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Steam Generator Tube Repair for Westinghouse Designed Plants with 7/8 Inch Inconel 600 Tubes Using Leak Limiting Alloy 800 Sleeves

Westinghouse

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WESTINGHOUSE NON-PROPRIETARY CLASS 3

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Revision 2

Steam Generator Tube Repair for Westinghouse Designed Plants with 7/8 Inch Inconel 600 Tubes Using Leak Limiting Alloy 800 Sleeves

Wayne R. Gahwiller
Edward P. Kurdziel
Bruce A. Bell
Richard S. Maurer
William K. Cullen

January 2006

Approved: David G. Stepnick 1-17-06
David G. Stepnick
SG Primary Services and Technology

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

RECORD OF REVISIONS

Rev.	Date	Page	Revision Description
0	August 2003		Original Issue
1	June 2004	pp. iv-xiii p.2-2 p.2-3 p.4-3 p.4-5 p. 4-6 p. 4-7 p. 5-2 p. 5-3 p. 5-4 p. 5-5 p. 5-6 p. 6-2 Section 8 p. 9-2 p. 9-3 p. 9-4	Revised to reflect page changes and added Tables Added explanation of sleeve performance Added information to experience table Clarified criteria for plugging defective sleeve Clarified tube conditioning verification Added reasons for sleeve re-expansion Added reasons for re-rolling Clarified ECT criteria, analysis training and guidelines Modified definition of pressure boundary Clarified description of ECT qualification samples Revised Figure 5-1 Revised Figure 5-2 Clarified discussion of sleeve/tube crevice corrosion Extensive revision to include analysis of additional transients. Tables 8-4A, 8-5D, 8-6D, 8-7D, 8-8D and associated text references added. Title of Tables 8-5A-C, 8-6A-C, 8-7A-C, and 8-8A-C and Table 8-4B note (a) changed to correct typographical error with respect to tube condition Clarified tube conditioning verification Clarified reasons for sleeve re-expansion Clarified reasons for re-rolling operation
2	January 2006	p. vi p. 5-2 p. 5-3 p. 5-4 p. 5-4 p. 5-4 p. 5-5 p. 7-14 p. 7-15	Added Sections 7.6, 7.6.1, and 7.6.2 to TOC Updated number of plants and sleeves referenced Revised definition of tube pressure boundary Revised statement about flaws behind nickel band Added explanation of NDE capability in nickel band region Added references Revised pressure boundary in Figure 5-1 Added section on effect of degraded tube adjacent to nickel band Added references

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ABSTRACT

A technique is presented for repairing degraded steam generator tubes in pressurized water reactor Nuclear Steam Supply Systems (NSSS). The described repair technique alleviates the need for plugging steam generator tubes that require repair. The technique consists of installing an Alloy 800 sleeve that spans the defective section of the original steam generator tube. The upper end of the sleeve is hydraulically expanded into the steam generator tube and the lower end is mechanically rolled into the tubesheet for repair of a defect in the expansion transition or roll transition zone. For a defect at a tube support or in a free span section of the tube, the sleeve is hydraulically expanded into the steam generator tube at both ends.

This report details analyses and testing performed to verify the adequacy of Alloy 800 sleeves for installation in a nuclear steam generator tube. These verifications show sleeving to be an acceptable repair technique.

1 INTRODUCTION

1.1 PURPOSE

The purpose of this generic report is to document the acceptability of an Alloy 800 sleeve in a hot or cold leg steam generator tube of Westinghouse designed steam generators with 0.875 inch OD Alloy 600 tubes. The report includes sufficient information to support a technical specification change allowing installation of these sleeves. The sleeves are designed for installation in steam generator tubes, and span the defective section of the tube. This report demonstrates that reactor operation with sleeves installed 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.

Westinghouse provides two types of leak limiting Alloy 800 sleeves. The first type of sleeve spans the transition zone (TZ) of the parent steam generator tube at the top of the tubesheet. This sleeve is hydraulically expanded into the steam generator tube at the upper end and is hard rolled into the tube within the steam generator tubesheet. The second type of sleeve spans degraded areas of the steam generator tube at a tube support (TS) elevation or in a free span section. The sleeve used for both of these locations is called a TS sleeve. This TS repair sleeve is hydraulically expanded into the steam generator tube near each end of the sleeve.

The steam generator tube with the installed sleeve meets the structural requirements of tubes that are not degraded. Even in the event of the severance of the steam generator tube, the sleeve will provide the required structural support and acceptable leakage between the primary and secondary systems for normal operating and accident conditions. Design criteria for the sleeve were prepared to ensure that all design and licensing requirements are considered. Extensive analyses and testing have been performed on the sleeve and repair joints to demonstrate that these design criteria are met. The effects of sleeve installation on steam generator heat removal capability and system flow rate are also discussed in this report.

After sleeves are installed, a baseline examination is performed using eddy current (ET) techniques. The ET examination is used to verify certain installation process steps, as well as to provide a baseline to determine if there is sleeve degradation or degradation of the pressure boundary portion of the steam generator tube spanned by the sleeve in later operating years. The ET examination and criteria for plugging sleeved generator tubes if there is degradation are described in this report.

Plugs will be installed if for any unforeseen circumstance a sleeve installation is not successful or if there is degradation in the pressure boundary section of the sleeves or sleeved steam generator tubes. Standard, site approved mechanical or welded plugs installed at each end of a steam generator tube may be used to take a sleeved tube out of service.

1.2 BACKGROUND

The operation of Pressurized Water Reactor (PWR) steam generators has, in some instances, resulted in localized corrosive attack on the inside (primary side) or outside (secondary side) of the steam generator tubing. Historically, the corrective action taken for severe steam generator tube wall degradation has been to install plugs at the inlet and outlet of the steam generator tube when the degradation reached a value referred to as a plugging criterion. Eddy current examination has been used to measure steam generator tubing degradation with the tube plugging criteria accounting for ET measurement uncertainties and degradation growth rate.

Installation of steam generator tube plugs removes the plugged tube from service, eliminating the heat transfer surface associated with that tube. In addition, plug installation leads to reduction in the primary coolant flow available for core cooling. The repair technique described in this report for installation of sleeves allows the steam generator tube to remain in service, with minimal effect on heat transfer surface and coolant flow. The sleeves are installed at the local area of tube wall degradation and impose only a minor restriction to primary coolant flow. Thus, while providing structural integrity to the weakening effect of tube wall degradation, the effects on heat transfer and primary coolant flow are minimized.

2 SUMMARY AND CONCLUSIONS

This report has been prepared and reviewed in accordance with 10 CFR 50, Appendix B.

The Alloy 800 sleeve is similar to many other sleeves, except new features are provided to improve the design as follows:

- No welding, brazing, or heat treatment is required, thereby greatly reducing the complexity of the installation process.
- The strain within the tube is low, thereby reducing the likelihood of future corrosion cracking. Specifically, the target tube diametrical expansion is between [ ]^{a,c} which is significantly lower than other mechanical sleeve designs.

To utilize its attractive features, the Alloy 800 repair sleeve is a leak limiting design. Specifically, a small leakage, well within all requirements, will be permitted.

The Alloy 800 sleeves were designed to the applicable sections of the ASME Boiler and Pressure Vessel Code. An extensive analysis and test program was undertaken to prove the adequacy of both the upper and lower mechanically expanded joints. This program determined the effect of normal operating and postulated accident conditions on the repair sleeve-tube assembly, as well as the adequacy of the assembly to perform its intended function. The mechanical testing verified that the sleeve meets the cyclic load requirements of the original plant design. In addition, to fully confirm the adequacy of these repairs for U.S. plants, primary and secondary side caustic corrosion tests have been completed and the results evaluated relative to previous testing performed in support of both the Alloy 800 sleeve and the TIG welded sleeve.

The proposed repair has no significant effect on the configuration of the plant, and the change does not affect the way in which the plant is operated. The sleeve was designed to meet criteria that would prove that the sleeve is an acceptable repair technique. These criteria conformed to the stress limits and margins of safety in Section III of the ASME B&PV Code. Based upon the results of the analytical and test programs described in this report, the Alloy 800 sleeve fulfills the intended function as a leak limiting structural member and meets or exceeds all the established design criteria. Installation of the sleeves will conform to ASME B&PV Code Section XI, IWA-4720.

Evaluation of the sleeved tubes indicates no detrimental effects on the sleeve-tube assembly resulting from reactor system flow, coolant chemistries, or thermal and pressure conditions. Structural analysis of the sleeve-tube assembly, using the demonstrated margins of safety, establishes its integrity under normal and accident conditions. The structural analysis has been performed for both TZ and TS sleeves. The TZ sleeves have a length of up to [ ]^{a,c} inches, which spans the degraded tube section at the top of the tubesheet and generally places the expansions above the sludge pile. The TS sleeves have a length of up to [ ]^{a,c} inches for a sleeve spanning a tube support section of the tube or a tube free span. The analyses also address the sleeve to plug equivalency with respect to system thermal and hydraulic effects for installation of one TZ sleeve and/or up to two tube support sleeves. Acceptable sleeve locations covered in this report are from the top of the tubesheet up to the u-bend region in both the hot and cold legs. The analysis was performed for Westinghouse designed plants with 7/8 inch, Alloy 600 steam generator tubes.

A TZ sleeve with a length of [ ]^{a,c} inches would result in approximately a [ ]^{a,c} inch span between the top-of-tubesheet and the lowermost part of the sleeve/tube joint above the tubesheet.

Mechanical testing has been performed to support the analysis prepared using ASME code stress allowable values. Corrosion testing of typical sleeve-tube assemblies has been completed and revealed no evidence of sleeve or tube corrosion considered detrimental under anticipated service conditions.

In addition to the analysis and test programs discussed in this report, a significant number of sleeves have been in operation for a number of years with no service induced degradation. Additionally, no detectable leakage has been associated with a tube with an Alloy 800 leak limiting sleeve. Table 2-1 provides the operational experience of the design described herein as well as two earlier variations of this same type sleeve. No degradation of the installed sleeve or steam generator tube in the area of the expansions has been identified. A portion of these sleeves were installed with a [ ]^{a,c} diametrical expansion, well above the [ ]^{a,c} target expansion of the sleeve described in this report. The sleeve installations are listed below. Based upon the testing and analysis performed, the sleeves do not result in a significant increase in the probability of occurrence or consequence of an accident previously evaluated, create the possibility for a new or different kind of accident, or result in a significant reduction in a margin of safety.

In conclusion, the Alloy 800 mechanical sleeve is established as an acceptable repair method.

Table 2-1 Alloy 800 Sleeve Installations and Operational Experience

Plant	S/G Model	T_{hot} (°F)	Joint Tube Expansion	Joint Design	Quantity of Sleeves	Cycle (Year) Installed	EFPY	Comments
Angra	W-D3	620		a,c	79	10 (04/01)	0.5	Operational
					179	11 (07/02)	-	P-RSG* 2006
					351	12 (10/03)	<1	
Calvert Cliffs 1	CE-67	595			68	14 (04/00)	1.8	RSG** 02/02
Calvert Cliffs 2	CE-67	595			365	13 (04/01)	~1.0	P-RSG 2003
Comanche Peak 1	W-D4				559	10 (04/04)	<1	Operational
Kori 1	W-51	607			1205	14 (03/96)	1.4	RSG 07/98
Krsko	W-D4	613			135	14 (05/98)	1.7	
					110	15 (05/99)	0.9	RSG 06/00
Ringhals 4	W-D3	610			76	17 (09/01)	~2.5	Operational
					91	18 (09/02)	~0.9	Operational
Tihange 2	FRAM-51M	617			10	13 (08/97)	3.6	RSG 06/01
Tihange 3	ACE-E	617			20	9 (08/95)	2.4	
					104	10 (11/96)	1.4	RSG 08/98
Ulchin 1	FRAM51B	613			986	9 (02/99)	~4.0	Operational
					702	10 (07/00)	~3	Operational
Ulchin 2	FRAM51B	613			1234	9 (02/00)	~3.2	Operational
					527	10 (09/02)	~1.2	“
Watts Bar 1	W-D3				148	5 (10/03)	<1	Operational
Yonggwang 4	CE-KSNP	621			35	5 (06/01)	~2.5	Operational
					151	6 (10/02)	~1.2	
Yonggwang 3	CE-KSNP	621			136	7 (06/03)	<1	Operational
TOTAL					7271			

Note:
* RSG-P: Replacement Steam Generator Planned for Year Shown ** RSG: Replaced Steam Generator in Year Shown

3 ACCEPTANCE CRITERIA

The objective of installing sleeves in steam generator tubes is twofold. The sleeve must maintain structural integrity of the steam generator tube during normal operating and postulated accident conditions and the repair sleeve must limit the primary to secondary leakage in the event of a through wall defect in the section of the steam generator tube spanned by the sleeve. Numerous tests and analyses were performed to demonstrate the capability of the sleeves to perform these functions under normal operating and postulated accident conditions. In doing so, the conditions for all of the Westinghouse operating plants with 7/8 inch Inconel 600 tubes were considered. Although the absolute values may differ from those at any specific plant, the evaluations are a function of the differential pressures and temperatures which are bounded by the conservative design basis values below.

Westinghouse Models '44,' '44F,' '51,' and '51M'

Primary Side:	594°F (operating)	2250 psia (operating)
	650°F (design)	2500 psia (design)
Secondary Side:	467.5°F (operating)	700 psia (operating)
	550°F (design)	1130 psia (design)
Accident Conditions:	Primary to Secondary ΔP	2650 psi (FWLB)
	Secondary to Primary ΔP	1130 psi (LOCA)

Table 3-1 provides a summary of the criteria established for sleeving in order to demonstrate the acceptability of the Alloy 800 sleeving techniques. Justification for each of the criterion is provided. Results indicating the minimum level with which the sleeves surpassed the criteria are tabulated. The sections of this report that describe the tests or analyses which verify the characteristics for a particular criterion are referenced in the table.

