Steam Generators
for
the First ReRolled Joint Location Case with Tube Lock-up

Table 8-3

Axial Loads in Locked Tube - Westinghouse Series "44" Steam Generators
for
the First ReRolled Joint Location Case

Table 8-4

Axial Loads in Locked Tube - Westinghouse Series "51" Steam Generators
for
the First ReRolled Joint Location Case

8.1.2 Axial Loading for the Second ReRolled Joint Location Case

The rerolled tube schematics for both the Westinghouse Series 44 and 51 steam generators are shown in Figures 8-4 and 8-5, respectively, for the second rerolled location case. The rerolled joint is [ ] for both series steam generators. The structural model is a system of axial members with properties and boundaries as shown in Tables 8-5 and 8-6 for Series 44 and 51 steam generators, respectively. The [ ] come from Reference 8.3.6. The axial load on the rerolled tube is due only to the [ ] between Points A and B.

The calculations use the same equations that are detailed in Section 8.1.1 and result in a [ ]. The results are tabulated in Tables 8-7 and 8-8.

Figure 8-4
Tube Schematic - Series "44" Steam Generators for the
Second ReRolled Joint Location Case

Figure 8-5
Tube Schematic - Series "51" Steam Generators for the
Second ReRolled Joint Location Case

Table 8-5

Axial Member Physical Properties - Westinghouse Series "44" Steam Generators
for
the Second ReRolled Joint Location Case with Tube Lock-up

Table 8-6

Axial Member Physical Properties - Westinghouse Series "51" Steam Generators
for
the Second ReRolled Joint Location Case with Tube Lock-up

[ ]

Table 8-7

Axial Loads in Locked Tube - Westinghouse Series "44" Steam Generators
for
the Second ReRolled Joint Location Case

Table 8-8

Axial Loads in Locked Tube - Westinghouse Series “51” Steam Generators
for
the Second ReRolled Joint Location Case

8.1.3 Axial Loading for the First ReRolled Joint Case with <u>No</u> Tube Lock-up

The rerolled tube schematics for both the Westinghouse Series 44 and 51 steam generators are shown in Figures 8-2 and 8-3, respectively, for the first location case. The rerolled joint is

] for the Series 44 and 51 units, respectively. The structural model is a system of axial members with properties and boundaries as shown in Table 8-9 for Series 44 and 51 steam generators. The [

] come from Reference 8.3.6. The maximum axial load on the rerolled tube is obtained when it is [

].

From Figure 8-1, at Point A, [

].

From equation 15.142, page 15-27, of Reference 8.3.5; [

] is:

[ ]

From the model in Figure 8-1, the [

] is:

[ ]

Also, from equation 15.142, page 15-27, of Reference 8.3.5; the axial load, [

] is:

[ ]

The axial load, [ ] is:

[ ]

where:

P_2 and P_1 are the Secondary and Primary Pressures, respectively.

R_o and R_i are the outer and inner tube radii, respectively.

Therefore, the total axial load, F, is:

[ ]

The calculations from the above equations result in a [

]. For the [

]. for the Series 44 and 51 steam generators, respectively. The results are tabulated in Table 8-10.

Table 8-9

Axial Member Physical Properties - Westinghouse Series "44" and "51" Steam Generators
for
the First ReRolled Joint Location Case without Tube Lock-up

[ ]

Table 8-10

Axial Loads in Non-Locked Tube - Westinghouse Series "44" and "51" Steam Generators
for
the First ReRolled Joint Location Case

8.1.4 Axial Loading for the Second ReRolled Joint Case with [ ]

The rerolled tube schematics for both the Westinghouse Series 44 and 51 steam generators are shown in Figures 8-4 and 8-5, respectively, for the second rerolled location case. The rerolled joint is [ ] for both series steam generators. The structural model is a system of axial members with properties and boundaries as shown in Table 8-11 for Series 44 and 51 steam generators. The [ ] come from Reference 8.3.6. The maximum axial load on the rerolled tube is obtained when it is [ ].

The calculations use the same equations that are detailed in Section 8.1.3 and result in a [ ] for the Series 44 and 51 steam generators, respectively, at [ ]. For the [ ] for the Series 44 and 51 steam generators, respectively. The results are tabulated in Table 8-12.

Table 8-11

Axial Member Physical Properties - Westinghouse Series "44" and "51" Steam Generators
for
the Second ReRolled Joint Location Case without Tube Lock-up

[ ]

Table 8-12

Axial Loads in Non-Locked Tube - Westinghouse Series "44" and "51" Steam Generators
for
the Second ReRolled Joint Location Case

8.1.5 Tubesheet Ligament Stresses

In calculating the tubesheet ligament stresses for the Westinghouse Series 44 and 51 steam generators; the tubesheet ligament stresses in Reference 8.3.3 for a Series 44 are used as a basis for determining these stresses acting on the rerolled tube joint. These tubesheet ligament stresses are also applicable to the Series 51 steam generators based on the following observations.

1. [ ].

2. [ ].

3. [ ].

[

]:

[ ]

The tubesheet ligament stress results at the design condition for various rerolled locations are tabulated in Table 8-13.

[ ]

8.2 Plug and Sleeve Program Applicability

As previously discussed, ABB/CE has extensive experience in the area of rolling. The mechanical plug rolling program and the advanced sleeve rolling program both utilize torque levels similar to those developed for the tube reroll program. Numerous analyses and test programs have been performed to support the plug and sleeve installation processes. Discussions of these programs can be found in References 4.7 and 4.8 that were mentioned in Reference 8.3.7.

Table 8-13

Tubesheet Ligament Stresses for
Westinghouse Series "44" and "51" Steam Generators at
Design Condition

8.3 References

8.3.1 Westinghouse Steam Generator Standard Information Package, January 04, 1982 (REF-96-002).

8.3.2 Northern States Power Co. (Richard P. Pearson) Fax to ABB/CE (Dave Stepnick), dated 9/09/96.

8.3.3 "Primary/Secondary Boundary Components Steady State Stress Evaluation", prepared by P. Wedler, Westinghouse Electric Corp., April 1965 (REF-96-001).

8.3.4 Mark's "Standard Handbook for Mechanical Engineering", 8th Edition, 1979.

8.3.5 "Mechanical Engineering Reference Manual", by Michael R. Lindeberg, P.E., 9th Edition, 1994.

8.3.6 ASME Boiler and Pressure Vessel Code, Section III for Nuclear Power Plant Components, 1986 edition, no addenda.

8.3.7 ABB/CE Report No. CEN-620-P, Revision 01-P, "Series 44 & 51 Design Steam Generator Tube Repair Using a Tube Re-Rolling Technique", April 1995.

8.3.8 Westinghouse Report No. WCAP-14225, Revision 1, Table 2-3.

9.0 EDDY CURRENT EXAMINATION

9.1 Installation Verification

Upon completion of the re-roll process, an eddy current technique, using a [ ], is employed to verify that the [ ] have been placed in the proper location in the tube.

9.2 Rotating Probe Examination

Upon completion of the installation, an [ ], or equivalent, is pulled through the rerolled tube to detect tube indications. Since the parent tube, with known ECT indications, has been worked with [ ], an inspection is necessary to determine if the original indications have changed. The [ ] results will be compared with previous test results in order to determine whether or not the original indications have propagated. This test will be used to verify that the F* and L* criteria of undegraded hard roll tube length above previous indications are met.

10.0 EFFECT OF RE-ROLLING ON OPERATION

[

].