Table 3-1 Sleeving Criteria			
Criterion	**Approach**	**Results**	**Reference Section**
1. Repair sleeve-tube assembly structural integrity must be maintained for normal operating and accident condition per SAR.	Sleeve-tube assembly meets applicable ASME Code requirements, including fatigue.	[ ][a,c]	8.0
2. Sleeve/tube joint load capability 3 times normal Δp (4590 psi) and 1.4 times steam line break Δp (3584 psi) even for a severed tube.	Factor of safety of 3 for normal operating conditions and 1.4 for accident.	[ ][b]	7.0
3. Sleeve/tube joint load/ deflection capability sufficient for thermal expansion effects with non-severed or severed tube even if tube locked within tube supports.	No degradation of leak limiting or structural load capability for worst case thermal expansion cycles.	[ ][b]	7.0
4. Pressurization of annulus between sleeve and tube does not collapse sleeve during LOCA (1130 psi)	Prevention of sleeve failure based on tests.	[ ][b]	7.0
5. Exposure of sleeve-tube assembly to various primary and secondary chemistries without loss of functional integrity.	Demonstrate by corrosion testing and experience that sleeve-tube assembly corrosion resistance is adequate.	[ ][a,c]	6.0
6. Non-destructive exam of tube and sleeve pressure boundary with levels of detectability sufficient to show structural adequacy.	Periodic exams of tubes and sleeves are required to verify structural adequacy. Plug sleeved tube for any real degradation, irrespective of indicated penetration.	[ ][b]	5.0

Table 3-1 (cont.) Sleeving Criteria			
Criterion	**Approach**	**Results**	**Reference Section**
7. Sleeve installation to satisfactorily limit leakage in any direction and under normal and accident conditions.	Allowable leakage established by user per technical specification and other requirements (site boundary dose). Number of installed sleeves limited as needed with suitable margin assuming all sleeved tubes have through wall leakage paths.	[ ]^{b}	7.0
8. Sleeve installation effect on system flow rate or heat transfer capability of the steam generator is acceptable.	Allowable reduction in reactor coolant flow rate limited by user per technical specifications. Number of installed sleeves limited as needed. Steam pressure reduction due to reduced heat transfer to be limited by user based on commercial considerations.	[ ]^{b}	10.0

4 DESIGN DESCRIPTION OF SLEEVES AND INSTALLATION EQUIPMENT

4.1 SLEEVE DESIGN DESCRIPTION

The sleeve for defects at the top of the tubesheet, called a transition zone (TZ) sleeve, is shown in Figure 4-1. The sleeve for defects at tube support plates or egg crates, called a tube support (TS) sleeve, is shown in Figure 4-2. These Alloy 800 sleeves have a nominal outside diameter of [ ]^{a,c} and a minimum wall thickness of [ ]^{a,c}. Each sleeve type includes a chamfer at both ends to provide a lead in for equipment used to install the sleeve and to facilitate the inspection of the parent tube and sleeve. The TZ sleeve is [ ]^{a,c} long while the TS sleeve is [ ]^{a,c} long. [

]^{a,c} The TZ sleeve includes nickel band and a thermally sprayed nickel alloy band at the lower end. The nickel band improves sealing of the sleeve when it is rolled into the tube and the thermally sprayed nickel alloy band, which results in a rough surface, enhances the strength of the rolled mechanical joint. Based on the flow loss analysis detailed in Section 10, either sleeve type may be used in a steam generator tube. The flow loss analyses addressed up to two tube support sleeves in a steam generator tube and the combination of up to two TS sleeves and one TZ sleeve in the same tube.

4.2 SLEEVE MATERIAL SELECTION

The Alloy 800 tubing, from which the sleeves are fabricated, is procured to the requirements of the ASME B&PV Code Section II, Part B, SB-163, NiFeCr Alloy UNS N08800, and Section III, Subsection NB-2000. Additional requirements, as stated in the material specification (Ref. 4.7.1), are applied including a limit on [ ]^{a,c}. Other elements, [ ]^{a,c} are also more tightly controlled within the ASME specification limits. The final annealing temperature is specified as [ ]^{a,c}. The yield strength is specified to be between [ ]^{a,c} at 68°F.

The selection criteria for the sleeve material were its [ ]^{a,c} and its excellent corrosion resistance in both primary side and faulted secondary PWR environments (Ref. 4.7.2). Westinghouse's justification for selection of this material and condition is based on the data discussed in Section 6.

The following typical high temperature data has been used to assess the response of the sleeve/tube assembly under severe accident conditions.

Temperature (°F)	Alloy 600		Alloy 800	
	Yield Strength (ksi)	**Ultimate Strength (ksi)**	**Yield Strength (ksi)**	**Ultimate Strength (ksi)**
R.T. Min	35	80	30	75
1200	25.6	54.4	20.7	45.2
1500	12.8	23.4	10.7	21.3

4.3 SLEEVE-TUBE ASSEMBLY

The installed sleeve is shown in Figure 4-3 for a transition zone repair and in Figure 4-4 for a repair at a tube support. The [ ]^{a,c} inch long sleeve spans the defective region of the steam generator tube at the top of the tubesheet in the Transition Zone (TZ). [

]^{a,c}

The sleeve installed at a Tube Support (TS) elevation or in a free span section of the steam generator tube is [ ]^{a,c} inches long. [

]^{a,c}

A plant specific document specifies the allowable locations of tube ECT indications in order to perform a successful sleeve installation. This criterion is utilized to determine whether a tube is an acceptable sleeving candidate. Indications outside of the acceptable locations would not be sleeved.

A sleeve installed in a steam generator tube, which does not meet the minimum requirements, details of which are discussed in Section 9, may be re-rolled, for the rolled joint, or re-expanded for the hydraulic expansion.

4.4 PLUGGING OF A DEFECTIVE SLEEVED TUBE

In the unlikely event that a sleeved steam generator tube is found to have an unacceptable defect in the pressure boundary portion of the tube or sleeve, the steam generator tube can be taken out of service by installing standard, site approved mechanical or welded plugs at both ends of the tube. Additionally, should either of the joints not attain the required expansion/torque ranges within the number of allowed re-applications, not be positioned at the proper elevation, or have the required expansion spacing, the sleeve installation would be considered unacceptable and the tube plugged in accordance with installation procedures.

4.5 SLEEVE INSTALLATION EQUIPMENT

The equipment used for remote installation of sleeves in a steam generator is made up of the following basic systems. These systems are:

- Remote Controlled Manipulator
- Tool Delivery Equipment
- Tube Conditioning Equipment
- Sleeve Expansion Equipment
- Sleeve Rolling Equipment
- Nondestructive Examination Equipment

These systems, when used together, allow installation of the sleeves without entering the steam generator, hence reducing personnel exposure to radiation.

The tooling and methods described in the following sections represent the present technology for leak limiting sleeve installation. As technological advances are made in sleeve installation to improve the installation rate and/or decrease the personnel exposure, the new tooling and/or processes may be utilized after they have been laboratory-verified to provide improved sleeve installation methods.

4.5.1 Remote Controlled Manipulator

The remote controlled manipulator serves as a transport vehicle for inspection or repair equipment inside a steam generator primary head. These sleeves can be delivered off of a multitude of different manipulators, including the Genesis, ROSA and Roger manipulator systems.

The Genesis and Roger systems utilize a leg installed between the tubesheet and the bottom of the primary head, while the ROSA system utilizes a tubesheet mounted base plate. Each system has an arm configuration with a varying number of joints. These joints provide the degrees of freedom required for delivery of the tooling to the steam generator tube. Each arm is moved independently with position controlled electric motors. The arm allows motion for tool alignment in both square pitch and triangular pitch tube arrays. Computer control of the manipulator allows the operator to move and position sleeving tools accurately below the steam generator tube to be sleeved.

4.5.2 Tool Delivery Equipment

The purpose of the tool delivery equipment is to support and vertically position the various tools required for the sleeving operations. The tool delivery system consists of two major components; a probe pusher located outside the steam generator and a guide conduit extending from the probe pusher to the adapter on the robotic arm.

The probe pusher is a Zetec 10-D or similarly configured drive wheel system. The probe pusher is located outside the steam generator, adjacent to the manway. The guide conduit extends from the probe pusher to the adapter block located on the manipulator. The adapter block includes a fitting for mounting on the manipulator. Two pins extending above the adapter block are used to align the guide conduit relative to adjacent tube locations.

A remotely actuated sleeve loader may be used in conjunction with the probe pusher delivery system. The sleeve loader consists of a magazine mounted on an actuator which positions a single sleeve for insertion into the steam generator.

Alternate Sleeve Delivery Equipment

As an alternate to the probe pusher delivery system, a tool driver mounted directly on the robotic arm can deliver the sleeves.

The tool driver is attached to the end of the manipulator arm by a fitting and lock mechanism. The tool driver includes two sets of gripper wheels that work in conjunction with one another to insert or withdraw the tool. The drive grippers are powered by electric motors to insert and remove the various sleeving tools and the sleeve into the steam generator tube. Vertical positioning of the tool is accomplished by using hardstops and/or visual references that are verified by using a small camera located on the tool driver.

4.5.3 Tube Conditioning Equipment

Prior to sleeve installation, the steam generator tube I.D. is mechanically conditioned with a high speed buffing tool. This operation is performed using a tool similar to that shown in Figure 4-5. An air motor rotates the tool head as it is inserted into the bottom of the tube. The buffing tool removes raised material and some of the oxide, and prepares the sealing surface of the tube in the areas of the hydraulic expansions for the sleeve. Based upon current testing and evaluation, this process step may be eliminated in the future when a sufficient confidence level is developed.

An evaluation of field experience involving visual examination of over 600 conditioned tubes, in four different plants, indicated that process control, in the form of normal in-process instructions and quality assurance surveillance, is sufficient to ensure acceptable conditioning of the tube I.D. No axial scratches, loose particles, or other detrimental conditions were identified during these inspections.

4.5.4 Sleeve Positioning/Expansion Equipment

The sleeve expansion equipment is used to provide the required structural fit-up of the sleeve at the upper end, for a TZ, and at both the upper and lower joints for a TS location. The expansion of the sleeve is performed with a tool that makes [ ]a,c simultaneously. The expansion tool is then repositioned for the remaining [ ]a,c in an expansion joint.

The minimum distance between expansion joints for a [ ]a,c inch TS sleeve which must span a tube defect based on Figure 4-4 is [ ]a,c inches. This will adequately cover a maximum tube defect axial length of [ ]a,c inches, considering the sleeve elevation tolerance of [ ]a,c inches. This span will also adequately cover the uncertainty in the elevation of the tube support plate or eggcrate support.

The sleeve is located on the sleeve expansion tool by a sleeve hardstop approximately the same O.D. as the sleeve. The expansion tool functions to guide the sleeve into the tube and install the sleeve to the selected elevation within the steam generator tube. For both the TZ and TS sleeves a tool hardstop on the sleeve expansion tool, which contacts the tube end is provided for proper sleeve vertical positioning within the steam generator tube. Once the sleeve is at the proper elevation within the steam generator tube, it is hydraulically expanded.

The expansion tool, shown in Figure 4-6, consists of a mandrel and a bladder. The bladder contains the water that is used as the pressurization fluid. The expansion tool simultaneously performs [three of the six expansions]a,c per expanded joint. The expansion tool is then repositioned within the sleeve [to complete the remaining expansions]a,c. For a sleeve at a TZ elevation, the expansion tool is [repositioned once]a,c. For a sleeve at a TS elevation, the expansion tool is [repositioned three times]a,c. The sleeve is located on the expansion tool prior to insertion in the steam generator tube. A low pressure hold is applied to the bladder to secure the sleeve on the expansion tool without distortion of the sleeve. When the sleeve is in position within the tube, the hydraulic expansion tool is pressurized, expanding the bladder directly against the inside diameter of the sleeve causing expansion of the sleeve.

[

]a,c

A sleeve not meeting the minimum criteria for hydraulic expansion may be re-expanded. Re-expansion would be required only if inadequate volume is injected into the bladder and applied to the sleeve/tube assembly. Operator error is eliminated by use of the repair software loaded on the workstation for parameter control. There is no operator control of the process, other than to terminate it. Only a malfunction in the system such as a loss of power, burst expansion bladder, leaking fittings, or other equipment failure would produce such a result. Pre-operational equipment calibration, functional checks, and periodic bladder replacement are included in the installation process procedures to minimize these events. Should an acceptable joint not be obtained after the allowed number of re-expansions, the tube would be plugged. Verification of this process is discussed in subsection 9.3.2.

4.5.5 Sleeve Rolling Equipment

The sleeve rolling equipment is used to expand the lower end of the TZ sleeve into contact with the steam generator tube within the tubesheet, forming a strong leak tight joint. The rolling tool is positioned within the steam generator tube by the manipulator. The rolling equipment consists of the air motor, the sleeve expander, torque readout, computer control and a torque calibration unit. The sleeve expander includes a shoulder which supports the bottom edge of the sleeve during the sleeve rolling process. The approximately [ ]a,c on the lower end of the TZ sleeve. The sleeve is expanded to a torque which has been demonstrated by testing to provide a leak tight joint. A record of the rolling tool torque is taken by the computer for further evaluation of the rolling process for individual sleeves. A rolled joint that fails to meet the minimum torque criteria may be re-rolled. Such a failure almost always results from a loss of air pressure to the tool or, less frequently, from equipment damage. Pre-operational equipment calibration and functional checks, are included in the installation process procedures to minimize these events. Should an acceptable roll not be obtained after the allowed number of re-rolls, the tube would be plugged. Experience with this process has shown re-rolling to be required in less than one-half of one percent of the cases. Verification of this process is discussed in Section 9.4

The roll expander (Figure 4-7) used to hard roll the sleeve within the tubesheet has an effective length of approximately [ ]a,c. The shoulder on the roll expander stops against the bottom of the sleeve during the rolling process. The sleeve is then rolled two times to a torque that results in a [ ]a,c sleeve wall reduction. This wall thinning is sufficient for leak/load requirements as well as providing adequate resistance for future corrosion cracking. The sleeve roller design and the rolling process are essentially a duplicate of those used for Westinghouse's welded sleeve and mechanical plug installations. This process does not include hydrostatic expansion of the sleeve before roll expansion.

4.5.6 Nondestructive Examination

As described in Section 5, the "+" point rotating probe will be used to perform an initial eddy current test (ET) acceptance and baseline inspection of 100% of the installed sleeves. Other eddy current coils and/or methods will be considered for any complementary inspection capability they may provide. The ET fixture, with conduit, is used on the manipulator arm to position the probe.

4.6 ALARA CONSIDERATIONS

The steam generator repair operation is designed to minimize personnel exposure during installation of sleeves. 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 sleeve delivery system allows the sleeve to be positioned on the expansion tool outside the steam generator and away from the manway. The expansion tool and sleeve are then delivered into the steam generator remotely through the guide conduit, further reducing the number of operations performed in the manway. The conduit adapter is designed so that the fitting quickly attaches to the manipulator.

The tools are simple in design and the majority of the sleeving operations are performed remotely. Spare tools are provided so that tool repair at the manway is not required. If tool repair is necessary, the tool is removed and the sleeving operation continues using a spare tool. The tool may or may not be repaired during the outage but repair is performed in an area which does not result in significant radiation exposure.

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

Installation of the Alloy 800 sleeve is also expected to reduce personnel exposure over that required to plug a steam generator tube. The operations required to install an Alloy 800 sleeve are similar to those required to install a plug in a steam generator tube. The Alloy 800 sleeving operations, however, are performed in one channel head, saving the exposure associated with the plugging operations in the second plenum.

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

4.7 REFERENCES TO SECTION 4

4.7.1 Purchasing Specification for Alloy 800 Tubing, Specification No. 00000-OSW-020, Latest Revision.

4.7.2 Corrosion Resistance of SG Tubing Material, Incoloy 800 mod. and Inconel 690 TT, by R. Kilian, N. Wieling, and L. Stieding, from Werkstoffe und Korrosion 42, pp. 490-496 (1991).

a,c

Figure 4-1 Leak Limiting TZ Sleeve

a,c

Figure 4-2 Leak Limiting TS Sleeve

a,c

Figure 4-3 Leak Limiting TZ Sleeve Installation

a,c

Figure 4-4 Leak Limiting TS Sleeve Installation

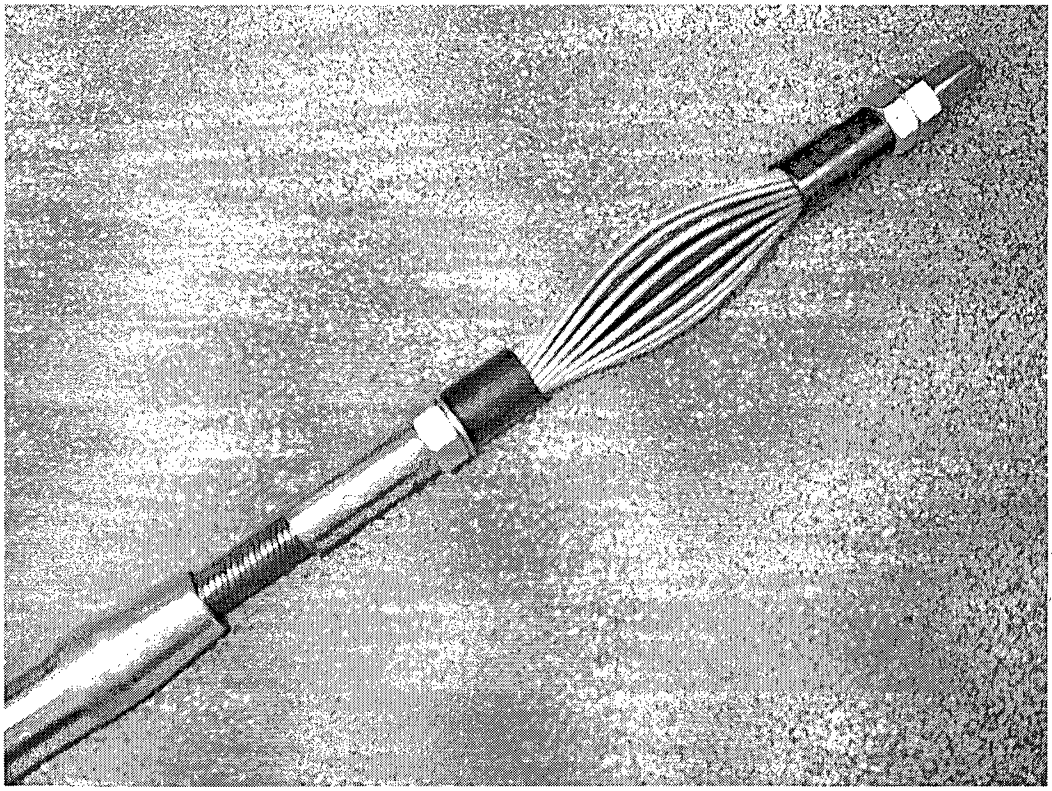

Figure 4-5 Tube Conditioning Tool

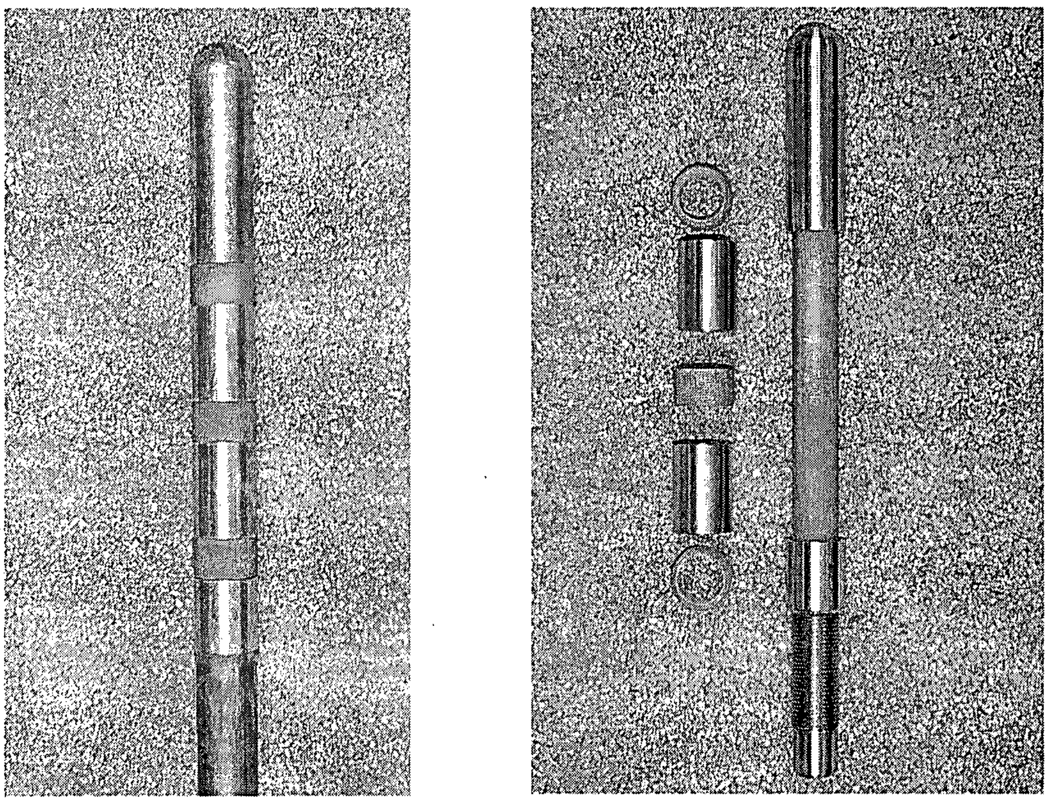

Figure 4-6 Sleeve Expansion Tool

Figure 4-7 Sleeve Rolling Tool

5 SLEEVE EXAMINATION PROGRAM

5.1 BACKGROUND

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In addition, there will be an inspection process for the dual purposes of process verification for individual steps as well as confirmation of the pressure boundary integrity. Eddy current inspection methods will be used for this purpose.

For process verification, the following inspection will be performed for all sleeves at all locations until sufficient confidence is developed to do otherwise.

[

]a,c

In-service inspection of the sleeved tubes will be done as part of the periodic inspection program of the steam generator tubing using eddy current testing techniques. The eddy current test method is a technique whereby electrical currents are induced electromagnetically from the test coil into the sleeves and parent tube material. The electrical currents are interrupted or impeded by the presence of flaws in the material, which results in a change in the test coil impedance. This impedance change is processed and displayed on the test instrument to indicate the presence of a flaw. During the installation, all sleeves will be examined. A sampling program consistent with inspection requirements will be used for subsequent examinations. The ISI inspection will be performed using the "+" point coil rotating probe. Other coils and/or methods will be considered for any complementary inspection capability they may provide. The inspection method qualified has been used in operating steam generators in fourteen plants for both the initial installation acceptance and the subsequent in-service inspection. Over 7200 sleeves have been installed and inspected as shown in Table 2-1.

The objective of the installation examination is to establish ISI baseline data and initial installation acceptance data on the primary pressure boundary of the sleeve-steam generator tube assembly. The eddy current inspection method used has a documented qualification, References 5.3.1 and 5.3.2, in accordance with Appendix H of the EPRI PWR Steam Generator Examination Guidelines, Revision 5 dated September 1997. The essential variables specified in the Appendix H portion are documented and will be used in the field procedures. Also, an analysis procedure for interpreting data has been written and used for field inspections. All data analysts are required to review the Appendix H report and analysis guidelines prior to performing any data analysis. EPRI Appendix H guidelines specify that adequate flaw detection capability be demonstrated for flaws > 60% throughwall. For the purpose of this sleeve inspection qualification, this value was reduced to >50% throughwall for the parent tube and >45% for the sleeve in order to provide an operational margin between the detection limit and the structural limit for defect growth. For sleeves with minimum wall thickness, the structurally limiting flaw depth per Regulatory Guide 1.121, calculated using a conservative crack configuration model (Section 8.2), is 45%, and for the tube the limit is greater than 60%. A sufficient number of flaw samples has been used to demonstrate that the statistical requirements for probability of detection are met.

Based upon Westinghouse's experience with the installation of Alloy 800 and TIG welded sleeves and the fact that Westinghouse has not established an ECT sizing error, it has been Westinghouse's recommendation and the plant owners' decision to plug a tube upon the detection of a defect in the pressure boundary portion of the sleeve or in the parent tube immediately adjacent to the sleeve nickel or microlok bands.

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]^{a,c}

The method used for sleeving inspections has been to establish detection capability with an operational margin relative to structurally limiting flaws and to plug flaws upon detection. Accordingly, no attempt was made to size flaws or to leave detected flaws in service at this time. By this approach, the sizing accuracy does not need to be quantified. If future developments provide a qualified flaw sizing technique, an updated Appendix H qualification report will be submitted.

The pressure boundary for a TZ sleeve-tube assembly is considered to be: a) the entire sleeve except for the portion above the [ ]^{a,c} hydraulic expansions, b) the steam generator tube above the hydraulic expansions and below the rolled joint and c) the steam generator tube behind the hydraulic expansion and rolled joint regions. The pressure boundary for a TS sleeve-tube assembly is considered to be: a) the sleeve from the lower of the [ ]^{a,c} expansions in the lower joint to and including the upper of the [ ]^{a,c} expansions for the upper joint, b) the steam generator tube above the upper expansion joint and below the lower expansion joint and c) the steam generator tube behind the hydraulic expansion joint region.

Consequently, there are four distinct regions of the pressure boundary, as shown in Figures 5-1 and 5-2, that have been addressed in the Appendix H qualification report:

1. The sleeve-tube assembly in the mechanical joint region (either expansion or rolled).
2. The sleeve between and including the upper joints and lower joints (either expansion or rolled depending on sleeve type).
3. The pressure boundary region of the steam generator tube behind sleeve.
4. The unsleeved region of the steam generator tube.

The tooling and methods described in this section represent the present technology for leak limiting sleeve inspection. As technological advances are made in NDE methods for sleeve inspection, the new equipment and/or processes may be utilized after they have been qualified to provide improved sleeve inspection.

5.2 SLEEVE/TUBE SAMPLES

Samples with the sleeve-tube configuration were made for the qualification testing effort. The qualification test program was performed in accordance with 10 CFR 50, Appendix B. Each of the samples was a configuration that represents the material, dimensions and geometries of the as-installed sleeves. Qualification was performed on the probable flaw orientation as required by Appendix H. Samples were fabricated with axially and/or circumferentially oriented notches in both components representing flaws at each of the transitions and expansion zones. Corrosion testing of sleeve/tube samples as well as industry experience to date indicate that in the event cracking did occur it would be oriented in these directions. In addition, sleeve and tube flaws in the pressure boundary away from the expansion regions were included in the sample set. Tooling representative of the field equipment was used to assemble the samples.

In addition to the samples with EDM notches, a limited number of samples with corrosion cracking in the parent tube were also included in the overall program. These tube samples included sixteen (16) sleeve/tube assemblies containing laboratory grown IGSCC in the parent tube behind the sleeve, as well as a pulled tube from an operating steam generator in Europe. Because of the Appendix H requirements, these flaws could not be used in the qualification data set, however, this data is useful for reviewing real flaws and supplementing the EDM data set. None of the flaws were behind the nickel band.

As it was originally postulated that degradation of the parent tube adjacent to the sleeve to tube hardroll joint elevation was unlikely, samples containing flaws in the tube adjacent to the nickel or microlok bands were not included in the Appendix H qualification program. However, evaluation of calibration standards concludes that axial and circumferential degradation of about 70% in the parent tube behind the nickel band shows these limited length notches are readily detectable with Plus Point RPC probes. While SCC indications offer a more challenging condition for detection compared to EDM notches, the condition that would potentially affect leakage integrity of the joint would be the case where the parent tube axial degradation extends from above to below the nickel band region. For this case, meaningful degradation of the parent tube is expected to be readily detectable using current techniques. A similar result is expected for circumferential degradation.

The observed circumferential degradation at significant depths below the top of tubesheet in units with sleeves or considering sleeving has involved limited arc lengths, and a postulated separated tube adjacent to the sleeve nickel band is not expected within these steam generators. If this condition were assumed to be present, it is expected that this condition would be detectable despite the NDE challenges associated with the sleeve nickel band. Both a postulated separated tube, and tube with a 100%TW SCC flaw extending for an arc length commensurate tensile overload capacity of the tube at 3ΔPNO conditions (approximately 280 degrees arc length) are expected to be readily detectable using current eddy current techniques. The Plus Point amplitude responses for both of these would be substantially larger than the EDM notch response of the standard due to the SCC length at 100%TW. Therefore, circumferential degradation of the parent tube that could possibly influence the axial load transference capability of the tube is expected to be detected.

As described in Section 7.6 and References 5.3.3 and 5.3.4, a testing program was conducted to verify a basis establishing that axial and circumferential degradation of the parent tube adjacent to the nickel band, at any depth, will not prevent the sleeve from satisfying the design requirements. Thus, flaw detection capabilities within the parent tube adjacent to the sleeve nickel band are not necessary in order to evaluate continued operation of the sleeved tube. Nevertheless, as current inspection methods can identify degradation of the parent tube beginning at depths that approach a through wall condition, sleeved tubes with identified degradation of the parent tube in this region will be removed from service by plugging prior to the degradation of the parent tube achieving the depths considered in the test program.

5.3 REFERENCES TO SECTION 5

5.3.1 EPRI Steam Generator Examination Guidelines Appendix H Qualification for Eddy Current Plus-Point Probe Examination of ABB CE I-800 Mechanical Sleeves, ABB CENO Report No. 97-TR-FSW-019P, Latest Revision.

5.3.2 Eddy Current Examination of I-800 Sleeves Equivalency Assessment 0.750 Inch Configuration to .875 Configuration, Westinghouse Report MRS-TRC-1425, September 2003.

5.3.3 WOG-05-338 Position Paper "NDE Issues Related to TIG Alloy 800 Sleeves with Regard to Sleeve Nickel Band NRC Discussion, Revision 1," July 19, 2005.

5.3.4 SG-SGDA-05-48-P, Revision 1, "Test Results Related to TIG and Alloy 800 Sleeve Installation in 3/4 Inch and 7/8 Inch OD SG Tubing In Service Inspection Requirements," January 2006.

a,c

Figure 5-1 TZ Sleeve Pressure Boundary Description

a,c

Figure 5-2 TS Sleeve Pressure Boundary Description

6 ALLOY 800 SLEEVE CORROSION PERFORMANCE

The corrosion assessment of the Alloy 800 sleeve is based on the following experiences and test programs:

- The long term service performance of Alloy 800 steam generator tubes and rolled tube plugs in operating steam generators
- Laboratory corrosion tests on full scale mock-ups of the Alloy 800 sleeve/Alloy 600 tube configuration
- Westinghouse's welded sleeve corrosion program
- Correlation of operating experience with these tests

Alloy 800 has been successfully used as a steam generator tube and plug material in a number of units located primarily in western European countries. Some of these units have operated with hot leg temperatures as high as 618°F. This data, in addition to evaluations by Westinghouse and others have indicated that Alloy 800 is a viable sleeve material for domestic steam generator applications. As is the case with many steam generator tube repair methods, the principal issue is whether the repair itself will create conditions that will lead to future failures of the susceptible Alloy 600 tubing. The Alloy 800 mechanical sleeve installation is specifically designed to address this issue by imparting the minimum amount of residual stress in the parent tube consistent with a very low leak rate. In so doing, the potential for future tube failures is minimized.

6.1 SUMMARY AND CONCLUSIONS

The Alloy 800 sleeve provides corrosion resistance under anticipated design and fault primary and secondary environments without increasing the potential for future corrosion induced failures of the pressure boundary section of the original tube. This conclusion is based on laboratory data and operating experience for both Alloy 800 and Alloy 600 steam generator tubing and is verified by corrosion tests conducted by Westinghouse.

6.2 LABORATORY DATA AND OPERATING EXPERIENCE

6.2.1 Primary Side Performance

The principal concern with a sleeve joint on the primary side is the potential for primary water stress corrosion cracking (PWSCC) as a result of the stresses imparted to the tube due to the sleeve installation. PWSCC of the Alloy 800 sleeve is not a principal concern because of excellent performance of Alloy 800 steam generator tubes during extensive operating experience as well as past test results. The corrosion resistance of the sleeve/tube joint will be governed by three elements: (1) the chemical and metallurgical conditions of the sleeve and tube material, (2) the water chemistry within the sleeve/tube crevice, and (3) the stresses (residual from sleeve installation plus operating) and strains associated with the sleeve/tube mechanical joint. The mechanical joint will not affect the chemical composition of either the tube or sleeve and will result in only a mildly cold worked condition in either material. Some oxygen will initially be present within the sleeve/tube crevice, however any tendency to trap oxygen will be reduced with this design because of joint leakage at lower temperatures. Based on this, oxygen-rich crevice conditions are not considered to last long enough after startup to be of concern. Experience with Alloy 800 tubes in European steam generators, as well as testing described herein, indicates Alloy 800 exhibits excellent corrosion resistance under both primary and secondary nominal and fault environments. Further, examination of in-service sleeved tubes with similar crevices, although of the welded Alloy 690 design, have not shown any corrosion attack associated with crevice deposits. Thus, the long term corrosion resistance of the sleeve/tube joint will depend primarily on the local stress and strain level which will be determined by the plastic deformation in the region of the joint.

Alloy 800 has seen considerable usage under PWR conditions without experiencing primary or secondary side stress corrosion cracking. As described in Reference 6.4.1, this experience is based on over two hundred thousand tubes in service for up to nineteen years with only minimal tube failures. This resistance is due to the alloy's chemical composition and heat treatment. In particular, the excellent performance of Alloy 800 in previously installed sleeves (see Section 9), hydraulically expanded tube to tubesheet joints and rolled blind steam generator tube plugs (similar to the Alloy 690 plugs employed by Westinghouse) have provided significant primary side experience at strain levels equal to or greater than those experienced during installation of this sleeve. For this reason the Alloy 800 sleeve is not considered to be the limiting component of the assembly.

An initial assessment of the Alloy 800 sleeve corrosion performance can be made by comparing the level of plastic deformation in the sleeve joint with that typically present at the top of the tubesheet in the steam generators. Whereas the strain in the tube due to sleeve installation is up to [ ]^{a,c}, tube expansions in the tubesheet are up to 1.5% strain over a comparable [ ]^{a,c} length. As such, it can be expected that the sleeve joint would have a longer life than the original tube to tubesheet expansion zone.

In some plants, such as ANO-2 and Calvert Cliffs 2, the tubing has not demonstrated significant PWSCC at the mechanically expanded tubesheet transition zone. For example, examinations of tubes removed from ANO-2 (total of 10 tubes) confirmed that the mode of degradation of the Alloy 600 tubes has been O.D. initiated intergranular stress corrosion cracking (IGSCC) and/or intergranular attack (IGA) (Ref. 6.4.2, 6.4.3, and 6.4.4). Only where severe plastic deformation has occurred, as in the case of kinetically expanded sleeves at ANO-2, has any PWSCC been indicated. In these cases, it can be argued that since the sleeve imparts less strain into the tube than the tube has experienced at the tubesheet, the sleeve joint would be expected to have a life greater than that of the original tube. Even in cases where PWSCC has been experienced, the resulting sleeve joint life would be expected to be no less than the original tube life. This conclusion would be applicable to either Westinghouse or Combustion Engineering designed steam generators.

6.2.2 Secondary Side Performance

In addition to the experience and laboratory data described in Reference 6.4.1, Westinghouse has evaluated Alloy 800 under model boiler conditions. In only one out of three boilers, run with as much as 30 ppm chloride in the secondary side bulk water, was any corrosion, in the form of modest pitting and shallow intergranular attack observed (Ref. 6.4.5). Additionally, a fourth model run with sulfate fault secondary chemistry found some wastage but no stress corrosion cracking (Ref. 6.4.6). Based on this data, the Alloy 800 sleeve is considered to be sufficiently resistant to potential fault chemistries to maintain its integrity in the event through wall penetrations are produced in the parent tube.

As stated in subsection 6.2.1, for some plants the mode of degradation of the Alloy 600 tubes has been O.D. initiated intergranular stress corrosion cracking (IGSCC) and/or intergranular attack (IGA). This has been the case for circumferentially oriented degradation in the tubesheet expansion transitions and for axially oriented degradation at tube support locations. The destructive examinations of over 20 removed tubes from ANO-2 and Calvert Cliffs 2 have revealed only one tube with primary side initiated stress corrosion cracking (PWSCC). The general lack of PWSCC to date at these plants indicates that the probability of having PWSCC is low and that the potential degradation of concern is O.D. initiated IGA or IGSCC.

In order to minimize the possibility of tube corrosion attack at the upper mechanical joints, the length and positioning of the sleeve have been designed such that the mechanical joints are located above the sludge pile and above and below the tube support elevation. Under these circumstances the potential for fault species to concentrate and cause stress corrosion failures is minimized. Nevertheless, as in the case of primary side performance, the strains and applied stresses associated with these joints are less than those experienced by the tube to tubesheet expansion joint and as such would be expected to provide lifetimes at least as great as this section of the tube.

6.2.3 Overall Performance and Experience

The sleeve/tube corrosion performance, including the mechanical joint area, is expected to be acceptable based on the following:

- Plus point inspections after more than one fuel cycle at KORI 2 and Tihange 3 indicated no degradation of the sleeve or tube hydraulic expansion area. Some of these sleeve installations involved tube expansions resulting in higher strains (up to 2.5%) than the current design.

- At ANO-2, many RPC eddy current examinations at the expansion transition at the top of the tubesheet have been performed over many fuel cycles. No substantial degradation has been found provided the tube location was not within the sludge pile. Since the Alloy 800 tube sleeve joint will be above the sludge pile and since tube strain for the joint will be on the order of 10% of that of an expansion transition, satisfactory tube service is expected with this design.

- Although temperatures are lower, the U-bend region of the tubes at ANO-2 and Calvert Cliffs 1 and 2 provides another base of comparison which indicates good expected tube performance with the Alloy 800 sleeve design. Here, tube strain levels about 100 times that for the subject tube repair have been in service for many fuel cycles with satisfactory corrosion performance.

6.3 SLEEVE/TUBE ASSEMBLY CORROSION TESTS

6.3.1 European-Based Corrosion Tests

Since late 1995, Westinghouse Reaktor has prepared sleeve/tube test assemblies for corrosion tests performed by Laborelec Laboratories in preparation for Alloy 800 sleeve installation at Tihange 2 and 3.

Two sets of tests were performed. The first set, using archive tubing from Tihange 3, was performed for a pre-established time in order to verify a minimum sleeved tube life. The second set, using SCC susceptible tubing, was conducted until such time as all the sleeved tubes had cracked.

The sleeved specimens were prepared with tube diametrical expansions of up to [ ]b. In addition, reference roll transition assemblies, prepared from the same tubing, were expanded to the original generators' design configuration (approximately 2.5% with 4% wall reduction).

All assemblies were pressurized to a differential pressure of 1300 psi at 660°F with deaerated 10% sodium hydroxide as the I.D. test environment.

The goal of the Tihange 3 Alloy 800 sleeving program was to keep the steam generators in service for three cycles until replacement units were available. Inasmuch as the roll transitions had begun to crack after one cycle of operation, the goal of the corrosion program was for the time to failure of the sleeved assemblies to be at least three times as long as that for the reference roll transition specimens.

The four reference roll transition specimens failed after [ ]b. Based on this value, the goal of the sleeved specimens was a time to failure of greater than [ ]b. The three sleeved assemblies maintained pressure throughout the test and the test was stopped after [ ]b of operation. No cracks were observed in the parent tube expansion transitions of these specimens.

In the case of Tihange 2, a more long term goal was desired thus requiring an assessment of the total lifetime of the sleeved tube. Two roll expansion reference samples exhibited through wall cracking in [ ]b. Nine sleeved samples were also tested and exhibited lifetimes of [ ]b representing an increased life of [ ]b times that of the roll transition.

6.3.2 Welded Sleeve Corrosion Tests

Westinghouse conducted a similar corrosion test in support of welded sleeve installation in Westinghouse "D" Series steam generators. The purpose of the test was to determine the approximate life of the sleeve/tube joint in the as-welded and the post weld heat treated conditions. The sleeved tube specimens were prepared using EPRI-supplied PWSCC susceptible Alloy 600 tubing. All eight samples were expanded to a tube diametrical expansion of [ ]b and welded using standard welding parameters. Four samples were then post weld heat treated. Additionally, a series of c-rings were prepared for stress determination. The assemblies were pressurized to a differential pressure of 2250 psi at 660°F with deaerated 10% sodium hydroxide.

The as-welded specimens failed at an average time of [ ]b, while the PWHT specimens failed at an average time of [ ]b. All cracks occurred in the [ ]b. Experience has shown that the roll transition region in "D" Series tubes begins to crack after two cycles of operation. Using this data, as well as relationships developed for time to failure for pure water stress corrosion cracking of Alloy 600, it was determined that the as-welded joint life was [ ]b.

6.3.3 Confirmatory Alloy 800 Tests

In order to verify the assessments described earlier, accelerated corrosion tests were conducted with full length sleeved tube assemblies (Figure 6-1). This set of tests was performed with the goal of verifying the viability of the installed Alloy 800 sleeve in a caustic environment, as well as confirming the joint performance under aggressive conditions. These assemblies were fabricated with tube expansions ranging from the nominal value of [ ]^b to the maximum value of [ ]^b, duplicating the anticipated range of expansions for sleeve installation.

This configuration was used to test both primary and secondary side response in accelerated environments. In the primary side case, the sleeve/tube assembly was pressurized on the I.D. to a differential pressure of approximately 1600 psi with deaerated 10% sodium hydroxide at 660°F.

For the secondary side tests, the O.D. environment consists of deaerated 10% sodium hydroxide at 660°F. In this case, the samples are immersed in an autoclave and pressurized, with deionized water, to a differential pressure of 1600 psi. C-ring samples stressed to various levels were also included in the secondary side test capsules.

It is considered that these samples represent the worst case scenario for tubes that are either locked or that are free to move at the tube supports. This conclusion is based on the stresses measured in the installation stress assessment described in Section 7.4 and the operating stresses described in Section 8. In the case of the corrosion samples, the higher pressure stresses resulting from the higher test temperature and the capped tube end, produce a higher applied axial tensile stress in that section than would be experienced by the in-service sleeved tube.

The assemblies were monitored on a continual basis in order to determine whether or not the assemblies maintained pressure. Loss of pressure would indicate a through wall crack in the parent tube or a test fixture problem and would require the test to be interrupted for inspection. The autoclaves containing the test assemblies were removed from service at various junctures in order to visually inspect the assemblies.

The primary side tests, which had average tube expansions of [ ]^b, were exposed for over [ ]^b with no leakage as defined by loss of pressure. Two of the three assemblies developed [ ]^b.

The secondary side tests, which had average tube expansions of [ ]^b, were exposed for over [ ]^b, with two assemblies being exposed for [ ]^b, respectively. One of the assemblies developed a [ ]^b during the test, while the other three maintained pressure until shutdown.

The Alloy 800 sleeves showed no signs of cracking in both the primary and secondary side tests.

6.3.4 Discussion

The corrosion tests performed on various Alloy 800 sleeve and tube configurations, in conjunction with operating experience, indicate that the Alloy 800 sleeve is a viable repair methodology for use in steam generators with degraded Alloy 600 tubing.

The results of the welded sleeve corrosion tests performed by Westinghouse indicate that weld joints in the as-welded condition will have a service life, as a minimum, of [ ]^{b} times the time to failure of the roll transition regions of the parent tube. Removal of an as-welded sleeved tube from Prairie Island after [ ]^{a,c} of service revealed no evidence of weld joint degradation. This field data tends to confirm the test results of the program if only on a preliminary basis. This data is applicable to the Alloy 800 program for the following reasons. The corrosion tests were performed in a similar manner for both programs. The expansions placed in the tube for the two types of sleeves are similar, with the expansions of a larger diameter imparted on the welded sleeved tube. Even with this larger diameter expansion, the [

]^{a,c}. To reiterate, this would be the equivalent of 2.5 times the time to failure of the parent steam generator tubes.

The final set of confirmatory tests performed by Westinghouse support the previous data generated, as well as the field experience. The samples accumulated [ ]^{b} times the exposure time of the Westinghouse Reaktor samples and [ ]^{b} times the exposure time of the as-welded samples while maintaining pressure and not exhibiting any leakage. The Alloy 800 exhibited no degradation, confirming both field experience and previous corrosion tests performed on the alloy during its development phase for nuclear applications.

The results of corrosion tests performed for Westinghouse Reaktor indicate that the installation of Alloy 800 sleeves in SCC tubing will result in a repair with a service life many times the original roll transition life.

The actual lifetime of sleeved tubes in a particular plant will depend specifically on the tube condition, the failure mechanism and tube joint designs of that plant. As such, a method which compares the ratio of failure times during the corrosion testing to that for the life of the original tube is the most appropriate method for determining the potential sleeved tube life.

In order to evaluate the life of sleeved tubes, the Arrhenius relationship established for stress corrosion cracking can be applied. Using this relationship, comparisons can be made between the ratio of failure times for the roll transition baseline and the sleeved tube, in the test environment and under primary coolant conditions.

Inasmuch as the NaOH tests were conducted under isothermal conditions for both the roll transition and the sleeve mechanical joint, the temperature component of this relationship is unity. As such, the determining factor with respect to life is the total stress associated with the joints. Where tests conditions were controlled to apply the same differential pressure at temperature as is generally experienced in the steam generator (9 Mpa / 1300 psi), no correction to operating conditions is required. Sleeve life can therefore be determined from the following relationship and the appropriate value for n:

$$\frac{t_{sleeve}}{t_{rolltrans}} = \left(\frac{\sigma_{sleeve}}{\sigma_{rolltrans}}\right)^{-n}$$

Where:

t_{sleeve}	=	Time to failure of the sleeved tube
$t_{rolltrans}$	=	Time to failure of the original tube at the roll transition
σ_{sleeve}	=	Stress in the sleeved tube
$\sigma_{rolltrans}$	=	Stress in the tube at the roll transition
n	=	Empirically determined exponent

The value of n, for caustic stress corrosion cracking has been given as 2.4 to 4 and as 4.0 to 4.2 for primary water stress corrosion cracking (PWSCC). (Ref. 6.4.10 and 6.4.12)

Using the minimum times to failure in the caustic test:

$$\frac{t_{sleeve}}{t_{rolltrans}} = \left(\frac{\sigma_{sleeve}}{\sigma_{rolltrans}}\right)^{-n} = \left[\qquad \right]^{a,b,c}$$

A mean stress ratio can then be calculated as:

$$\left[\qquad \right]^{a,b,c}$$

Using this ratio with the exponent for PWSCC the stress component of the sleeve life can be determined by:

$$\left[\qquad \right]^{a,b,c}$$

A further adjustment to the roll transition life would then be made to compensate for any temperature difference between the original and sleeved tube. Due to the insulating effect provided by the sleeve, calculations have determined that the tube temperature may be as much as 5 to 10°C lower in the region of the sleeve joint as it was at the original roll transition.

Using the temperature dependent function of the Arrhenius relationship,

$$\frac{t_{sleeve}}{t_{rolltrans}} = \left(\frac{e^{Q / RT_{sleeve}}}{e^{Q / RT_{rolltrans}}} \right)$$

Applying a value of Q equal to 50 Kcal/mole, a factor of 2 would be applied to the roll transition life for every 10°C of temperature differential (Ref. 6.4.10)

Therefore, for example in a plant which had experienced roll transition cracking after two (2) years and in which the temperature differential was calculated to be 10°C; the life of the sleeved tube would be estimated as:

[ ] a,b,c

Further margin may be applied to this calculation by considering the average time to cracking. The ratio for the average time to cracking is approximately 70% greater than that for the minimum times. This would result in additional margin of 2.5 times that estimated.

An assessment of the corrosion testing performed results in the conclusion that Alloy 600 tubes repaired with the Alloy 800 sleeve can be expected to have a life considerably longer than that of the original tube.

6.4 REFERENCES FOR SECTION 6

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6.4.11 "Tihange 2 S.G.'s Sleeving Campaign 1997 – ABB Pluss Sleeves Corrosion Tests," Report No. MATER-97-200-0047/R-Lz, Laborelec Laboratories, May 1997.

6.4.12 1987 EPRI Workshop on Secondary Side Intergranular Corrosion Mechanisms: Proceedings, NP-5971, 1988.

b

Figure 6-1 Sleeve Corrosion Specimen

7 MECHANICAL TESTS OF SLEEVED STEAM GENERATOR TUBES

7.1 SUMMARY AND CONCLUSIONS

Mechanical tests were performed on both 3/4 and 7/8 inch mockup steam generator tubes containing sleeves, to provide qualified test data describing the basic properties of the completed assemblies. The majority of these tests were performed on assemblies using 3/4 inch diameter tubes to determine axial load, collapse, burst, leak rates and thermal cycling capability. Confirmatory tests, described in Section 7.5, were conducted on assemblies using 7/8 inch diameter tubes. The results of these tests verify that the leak rates established for the 3/4 inch sleeve, described in subsection 7.3.1, may be applied to sleeved 7/8 inch tubes.

Table 7-1 summarizes the results of the mechanical testing performed on the sleeve/tube assemblies. The demonstrated load capacity of the assemblies provides an adequate safety factor for normal operating and postulated accident conditions. The load capability of the upper and lower sleeve joints is sufficient to withstand thermally induced stresses and displacements resulting from the temperature differential between the sleeve and the steam generator tube and pressure induced stresses resulting from normal operating and postulated accident conditions. The burst and collapse pressures of the sleeve provide margin over limiting pressure differential. Mechanical testing revealed that the installed sleeve will withstand the cyclical loading resulting from power changes in the plant and other transients.

Table 7-2 summarizes the results of the leak testing performed for the tubesheet sleeves at various test and operating conditions. Table 7-3 summarizes the leak test results for the tube support sleeves under the same test conditions. The overall results of these leak tests are that leak rates are sufficiently small so as to allow a large number of sleeves to be installed, without exceeding typical plant allowable leak rates for either accident or normal operating conditions. As described in Section 7.4, tests were performed to determine the residual stresses in a steam generator tube resulting from installation of a sleeve, where the steam generator tube is locked at the first tube support. These stresses are well within yield stress and are expected to be acceptable based on corrosion tests in Section 6.

To confirm the sleeve assembly capability to withstand thermal and mechanical cyclic loads without degrading the strength or leak resistance of the expansion joint, thermal and load cycling tests which considered the operating thermal gradient and maximum expansion loads were performed. In some cases the leakage was reduced, and in other cases it increased somewhat. In all cases the leakage remained small and within the range of measurement variability and with no degradation in strength.

7.2 MECHANICAL TESTS

The following mechanical tests were performed on the 3/4 inch sleeve/tube assemblies: leakage, axial load, load cycling, burst and collapse. Leakage, axial load and load cycling tests were performed on assemblies using 7/8 inch tubes. Loads were applied per the design requirements for the respective tube size, or, in the case of cyclic loading, until the number of cycles exceeded the expected number of cycles for the original design life of the plant. Clean, unoxidized sleeve and steam generator tube samples were used for all tests. [

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Also, based on our experience, any oxide remaining on the inside of the tube after conditioning is expected to have no effect on the structural capability or leak resistance of the mechanical joint between the sleeve and tube. Therefore mechanical testing with properly conditioned unoxidized tubes is sufficient to qualify the sleeve design. This would not necessarily be true if a welded joint were used.

The steam generator tubes used for construction of the 3/4 inch test assemblies all had a room temperature yield strength of 49 ksi. The results of the tests performed on these assemblies are contained in Tables 7-1 through 7-3. A finite element stress analysis described in Reference 7.7.7 was performed to determine the effect of different tube yield strengths and different sleeve to tube radial gaps. The analysis considered tube room temperature yield strengths from 35 to 60 ksi. The contact stress at the expansions after sleeve installation was shown to be greater when the tube yield stress was higher. Depending on the gap size, the contact stress for the cases with the highest tube yield stress ranged from 8.7 to 14.8 ksi compression, and for the lowest tube yield stress the contact stress ranged from 6.3 to 7.8 ksi compression. In all cases the contact stress increased significantly, (7.7 ksi on the average) at operating conditions. [

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]a,c Sufficient load capability margin is demonstrated in the tests to cover such an extreme case. From this study it is judged that the tube yield stress variation anticipated to be encountered in steam generators is not a dominant parameter in the sleeve to tube leakage resistance and joint strength, provided that the extent of the tube expansion is in the range of the values tested.

A series of leak and thermal cycle tests were performed to verify this analytical prediction. Test samples were assembled with tubing having a room temperature yield strength of 38-39 ksi. The results of this program are contained in Reference 7.7.9. All samples met minimum joint strength requirements, and experienced leak rates similar to those found using nominal strength tubing.

With respect to the tube joint at severe accident conditions of high pressure (2500 psi) and temperature (1200–1500°F), pressure tends to loosen the joint and temperature tends to tighten it. As the temperature increases toward 1500°F, both the sleeve and tube will yield at steam line break pressures. Because the sleeve material is specified to have a low yield stress (30 ksi minimum, carefully controlled maximum), the sleeve will yield at a lower temperature (or pressure) than the tube, thereby tending to tighten the joint.

At 1500°F the ultimate stress of the sleeve material is comparable to that of the tube therefore the integrity of the sleeve repair is commensurate with the integrity of the inservice steam generator tubes. Because of this, sleeving should have no impact on the risk

7.2.1 Axial Load and Pressure Tests

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7.2.2 Collapse Testing

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Since collapse testing of the sleeve is not dependent on the steam generator tube wall thickness, these test results are applicable to sleeves in .042 to .050 inch nominal wall.

7.2.3 Thermal and Load Cycling Tests

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7.3 LEAKAGE ASSESSMENT

7.3.1 Leak Rate Tests

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7.3.2 Leak Test Evaluation

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7.3.3 Leak Test Results Under Abnormal Installation Conditions

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7.4 INSTALLATION STRESSES

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7.5 LEAK TESTS OF SLEEVES FOR 7/8 INCH DIAMETER TUBES

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7.6 EFFECT OF DEGRADED SG TUBE ADJACENT TO THE NICKEL BAND

Section 5.2 discussed the issues with flaw detection capabilities in the pressure boundary portion of a sleeved tube adjacent to the nickel band. In order to evaluate the effects of these limitations, a test program (Reference 7.7.14) has been conducted to verify that severe forms of tube degradation within the parent tube adjacent to the sleeve nickel band do not detract from the sleeve anchorage or leak characteristics. Based on the data described below and detailed in Reference 7.7.14, the conclusion that the inability to detect degradation in the parent tube adjacent to the nickel band of the sleeve at depths consistent with the technical specification does not result in a significant reduction in joint capability are validated.

7.6.1 Tensile Testing

The program included testing of sleeves in 0.875 inch OD x 0.050 inch wall thickness hydraulically expanded tubes simulating the Westinghouse Model 51 steam generator configuration, 0.75 inch OD x 0.043 inch wall thickness hardroll expanded tubes simulating the Westinghouse Model D steam generator configuration, and 0.75 inch OD x 0.048 inch wall thickness hydraulically expanded tubes simulating the C-E steam generator configuration. Tube flaws were introduced to simulate tubes either completely severed circumferentially or containing multiple 85% through wall axial OD defects.

The results of the tensile testing program show that for a postulated circumferential separation of the parent tube adjacent to the microlok to nickel band interface, which represents the bounding elevation for this degradation mechanism, a complete circumferential separation of the parent tube does not prevent the tube to sleeve joint from meeting its design requirement (i.e., that the hardroll joint maintain axial resistive load capability of greater than the three times normal end cap load condition). All first slip and peak loads exceeded the three times normal operating pressure differential end cap loading contained in Section 8.0.

A postulated circumferential separation of the parent tube above the microlok to nickel band interface is expected to be detected through normal +Pt coil analysis. A postulated circumferential separation of the parent tube below the microlok to nickel band interface is expected to result in a condition bounded by these tests.

For the postulated case of severe axial degradation in the parent tube, the tube to sleeve hardroll joint continues to satisfy the design requirement. Therefore, the inability to detect degradation in the parent tube adjacent to the nickel band of the sleeve at depths consistent with the technical specification does not result in a significant reduction in joint capability.

7.6.2 Leak Testing

Leak testing was also performed on samples simulating flawed tubes adjacent to sleeve nickel band. The specimens were first leak tested at room temperature at pressure differentials of 1500 and 2560 psi. Previous testing has shown that the thermal expansion characteristics of the sleeve in tube and tube in collar configuration will result in increased contact pressures at elevated temperature, thus resulting in a lesser leak rate at elevated temperatures. Any specimen that leaked at room temperature was also leak tested at 600°F in a high pressure autoclave.

With regard to leakage contribution during a postulated steam line break (SLB) event, it is recommended that the maximum observed elevated temperature SLB leakage of 2 x 10^{-5} gpm be applied to all sleeved tubes in which degradation of the parent tube behind the sleeve to tube hardroll joint is observed. This allowance is applied to only those sleeved tubes with degradation. For sleeved tubes with no observed degradation behind the sleeve to tube hardroll joint no leakage allowance is to be applied.

The results of the room temperature leak test show that the postulated condition of a degraded parent tube has essentially no impact to leakage performance of the sleeve to tube joint.

7.7 REFERENCES FOR SECTION 7

7.7.1 3/4" US NSSS Sleeving Summary of Test Results Report no. GBRA 039-927, Rev. B.

7.7.2 Design Verification and Qualification Report Sleeving of E1 Steam Generator Tubing (3/4" SG) by Weldless Sleeves, Report No. GBRA 033 431.

7.7.3 Fatigue Testing of I800 Sleeved Tube Samples at Operating Temperature, Report no. MISC-PENG-TR-096, Rev. 00.

7.7.4 Steam Generator Tube Leak Rate Testing of A800 Sleeve Samples, Test Report No. 00000-NOME-TR-0049, Rev. 00.

7.7.5 Test Report for the Locked Tube Support Mock-up Strain Testing for Installation of A800 Sleeves, Report No. 00000-NOME-TR-0051, Rev. 00.

7.7.6 Test Report on Thermal and Load Cycling Tests on Alloy 800 Sleeves, Report No. MISC-PENG-TR-100, Rev. 00.

7.7.7 Calculation Report: Sleeving of ANO2 Steam Generator Tubing (3/4") by PLUSS Sleeves with 6 x 8 mm Zero-Expansions, Report GBRA 040194.

7.7.8 Telefax # RU-WG R1214-CE, from ABB Reaktor to ABB CENO, June 11, 1997, and subsequent telefax from ABB Reaktor to ABB CENO on June 19, 1997.

7.7.9 Test Report On the Alloy 800 Mechanical Sleeve – Additional Qualification Testing Using Low Yield Strength Tubing, Report No. 98-TR-FSW-005.

7.7.10 "Alloy 800 Sleeve Leak Test Summary," Report No. 99-TR-FSW-0044.

7.7.11 "Alloy 800 Sleeve Installation and Operational Stress Test and Analysis Summary," Report No. 99-TR-FSW-045.

7.7.12 "Steam Generator Tube Repair for Combustion Engineering and Westinghouse Designed Plants with 3/4 Inch Inconel 600 Tubes Using Leak Limiting Alloy 800 Sleeves," WCAP-15918-P, November 2002.

7.7.13 "Leak Rate Testing of Alloy 800 Sleeves Installed in 7/8" Diameter Alloy 600 Steam Generator Tubes," MRS-DFD-1362-SGSLV, March 2003.

7.7.14 SG-SGDA-05-48-P, Revision 1, "Test Results Related to TIG and Alloy 800 Sleeve Installation in 3/4 Inch and 7/8 Inch OD SG Tubing In Service Inspection Requirements," January 2006.

Table 7-1 Sleeve-Tube Assembly Mechanical Testing Results

	Component test	Test Quantity	Results
Room Temperature Tests:			
Cyclic Loading (Wear Test) Upper Joints Intact Tube			b
Cyclic Loading (Axial Capability) Upper Joints Severed Tube			
Operating Temperature Tests:			
Axial Capability Severed Tube			
Sleeve Assembly Burst Pressure			
Sleeve Assembly Collapse Pressure			
Cyclic Loading (Axial Capability)			
Thermal and Load Cycling Tests			
Sleeve Assembly Collapse Pressure			
Cyclic Loading (Axial Capability)Capability)			

Table 7-2 Tubesheet Sleeve-Tube Assembly Leak Testing Results

Primary Pressure (psi)	Secondary Pressure (psi)	Primary Temperature (°F)	Average Leak Rate (gal/hr)	95% Upper Mean (gal/hr)	Maximum Leak Rate (gal/hr)	Minimum Leak Rate (gal/hr)
						b

The upper (one sided) 95% confidence limit on the mean is calculated as follows:

- X_1, X_2, ...X_N are the leakage data for each of the N tests.
- X_M is the arithmetic average, or the sum of the data values / N tests.
- S, the standard deviation of the sample, is the square root of the sum of the (X_M-X_i) squared divided by the square root of N-1.
- X_M(95) is X_M + t(95) times S divided by the square root of N. t(95) is the 95% value from Student's "t" distribution with N-1 degrees of freedom. In this case, since N is 6, t(95) is 2.02.

Table 7-3 Tube Support Sleeve-Tube Assembly Leak Testing Results

Primary Pressure (psi)	Secondary Pressure (psi)	Primary Temperature (°F)	Average Leak Rate (gal/hr)	95% Upper Mean (gal/hr)	Maximum Leak Rate (gal/hr)	Minimum Leak Rate (gal/hr)
						b

The upper (one sided) 95% confidence limit on the mean is calculated as follows:

- X_1, X_2, ...X_N are the leakage data for each of the N tests.
- X_M is the arithmetic average, or the sum of the data values / N tests.
- S, the standard deviation of the sample, is the square root of the sum of the (X_M-X_i) squared divided by the square root of N-1.
- $X_M(95)$ is X_M + t(95) times S divided by the square root of N. t(95) is the 95% value from Student's "t" distribution with N-1 degrees of freedom. In this case, since N is 6, t(95) is 2.02.

Table 7-4 Effects of Different Sleeve and Tube Dimensions TZ Sleeves

Sleeve Type	Tube thickness (inches)	Tube yield strength (ksi)	Leakage at 510 psi and room temperature (gal/hr)
Series 1 Tests (3/4" Diameter Tubes)			
TZ	.042	47	b
TZ	.042	47	
TZ	.042	47	
TZ	.042	47	
Series 2 Tests (3/4" Diameter Tubes)			
TZ	.042	38	
TZ	.042	47	
TZ	.042	57	
TZ	.048	35	
TZ	.048	49	
TZ	.048	55	
Series 3 Tests (7/8" Diameter Tubes)			
TZ	.050	39	
TZ	.050	39	
TZ	.050	39	
TZ	.050	44	
TZ	.050	44	
TZ	.050	44	
TZ	.050	56	
TZ	.050	56	
TZ	.050	56	

Table 7-5 Effects of Different Sleeve and Tube Dimensions TS Sleeves			
Sleeve Type	**Tube thickness (inches)**	**Tube yield strength (ksi)**	**Leakage at 510 psi and room temperature (gal/hr)**
Series 1 Tests (3/4" Diameter Tubes)			
TS	.042	38	[ ]b
TS	.042	47	
TS	.042	47	
TS	.042	57	
TS	.042	57	
Series 2 Tests (7/8" Diameter Tubes)			
TS	.050	44	
TS	.050	44	
TS	.050	44	

Table 7-6 Leakage Before and After Cyclic Load Tests					
Sleeve Type	**Tube thickness (Inches)**	**Tube yield strength (Ksi)**	**Leakage at 510 psi and room temperature**		**Number of Load Cycles**
			Before Test (gal/hour)	**After Test (gal/hour)**	
3/4" Diameter Tubes					
TZ	0.042	57	[	]b	1000
TZ	0.048	49			2000
TZ	0.048	55			1000
7/8" Diameter Tubes					
TZ	0.050	39			1000
TZ	0.050	44			1000
TZ	0.050	56			1000
TZ	0.050	56			1000

[ ]b

Figure 7-1 Axial Load/Cyclic Load-TZ Test Assembly

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Figure 7-2 Axial Load Test Set-Up

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Figure 7-3 Cyclic Load Test Assembly-Intact Tube

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Figure 7-4 Cyclic Load Test Assembly-Severed Tube

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Figure 7-5 TS Leak Test Assembly

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Figure 7-6 Locked Tube Test Fixture

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Figure 7-7 Average Leak Rate Projections for Different ΔP's

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Figure 7-8 95% Confidence on Mean Projections of Leak Rate

8 STRUCTURAL ANALYSIS OF SLEEVE-TUBE ASSEMBLY

This analysis establishes the structural adequacy of the sleeve-tube assembly. The methodology used is in accordance with the ASME Boiler and Pressure Vessel Code, Section III. The work was performed in accordance with 10CFR50 Appendix B and other applicable U.S. Nuclear Regulatory Commission requirements.

8.1 SUMMARY AND CONCLUSIONS

Based on the analytical evaluation contained in this section and the mechanical test data contained in Section 7, it is concluded that both the Transition Zone (TZ) and Tube Support (TS) sleeves described in this document, meet all pertinent requirements with substantial additional margins. In performing the analytical evaluation on the tube sleeves, the operating and design conditions for all of the Westinghouse "44," "44F," "51," and "51M" Steam Generator <u>operating</u> plants with <u>7/8 inch Inconel 600 tubes</u> are considered (Ref. 8.2 and 8.4). Inasmuch as the tube dimensions and geometry in the area of interest are the same, future reference to model "51" steam generators also includes model "51M". The results of this analytical evaluation are summarized in Table 8-1. Recognize that plant conditions are different for different steam generator designs.

8.1.1 Design Sizing

In accordance with ASME Code practice, the design requirements for tubing are covered by the specifications for the steam generator "vessel". The appropriate formula for calculating the minimum required tube or sleeve thickness is found in Paragraph NB-3324.1, tentative pressure thickness for cylindrical shells (Ref. 8.1). The following calculation uses this formula for the tube sleeve material which is Alloy 800 material (SB-163, UNS N08800) with a specified minimum yield of 30.0 ksi and a design stress intensity of 20.0 ksi.

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Where

- t = Minimum required wall thickness, in.
- P = Design Primary Pressure, ksi (maximum value for intact tube situation)
- R = Inside Radius of sleeve, in. (maximum value for t_{min} in Reference 8.18).
- S_m = Design Stress Intensity, S.I. @ 650°F maximum design (per Reference 8.1)

8.1.2 Detailed Analysis Summary

In determining the axial loads acting on the TZ sleeve at 25.0 inches (Figure 8-1 and Reference 8.9) there are several combinations of tube and tube support conditions which are considered. The two extreme cases for the tube condition are:

1. the tube is <u>intact</u>.
2. the tube is totally <u>severed</u> at the defective location.

The two extreme cases for the tube support condition are:

1. the tube is <u>free to move past</u> the supports.
2. the tube is <u>locked</u> in the first support and is prevented from axial motion.

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Table 8-1 Summary of Sleeve Design and ASME Code Analysis for TZ and TS Sleeves

Category	**Results**	
Axial Load during 100% Steady State Operation	[$]^c$ lb for intact tube unlocked in the supports [$]^c$ lb for severed tube unlocked in the supports [$]^c$ lb for intact tube locked in the supports [$]^c$ lb for severed tube locked in the supports	
Tentative Sizing	$t_{req'd}$ = 0.0435 in. (per ASME Code) < t_{min} = 0.048 in.	
% Allowable Degradation Limit	45% (per NRC Regulatory Guide 1.121, Ref. 8.3) for Westinghouse "44," "44F," & "51" Steam Generators	
Category	**Analysis Results (Maximum Stress in ksi)**	**Allowable (per ASME Code, ksi)**
General Primary Membrane Stress for Sleeve Material	Stress Intensity = [$]^c$	$S_m = 20.0$
Primary Local Membrane Plus Primary Bending Stress for Sleeve Material	Stress Intensity = [$]^c$	$1.5\ S_m = 30.0$
Primary Plus Secondary Stress for Sleeve Material	Stress Intensity = [$]^c$	$3\ S_m = 60.0$
Fatigue of Sleeve Material	U = [ ] c	U = 1.0
Main Steam Line Break	Stress Intensity = [$]^c$	$0.7\ S_u = 52.5$
Feedwater Line Break	Stress Intensity = [$]^c$	$0.7\ S_u = 52.5$
Primary Pipe Break (LOCA)	Stress Intensity = [$]^c$	$0.7\ S_u = 52.5$

GENERAL MEMBRANE STRESSES SUMMARIZED

1. General Primary Membrane Stress (P_m)
(per Par. NB-3221.1 of Ref. 8.1 w/ Design Primary Pressure of 2.5 ksi and R_i = [0.326]^c in., maximum inner radius for t_{min} =[0.048]^c in. per Reference 8.18)

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2. Primary Local Membrane Plus Bending Stress Intensity ($P_L + P_B$)
(per Par. NB-3221.3 of Ref. 8.1 w/Design Primary Pressure of 2.5 ksi, S_{OBE} (seismic stress) of 4.3 ksi, and R_i of [ ]^c in., maximum inner radius for t_{min} = [ ]^c in. per Reference 8.18)

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3. Primary Plus Secondary Stress Intensity
(per Paragraph NB-3222.2 of Ref. 8.1 w/ Spec. Service Pressure for Intact Tube Situation on Sleeve's Inside Surface)

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(where σ_θ = secondary hoop stress due to sleeve/tube differential temperature at respective transient)

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4. Main Steam Line Break

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5. Feedwater Line Break

[ ]c

6. Primary Pipe Break (LOCA) (assumes a severed tube)

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$$S.I._{LOCA} = \frac{(1.130)\,(0.374)}{.048} + \frac{(1.130)}{2}$$

$$S.I._{LOCA} = 9.4 \text{ ksi} < \text{Allowable of } 0.7\ S_u = 52.5 \text{ ksi}$$

8.2 EVALUATION FOR ALLOWABLE SLEEVE WALL DEGRADATION USING REGULATORY GUIDE 1.121

NRC Regulatory Guide 1.121 (Ref. 8.3) requires that a minimum acceptable tube (or sleeve) wall thickness be established to provide a basis for leaving a degraded tube in service. For partial thru-wall attack from any source, the requirements fall into two categories, (a) normal operation safety margins, and (b) considerations related to limiting postulated accidents.

8.2.1 Normal Operation Safety Margins

It is the general intent of these requirements to maintain the same factors of safety in evaluating degraded tubes as those which were contained in the original construction code, ASME Boiler and Pressure Vessel Code, Section III (Ref. 8.1).

For Inconel Alloy 600 tube or Alloy 800 sleeve material the controlling safety margins from NRC Regulatory Guide 1.121 (Ref. 8.3) for partial thru-wall attack are:

1. "Tubes with detected part thru-wall cracks should not be stressed during the full range of normal reactor operation beyond the elastic range of the tube material."

2. "Tubes with part thru-wall cracks, wastage, or combinations of these should have a factor of safety against failure by bursting under normal operating conditions of not less than 3 at any tube location."

From Reference 8.24 the normal operating conditions for the "worst" case envelopment of steam generators from the Westinghouse "44," "44F," and "51" Steam Generators are:

Primary Pressure P_{pri} =	2250 psia
Secondary Pressure P_{sec} =	699.5 psia
Differential Pressure $\Delta P = P_{pri} - P_{sec}$ =	1550.5 psi
Average Pressure $P_{avg} = 0.5\,(P_{pri} + P_{sec})$ =	1474.5 psi

Assuming the parent tube is totally severed, the sleeve is required to carry the pressure loading. The following terms are used in this evaluation.

R_{is} = sleeve nominal inside radius, i.e., [ ]^c in. per Reference 8.18
Sy_{rm} = minimum required yield strength (per U.S. NRC Reg. Guide 1.121, Ref. 8.3)
Sy_{min} = minimum yield strength of sleeve (S_y = 23.7 ksi minimum at 650°F, Ref. 8.1)

Based on the information provided in Reference 8.1, the Alloy 800 tube sleeve material (SB-163, UNS N08800) has an ultimate strength of 75.0 ksi at 650°F. The required thickness is shown below using a derivation of the formula in Paragraph NB-3324.1 of Reference 8.1 with 3 times ΔP as mentioned in Regulatory Guide 1.121 (Ref. 8.3) and S_u in place of S_m per controlling safety margin 2 above.

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8.2.2 Postulated Pipe Rupture Accidents

NRC Regulatory Guide 1.121 requires the following:

"The margin of safety against tube failure under postulated accidents, such as a LOCA, steam line break, or feedwater line break concurrent with the safe shutdown earthquake (SSE), should be consistent with the margin of safety determined by the stress limits specified in NB-3225 of Section III of the ASME Boiler and Pressure Vessel Code."

The above referenced ASME code paragraph deals with "faulted conditions," where for an elastic analysis of Alloy 800 sleeves, a general membrane stress of 0.7 S_u = 0.7(75.0) = 52.5 ksi is allowed. In conjunction with the NRC Regulatory Guide 1.121, the following accidents are postulated:

1. For a downcomer feedring steam generator, a feedwater line break (FWLB) accident, concurrent with the safe shutdown earthquake (SSE), would have very little effect on steam generator internals. The feedwater line break (FWLB) accident causes a significant pressure differential between the inside of the steam generator and the containment atmosphere. However, the many discharge elbows in the feedwater ring and the ring itself result in large pressure losses for the flow exiting the break. Thus, the flow at the break is limited and the associated forces acting on the steam generator internals (i.e., tubes and tube supports) is not significant when compared to other accident loads. For a Westinghouse "44," "44F," and "51" steam generator, a feedwater line break (FWLB) accident causes large tube bending stresses near the feedwater nozzle but would

have very little effect on the tube spans just above the tubesheet. For a Westinghouse "44," "44F," and "51" steam generator, a feedwater line break (FWLB) accident produces a maximum differential pressure loading of 2.65 ksi (page 8-7) on the sleeve. A small axial stress could be induced in a sleeved tube if it were locked into the first tube support plate. However, this stress would be negligible compared to the dominant hoop stress due to differential pressure.

2. A LOCA accident causes large tube bending stresses in the upper tube bundle but produces only negligible compressive stresses in the region of interest. Thus, the axial loading, etc. in this evaluation applies to sleeves in the lower end of the tube bundle from the fourth support plate down to the tubesheet.

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The required thicknesses for a main steam line break (MSLB) or feedwater line break (FWLB) accident are shown below using the derivation of the formula in Paragraph NB-3324.1 of Reference 8.1 with .7 S_u in place of S_m.

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8.3 EFFECTS OF TUBE LOCK-UP OR UNLOCKED SITUATION ON SLEEVE AXIAL LOADING

Objective: Conservatively determine the maximum axial loads on the sleeve (tension and compression) during normal operation for both intact and severed tube situations.

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8.3.1 Sleeved Tube in Westinghouse Plants, Unlocked at First Tube Support

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From the diagram in Figure 8-3, the following equations are derived with the basic "mechanics of materials" equations in Reference 8.16.

The deflection of an axially loaded member in compression or tension, Δ, is defined from Equation 14.6 in Reference 8.16 or:

$$\Delta = F/K \quad \text{with} \quad K = AE/L$$

where:

F = Force on the respective body, lb.
K = Spring constant for the respective body, lb./in.
A = Cross-sectional area of the respective body, in^2.
E = Modulus of Elasticity of the respective body, psi
L = Length of the respective body, in.

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8.3.2 Sleeved Tube in Westinghouse Plants, Locked at First Tube Support

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The sleeve loads, F_l, for the locked case are in Tables 8-3A thru 8-3C at the transient conditions shown in the same tables.

The sleeve loads, F_l*, for the unlocked case and, F_l, for the locked case are in Table 8-3D for the "51" steam generators with a power uprate.

Table 8-2A 25.0 Inch Sleeve Axial Member Physical Properties for Westinghouse "44" Steam Generators With Effective Length Between Lower Joint and Last Upper Joint

Component	Outside Radius R_o (in)	Inside Radius R_i (in)	Effective Length L (in)	Section Area A (in^2)	Correspond Temp. T_c (°F)	Young's Modulus E $lb/in^2 \times 10^6$	Stiffness K = AE/L $lb/in \times 10^3$	Mean Coef Therm. Exp. α_m $In/In\ °F \times 10^{-6}$
(1) Sleeve	[							]c
(2) Lower Tube								
(3) Tube in Tubesheet								
(4) Upper Tube								
(5) Surrounding Tubes								

Reference Temperatures: Primary (Hot) = 594°F (sleeve I.D. temperature)
Secondary = 467°F (tube O.D. temperature)
Normal Tubes = $(2\ T_{pri} + T_{sec})/3$ = 551.7°F

Note:s:

1. Nominal Dimensions for sleeve from Reference 8.18.
2. α_m and E for Inconel 600 and 800 from Reference 8.1.
3. Nominal Dimensions for tubes from Reference 8.4.
4. α_m for Carbon Moly Steel from Reference 8.1.

Table 8-2B 25.0 Inch Sleeve Axial Member Physical Properties for Westinghouse "44F" Steam Generators With Effective Length Between Lower Joint and Last Upper Joint

Component	Outside Radius R_o (in)	Inside Radius R_i (in)	Effective Length L (in)	Section Area A (in^2)	Correspond Temp. T_c (°F)	Young's Modulus E $lb/in^2 \times 10^6$	Stiffness K = AE/L $lb/in \times 10^3$	Mean Coef Therm. Exp. α_m In/In °F x 10^{-6}
(1) Sleeve								c
(2) Lower Tube								
(3) Tube in Tubesheet								
(4) Upper Tube								
(5) Surrounding Tubes								

Reference Temperatures: Primary (Hot) = 594°F (sleeve I.D. temperature)
Secondary = 467°F (tube O.D. temperature)
Normal Tubes = $(2\ T_{pri} + T_{sec})/3$ = 551.7°F

Note:s:

1. Nominal Dimensions for sleeve from Reference 8.18.
2. α_m and E for Inconel 600 and 800 from Reference 8.1.
3. Nominal Dimensions for tubes from Reference 8.4.
4. α_m for Carbon Moly Steel from Reference 8.1.

Table 8-2C 25.0 Inch Sleeve Axial Member Physical Properties for Westinghouse "51" Steam Generators With Effective Length Between Lower Joint and Last Upper Joint

Component	Outside Radius R_o (in)	Inside Radius R_i (in)	Effective Length L (in)	Section Area A (in^2)	Correspond Temp. T_c (°F)	Young's Modulus E lb/in^2 x 10^6	Stiffness K = AE/L lb/in x 10^3	Mean Coef Therm. Exp. α_m In/In °F x 10^{-6}
(1) Sleeve								c
(2) Lower Tube								
(3) Tube in Tubesheet								
(4) Upper Tube								
(5) Surrounding Tubes								

Reference Temperatures: Primary (Hot) = 594°F (sleeve I.D. temperature)
Secondary = 467°F (tube O.D. temperature)
Normal Tubes = (2 T_{pri} + T_{sec})/3 = 551.7°F

Note:s:

1. Nominal Dimensions for sleeve from Reference 8.18.
2. α_m and E for Inconel 600 and 800 from Reference 8.1.
3. Nominal Dimensions for tubes from Reference 8.4.
4. α_m for Carbon Moly Steel from Reference 8.1.

Table 8-3A Axial Thermal Loads in Sleeve with Tube Unlocked and Locked into Tube Support for Westinghouse "44" Steam Generators

Transient Condition	P_{pri} (ksi)	P_{sec} (ksi)	T_{pri} (°F)	T_{sec} (°F)	Sleeve Load F_1* for Unlocked Condition – F_{min} (lb)	Sleeve Load F_1 for Locked Condition – F_{max} (lb)
1. 100% Power						c
2. 0% S.S.						
3. Reactor Trip						

Table 8-3B Axial Thermal Loads in Sleeve with Tube Unlocked and Locked into Tube Support for Westinghouse "44F" Steam Generators

Transient Condition	P_{pri} (ksi)	P_{sec} (ksi)	T_{pri} (°F)	T_{sec} (°F)	Sleeve Load F_1* for Unlocked Condition – F_{min} (lb)	Sleeve Load F_1 for Locked Condition – F_{max} (lb)
1. 100% Power						c
2. 0% S.S.						
3. Reactor Trip						

Table 8-3C Axial Thermal Loads in Sleeve with Tube Unlocked and Locked into Tube Support for Westinghouse "51" Steam Generators

Transient Condition	P_{pri} (ksi)	P_{sec} (ksi)	T_{pri} (°F)	T_{sec} (°F)	Sleeve Load F_1* for Unlocked Condition – F_{min} (lb)	Sleeve Load F_1 for Locked Condition – F_{max} (lb)
1. 100% Power						c
2. 0% S.S.						
3. Reactor Trip						

Table 8-3D Axial Thermal Loads in Sleeve with Tube Unlocked and Locked into Tube Support for Westinghouse "51" Steam Generators with a Power Uprate

Transient Condition	P_{pri} (ksi)	P_{sec} (ksi)	T_{pri} (°F)	T_{sec} (°F)	Sleeve Load F_l* for Unlocked Condition – F_{min} (lb)	Sleeve Load F_l for Locked Condition – F_{max} (lb)
1. 100% Power	2.250	0.735	617	484.4	[	]c
2. 0% S.S.	2.250	1.020	547	547		
3. Reactor Trip final	1.910	0.983	537	542.5		
4. Loss of Power initial and final	2.575 2.150	1.133 1.133	560 578	560 560		
5. Primary Leak Test	2.500	0.900	250	250		
6. RCS COMS minimum & maximum	0.215 0.815	0.247 0.210	350 388	400 386		]

8.3.3 Effect of Tube Prestress Prior to Sleeving

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8.3.4 Lower Sleeve Rolled Section Pushout Due to Restrained Thermal Expansion

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Plant	Compression Load (lb)
Westinghouse "44" Steam Generator	[ ]c
Westinghouse "44F" Steam Generator	[ ]c
Westinghouse "51" Steam Generator	[ ]c

8.4 SLEEVED TUBE VIBRATION CONSIDERATIONS

The vibration behavior of a sleeved tube is evaluated as follows:

8.4.1 Effects of Increased Stiffness

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8.4.2 Effect of Severed Tube

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8.4.3 Seismic Evaluation

The natural frequency of a sleeved tube for the span between the tubesheet and the first tube support for the "worst" case situation is:

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where:

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Since this analysis does not take credit for the additional support provided by the tubesheet, this conclusion applies to both the TS and TZ sleeve.

8.5 EVALUATION OF SLEEVE TO TUBE EXPANSION SECTION

The normal operating, design seismic, and transient conditions on the steam generator tube sleeves are used in accordance with ASME Code Section III evaluation, considering both temperature and pressure loads.

The transient conditions defined in Reference 8.25 represent the situation for a "51" steam generator with a power uprate. Table 8-4A shows the grouping of these transients, which are detailed below:

1. Heatups and Cooldowns – 250 cycles between ambient (room temperature) and 0% steady state.
2. Loading and Unloading – 18,300 cycles between 0% steady state and 100% steady state.
3. Step Load Events of 10% Full Power – 2500 cycles between 0% steady state and 100% steady state.
4. Large Step Load Decrease – 250 cycles between 0% steady state and 100% steady state.

5. Temperature Coast-downs – 50 cycles between 0% steady state and 100% steady state.
6. Reactor Trip – 500 cycles between 100% steady state and end of transient.
7. Loss of Flow – 100 cycles between 100% steady state and end of transient.
8. Loss of Load – 100 cycles between 100% steady state and end of transient.
9. Loss of Power – 50 cycles between 100% steady state and end of transient.
10. Inadvertent Spray – 60 cycles between 100% steady state and end of transient.
11. Design Earthquake Events – 400 cycles between 100% steady state and end of transient.
12. Primary Side Leak Tests – 200 cycles between ambient and leak test condition.
13. Turbine Roll Tests – 10 cycles between ambient and test condition.
14. RCS Cold Overpressure Events – 6,000 cycles between a primary pressure of 215 and 815 psia.

Hydro tests are isothermal and produce negligibly small sleeve loads regarding fatigue. Further details on the results of the load cycling tests are presented in Section 7.

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To illustrate the impact of a more realistic temperature gradient, the restrained thermal expansion axial loads were calculated for the transients shown in Tables 8-4A and 8-4B. The axial loads were calculated using the same methodology as discussed in Section 8.3, except the temperature distribution for the transients in Table 8-4A was determined using a one-dimensional steady-state heat balance for 100% power conditions. In all cases, the axial load (and associated stress) was lower for the transients in Table 8-4A when compared with the transients in Table 8-4B. The Table 8-4B transient conditions, defined in Reference 8.8, represent the worst case situation for a Westinghouse "44," "44F," or "51" steam generator. Thus, even though the revised conditions in Table 8-4A consider more transient cycles than those described in Table 8-4B, peak alternating stresses and the associated fatigue usage factor are lower as shown in the fatigue evaluation.

Table 8-4A Tube Sleeve Expansion Section – Transients considered for a Westinghouse "51" Steam Generators with Power Uprate (based on one-dimensional steady-state heat balance)

Transients	End Points	Cycles	Restrained Thermal Expansion Axial Load (lb)	Primary Pressure P_1 (psi)	Secondary Pressure P_2 (psi)	$(P_1 - P_2)$ (psi)
(1) Heatup / Cooldown	Ambient 0% SS	250[1]	[			] c
(2) Full Power	0% SS 100% SS	21,100[2]				
(3) Reactor Trip & Upset	100% SS 0% SS	1160[3]				
(4) Loss of Power	100% SS Increased Temp/Press	50[4]				
(5) Primary Leak Test	Ambient Leak Test	210[5]				
(6) RCS COMS*	Minimum Maximum	6000[6]				

Note:
* Reactor Coolant System Cold Overpressure Mitigation System

Conditions:
(a) Worst Case: Tube is locked-at the first tube support.
(b) Tube is Intact: Tube/sleeve restrained thermal expansion.
(c) Axial Loads are from Table 8-3D and Reference 8.25
(d) Sleeve is 25.0 inches long.
(e) Transient cycles are described in Section 8.5 and are grouped as follows:
1 – Transient 1 or 250 cycles
2 – Sum of Transients 2, 3, 4, and 5 or 18,300 + 2500 + 250 + 50 = 21,100 cycles
3 – Sum of Transients 6, 7, 8, 10, and 11 or 500 + 100 + 100 + 60 + 400 = 1160 cycles
4 – Transient 9 or 50 cycles
5 – Sum of Transients 12 and 13 or 200 + 10 = 210 cycles
6 – Transient 14 or 6000 cycles

Table 8-4B Tube Sleeve Expansion Section – Transients Considered for a Westinghouse "44," "44F," or "51" Steam Generator						
Transients	**End Points**	**Cycles**	**Restrained Thermal Expansion Axial Load (lb)**	**P_1 (psi)**	**P_2 (psi)**	**$(P_1 - P_2)$ (psi)**
(1) Heatup/Cooldown	Ambient 0% S.S.	310*	0 -1347	0 2250	0 1020	0 1230
(2) Full Power	0% S.S. 100% S.S.	21,100**	-1347 -2659	2250 2250	1020 720	1230 1530
(3) Reactor Trip and Upset	100% S.S. Loss of Flow	780***	-2659 -843	2250 2250	720 963	1530 1287

Conditions:
(a) Worst Case: Tube is un-locked at the first tube support.
(b) Tube is Intact: Tube/sleeve restrained thermal expansion.
(c) Axial loads are from Table 8-3C.
(d) Sleeve is [25.0][a,c] inches long.
(e) Transient cycles are from the previous table, grouped as follows:
  * Sum of heatup / cooldown and primary side leak test transients or 250 + 60 = 310 cycles
  ** Sum of loading / unloading, 10% full power step load, large step load decrease, and average temperature coastdown transients or 18,300 + 2500 + 250 + 50 = 21,100 cycles
  *** Sum of reactor trip, loss of flow, loss of load, loss of power, inadvertent spray, and design earthquake transients or 500 + 100 + 100 + 50 + 10 + 20 = 780 cycles

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During the initial plant heatup following Alloy 800 sleeve installation, the sleeve will expand more than the parent tube. As the sleeve lengthens, it will be restrained by the upper and lower joints and the tube will be in compression. At some point during the initial heatup, the sleeve will move (with respect to the tube) and the compressive stresses will be reduced. During subsequent plant heatups there will be no relative movement between the sleeve and tube and compressive stresses on the tube will be lower than occurred during the initial heatup. A more detailed explanation of this process is contained in Section 7.2 of the report.

The stresses on the sleeves that occur during the installation process are not neglected in the ASME Code analysis. The stresses are treated separately. A detailed description of the installation stresses is contained in Section 7.4 of the WCAP. As described therein, residual stresses were maintained below the yield stress of the material and were evaluated as part of the material evaluation in Section 6.

As described previously, axial stresses on the tube (tension) and sleeve (compression) are reduced during the initial plant heatup when the sleeve is displaced. This displacement does not occur during subsequent heatups and cooldowns and the stress on the components is less than during the first cycle. Further, axial loads on the sleeve are calculated assuming no displacement of the sleeve relative to the tube. Hence, the axial loads calculated in the report are conservative relative to those that would occur in a steam generator. Other stresses calculated in the report for normal and faulted conditions are dependent on the primary to secondary pressure differential and are unaffected by installation stresses.

8.5.1 Analysis of Sleeve Material

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Table 8-5A Stresses in Sleeve for Westinghouse "44" Steam Generator				
Transient Condition	Stress due to Axial Load σ_{axial} (ksi)	Hoop Stress due to Sleeve/Tube Differential Temperature, σ_{θ} (ksi)	Thermal Radial Differential Stress, $\sigma_{thermal}$ (ksi)	Thermal Skin Stress σ_{skin} (ksi)
1. Ambient				c
2. 0% S.S.				
3. 100% S.S.				
4. Reactor Trip				
5. End of Reactor Trip				

Table 8-5B Stresses in Sleeve for Westinghouse "44F" Steam Generator				
Transient Condition	Stress due to Axial Load σ_{axial} (ksi)	Hoop Stress due to Sleeve/Tube Differential Temperature, σ_{θ} (ksi)	Thermal Radial Differential Stress, $\sigma_{thermal}$ (ksi)	Thermal Skin Stress σ_{skin} (ksi)
1. Ambient				c
2. 0% S.S.				
3. 100% S.S.				
4. Reactor Trip				
5. End of Reactor Trip				

Table 8-5C Stresses in Sleeve for Westinghouse "51" Steam Generator

Transient Condition	Stress due to Axial Load σ_{axial} (ksi)	Hoop Stress due to Sleeve/Tube Differential Temperature, σ_θ (ksi)	Thermal Radial Differential Stress, $\sigma_{thermal}$ (ksi)	Thermal Skin Stress σ_{skin} (ksi)
1. Ambient				c
2. 0% S.S.				
3. 100% S.S.				
4. Reactor Trip				
5. End of Reactor Trip				

Table 8-5D Stresses in Sleeve for Westinghouse "51" Steam Generator with a Power Uprate

Transient Condition	Stress due to Axial Load σ_{axial} (ksi)	Hoop Stress due to Sleeve/Tube Differential Temperature, σ_θ (ksi)	Thermal Radial Differential Stress, $\sigma_{thermal}$ (ksi)	Thermal Skin Stress σ_{skin} (ksi)
1. Ambient				c
2. 0% S.S.				
3. 100% S.S.				
4. Reactor Trip				
5. End of Reactor Trip				
6. Loss of Power, initial				
7. Loss of Power, final				
8. Primary Leak Test				
9. RCS COMS, minimum				
10. RCS COMS, maximum				

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Table 8-6A Primary and Secondary Stresses and Stress Intensities on Inside Surface of Sleeve with Unlocked and Intact Tube for Westinghouse "44" Steam Generator

Transient Condition	Total Axial Stresses σx_{total} (ksi)	Total Hoop Stresses $\sigma\theta_{total}$ (ksi)	Total Radial Stresses σr_{total} (ksi)	Sxr (ksi)	Sθr (ksi)	Sθx (ksi)
1. Ambient	[					]^c
2. 0% S.S.						
3. 100% S.S.						
4. Reactor Trip						
5. End of Reactor Trip						

Sxr_{range} = [ ]^c ksi < 3.0 S_m = 60 ksi

$S\theta r_{range}$ = [ ]^c ksi

$S\theta x_{range}$ = [ ]^c ksi

Table 8-6B Primary and Secondary Stresses and Stress Intensities on Inside Surface of Sleeve with Unlocked and Intact Tube for Westinghouse "44F" Steam Generator

Transient Condition	Total Axial Stresses σx_{total} (ksi)	Total Hoop Stresses $\sigma\theta_{total}$ (ksi)	Total Radial Stresses σr_{total} (ksi)	Sxr (ksi)	Sθr (ksi)	Sθx (ksi)
1. Ambient	[					]^c
2. 0% S.S.						
3. 100% S.S.						
4. Reactor Trip						
5. End of Reactor Trip						

Sxr_{range} = [ ]^c ksi < 3.0 S_m = 60 ksi

$S\theta r_{range}$ = [ ]^c ksi

$S\theta x_{range}$ = [ ]^c ksi

Table 8-6C Primary and Secondary Stresses and Stress Intensities on Inside Surface of Sleeve with Unlocked and Intact Tube for Westinghouse "51" Steam Generator						
Transient Condition	Total Axial Stresses σx_{total} (ksi)	Total Hoop Stresses $\sigma\theta_{total}$ (ksi)	Total Radial Stresses σr_{total} (ksi)	Sxr (ksi)	Sθr (ksi)	Sθx (ksi)
1. Ambient	[					]^{c}
2. 0% S.S.						
3. 100% S.S.						
4. Reactor Trip						
5. End of Reactor Trip						]

Sxr_{range} = [ ]^{c} ksi < 3.0 S_m = 60 ksi

$S\theta r_{range}$ = [ ]^{c} ksi

$S\theta x_{range}$ = [ ]^{c} ksi

Table 8-6D Primary and Secondary Stresses and Stress Intensities on Inside Surface of Sleeve with Locked and Intact Tube for Westinghouse "51" Steam Generator with a Power Uprate						
Transient Condition	Total Axial Stresses σx_{total} (ksi)	Total Hoop Stresses $\sigma\theta_{total}$ (ksi)	Total Radial Stresses σr_{total} (ksi)	Sxr (ksi)	Sθr (ksi)	Sθx (ksi)
1. Ambient	[					]^{c}
2. 0% S.S.						
3. 100% S.S.						
4. Reactor Trip						
5. End of Reactor Trip						
6. Loss of Power, initial						
7. Loss of Power, final						
8. Primary Leak Test						
9. RCS COMS, minimum						
10. RCS COMS, maximum						]

Sxr_{range} = [ ]^{c} ksi < 3.0 S_m = 60 ksi

$S\theta r_{range}$ = [ ]^{c} ksi

$S\theta x_{range}$ = [ ]^{c} ksi

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Table 8-7A Peak Stress Intensity on Inside Surface of Sleeve with Unlocked and Intact Tube for Westinghouse "44" Steam Generator				
Transient Condition	**Spxr (ksi)**	**Spθr (ksi)**	**Spθx (ksi)**	**Number of Cycles**
1. Ambient	[			]c
2. 0% S.S.				
3. 100% S.S.				
4. Reactor Trip				
5. End of Reactor Trip				

Table 8-7B Peak Stress Intensity on Inside Surface of Sleeve with Unlocked and Intact Tube for Westinghouse "44F" Steam Generator				
Transient Condition	**Spxr (ksi)**	**Spθr (ksi)**	**Spθx (ksi)**	**Number of Cycles**
1. Ambient	[			]c
2. 0% S.S.				
3. 100% S.S.				
4. Reactor Trip				
5. End of Reactor Trip				

Table 8-7C Peak Stress Intensity on Inside Surface of Sleeve with Unlocked and Intact Tube for Westinghouse "51" Steam Generator

Transient Condition	Spxr (ksi)	Spθr (ksi)	Spθx (ksi)	Number of Cycles
1. Ambient				c
2. 0% S.S.				
3. 100% S.S.				
4. Reactor Trip				
5. End of Reactor Trip				

Table 8-7D Peak Stress Intensity on Inside Surface of Sleeve with Locked and Intact Tube for Westinghouse "51" Steam Generator with a Power Uprate

Transient Condition	Spxr (ksi)	Spθr (ksi)	Spθx (ksi)	Number of Cycles
1. Ambient				c
2. 0% S.S.				
3. 100% S.S.				
4. Reactor Trip				
5. End of Reactor Trip				
6. Loss of Power, initial				
7. Loss of Power, final				
8. Primary Leak Test				
9. RCS COMS, minimum				
10. RCS COMS, maximum				

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Table 8-8A Accumulated Fatigue in Sleeve Material for Spxr Peak Stress Range for Westinghouse "44" Steam Generator

Maximum Stress Intensity		Minimum Stress Intensity						
Transient	**SI ksi**	**Transient**	**SI ksi**	**Sa ksi**	**Sa*(1) ksi**	**N(2)**	**n**	**U = n/N**
End of Reactor Trip	[ ]c	100% S.S.	[					]c
Ambient		100% S.S.						
% S.S.		100% S.S.						
0% S.S.		Reactor Trip						

(1) Per Reference 8.1, Section III, Paragraph NB-3222.4 (e) (4), the definition for Sa* is:

$Sa^* = E_{curve} / E_{actual} (Sa) = 1.0755\ Sa$

Where: $E_{curve} = 28.3 \times 10^6$ psi; Reference 1, Section III, Figure I-9-2
$E_{actual} = 26.313 \times 10^6$ psi; Reference 1 for the sleeve material

(2) Reference 8.1, Section III, Figure I-9-2

Therefore, ΣU =[ ]c < Allowable = 1.0

Table 8-8B Accumulated Fatigue in Sleeve Material for Spxr Peak Stress Range for Westinghouse "44F" Steam Generator

Maximum Stress Intensity		Minimum Stress Intensity						
Transient	**SI ksi**	**Transient**	**SI ksi**	**Sa ksi**	**Sa*(1) ksi**	**N(2)**	**n**	**U = n/N**
End of Reactor Trip	[ ]c	100% S.S.	[					]c
Ambient		100% S.S.						
% S.S.		100% S.S.						
0% S.S.		Reactor Trip						

Therefore, ΣU =[ ]c < Allowable = 1.0

Table 8-8C Accumulated Fatigue in Sleeve Material for Spxr Peak Stress Range for Westinghouse "51" Steam Generator								
Maximum Stress Intensity		**Minimum Stress Intensity**						
Transient	**SI ksi**	**Transient**	**SI ksi**	**Sa ksi**	**Sa*(1) ksi**	**N(2)**	**n**	**U = n/N**
End of Reactor Trip	[ ]c	100% S.S.	[					]c
Ambient		100% S.S.						
0% S.S.		100% S.S.						
0% S.S.		Reactor Trip						

Therefore, ΣU =[ ]c < Allowable = 1.0

Table 8-8D Accumulated Fatigue in Sleeve Material for Spxr Peak Stress Range for Westinghouse "51" Steam Generator with a Power Uprate								
Maximum Stress Intensity		**Minimum Stress Intensity**						
Transient	**SI ksi**	**Transient**	**SI ksi**	**Sa ksi**	**Sa*(1) ksi**	**N(2)**	**n**	**U = n/N**
End of Reactor Trip	[ ]c	100% S.S.	[					]c
Ambient		100% S.S.						
0% S.S.		100% S.S.						
0% S.S.		100% S.S.						

Therefore, ΣU =[ ]c < Allowable = 1.0

8.6 EFFECTS OF SEVERED, UNLOCKED TUBE ON SLEEVE AXIAL LOADING

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8.2 Westinghouse Letter Report No. CSE-96-115, "Tube Sleeve History Data for 7/8 inch Steam Generator Tubes," May 03, 1996.

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8.4 Westinghouse Report No. NSD-RMW-90-070, SG-90-02-026, "Steam Generator Information Report," Revision 6, February 1990.

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8.20 NRC Generic Letter 95-05: "Voltage – Based Repair Criteria for Westinghouse Steam Generator Tubes Affected by Outside Diameter Stress Corrosion Cracking," Page 3 of Attachment 1, as applied to the Westinghouse plants.

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8.22 Westinghouse Report No. WCAP-14707, Revisions. 0 and 1, "Model 51 Steam Generator Limited Tube Support Plate Displacement Analysis for Dented or Packed Tube to Tube Support Plate Crevices," August 1996 and April 1997.

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Figure 8-1 Mechanical Sleeve/Tube Assembly

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Figure 8-2 System Schematic for Westinghouse "44," "44F," and "51" S.G. with Effective Length Between Lower Joint and Last Upper Joint

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Figure 8-3 Model of Sleeve, Lower Tube, and Tube in Tubesheet; Unlocked at Tube Support

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Figure 8-4 Model of Composite Member, Upper Tube, Surrounding Tubes, and Tubesheet; Locked at Tube Support

9 SLEEVE INSTALLATION VERIFICATION

9.1 SUMMARY AND CONCLUSIONS

The Westinghouse Alloy 800 repair sleeve installation process and sequence has been tested to ensure that the installation of a sleeve conforms to the design criteria described in Section 3. During this testing, actual steam generator conditions, such as the influence of tubes locked at tube supports, have been considered in assessing the acceptability of the various processes and the sequence in which they are performed. In addition, sleeve installation meets the requirements of ASME B&PV Code Section XI, IWA-4420.

9.2 SLEEVE-TUBE INSTALLATION SEQUENCE

9.2.1 Transition Zone Sleeve

The TZ sleeve with the rolled lower joint is described in Section 4.3 and Figure 4-3. Installation is accomplished using the processes described in Section 4.5 in the following sequence:

(1) Tube I.D. Conditioning
(2) Sleeve Installation and Expansion
(3) Sleeve Lower End Torque Roll
(4) Sleeve and Tube ET Examination

9.2.2 Tube Support Sleeve

The TS sleeve is described in Section 4.3 and Figure 4-4. Installation is accomplished using the processes described in Section 4.5 in the following sequence:

(1) Tube I.D. Conditioning
(2) Sleeve Installation and Expansion of Upper Joint
(3) Expansion of Lower Joint
(4) Sleeve and Tube ET Examination

9.3 EXPANSION JOINT INTEGRITY

Westinghouse has conducted a comprehensive test program, an Eddy Current Appendix H qualification and an analysis development program, as well as a corrosion test program to ensure expansion joint integrity. Tube I.D. conditioning tests and sleeve/tube expansion tests have been completed as part of the process verification.

9.3.1 Tube Conditioning Qualification

Steam generator tube conditioning is one of the preconditions for the leak limiting capability of the sleeve-tube expansion joint. In contrast to a welded sleeve, the surface preparation, not the oxide layer on the tube I.D., is the governing parameter for qualification of a conditioning process. The tube I.D.

conditioning is performed to accomplish the following; surface preparation, elimination of loose particles (i.e., boron crystals) and the mitigation of axial marks.

A series of tests have been completed to determine the optimum conditioning head design, the optimal work cycle and the life of the consumable elements of the system. Clean tubing, air oxidized tubing and primary side autoclaved tubing were used in the program. Results of the tests performed have shown that flexible hones, centrifugal brushes, abrasive cloth with a centrifugal brush carrier and a stainless steel buffing tool are all effective to achieve the desired I.D. surface condition. Because there is essentially no removal of tube material, the acceptability of the process is insensitive to the strength of the tubing. The test program is outlined in References 9.5.1, 9.5.2, 9.5.6, and 9.5.7.

As stated in subsection 4.5.3, an evaluation of field experience involving video examination of conditioned tubes indicated that process control, in the form of in-process instructions and quality assurance surveillance, is sufficient to ensure acceptable conditioning of the tube I.D. This experience involved over 600 conditioned tubes in eight steam generators at four different plants during five different outages. No scratches, loose particles, or other detrimental conditions were identified during these inspections.

9.3.2 Expansion Qualification

An important design and installation issue for the Alloy 800 sleeve is the hydraulic expansion. There are three variables associated with the expansion: the number of expansions, the axial length of each expansion, and the diametrical extent. A finite element stress analysis was performed to study the effects of expansion length and diametrical extent. The study addressed expansion lengths from [ ].[b] Maximum installation stresses and the effective strain on the inside surface of the tube and the O.D. diametrical expansion as a function of sleeve expansion pressure for [ ][b] expansion lengths were all considered.

The finite element stress analysis showed that the axial and hoop stresses increase rapidly with expansion pressure, with the hoop stress greater than the axial stress except for the higher expansion pressures. The radial stress, which is the stress between the sleeve and the steam generator tube, tends to be relatively constant as a function of expansion pressure. The radial stress is relatively more sensitive to expansion length than the other stress components, with a peak value at an expansion length of about [ ][a,c] for all diametrical expansions.

The selection of design parameters is intended to provide the best leak resistance and the best corrosion resistance. The best leak resistance should be associated with the greatest radial stress between the sleeve and the steam generator tube. This indicates that the expansion length of [ ][a,c] is the optimal length to resist leakage. The short expansion length also permits a greater number of expansions, which will also contribute to leak resistance. The number of expansions has been chosen to be [ ][a,c]. Leak testing was conducted for different diametrical expansions ranging from [ ][b], as described in subsection 7.3.1. The test results did not identify any significant improvement in the leak rate of sleeves installed with [ ][b] as compared to those with smaller diametrical expansions. The diametrical expansion is therefore targeted to be in the [ ][a,c] range for improved corrosion resistance. The minimum of the range, [ ][a,c], is established as acceptable by the load and leakage tests of Section 7. The upper limit on the strain, [ ]^{a,c}, is established by the results of the corrosion tests of Section 6 and the installation tolerances achievable.

Based on the above analytical study, an extensive test program was performed to qualify the expansion design. This program, as described in Section 7, considered structural and leakage limits of the design.

References 9.5.3 and 9.5.5 contain information related to one of the expansion system qualifications. This expansion system monitors the stroke of the intensifier and corresponding pressure to the expansion tool. With this system, the diametrical expansion is controlled to [ ]^{a,c} for steam generator tubing within the range of anticipated yield strengths.

As discussed in subsection 4.5.4, re-expansion of the joint can be performed should the initial expansion not reach the required minimum pressure. Failure to reach the minimum pressure would result in failing to achieve the expansion size associated with the structural integrity established in the test matrix. The re-expansion is intended to increase expansion size by increasing the applied pressure. There would be a necessary increase in cold working due to this operation, but no more than had the proper pressure been reached during the initial pressurization. Limits on the number of re-expansions are specified in the process procedures.

9.3.3 Summary

In summary, Westinghouse has conducted a comprehensive development and verification program to ensure the integrity of the expansion joint.

9.4 ROLLED JOINT INTEGRITY

The rolled joint at the lower end of the Alloy 800 sleeve was developed to duplicate the rolled joint of the Alloy 800 mechanical plugs used by Westinghouse in Europe and Korea. These rolled joints have been demonstrated by testing and operating experience to be leak tight and capable of withstanding operating conditions. The Alloy 800 mechanical plugs have operated many years with no degradation of the rolled joint in the roll transition area. Westinghouse has drawn on this successful experience in designing the lower rolled joint of the Alloy 800 sleeve.

A development program was conducted to ensure the rolled joint of the TZ sleeve was leak tight and capable of withstanding the design loads. The sleeves were rolled into mock-ups consisting of steam generator tubes which had been rolled into blocks simulating the tubesheet. The sleeves were then tested to confirm the rolled joint was leak tight both before and after cyclic load testing. Tests of the rolled joint were also conducted where process parameters such as torque, tube diameter and roll location relative to the [ ]^{a,c} were varied. A test matrix was used to verify the sleeve installation with sleeve rolling process parameter tolerances. The test program confirmed that the rolled joint integrity is acceptable within the allowable rolling process tolerances.

As discussed in subsection 4.5.5, re-rolling of the joint can be performed should the initial rolls not reach the required minimum torque value. Failure to reach the minimum torque value would result in failing to achieve the wall thinning associated with the structural integrity established in the test matrix. The re-roll operation is intended to increase the wall thinning value by increasing the torque applied. There would be a necessary increase in cold working due to this operation, but no more than had the proper torque value (and wall thinning) been reached on the initial rolling operation. Limits on the number of rolling operations are specified in the process procedures.

References 9.5.4, 9.5.8, 9.5.9, and 9.5.10 contain information concerning the qualification of the rolled joint.

9.5 REFERENCES FOR SECTION 9

9.5.1 GBRA 031 980, "Tihange 3 Steam Generator Sleeving, Surface Treatment of Steam Generator Tubes For Weldless Sleeving."

9.5.2 Memo From E. P. Kurdziel To D. Proctor, "Alloy 800 Tube Conditioning and Surface Roughness Measurements," October 22, 1998.

9.5.3 Report No. GBRA 039-930, "3/4" US NSSS Sleeving, Volume-Controlled Hydraulic Expansion of Sleeve."

9.5.4 Report No. GBRA 039-933, "3/4" US NSSS Sleeving, Torque-Controlled Hard Rolling of Sleeve."

9.5.5 Report No. 00000-NOME-TR-0097, "Test Report Qualification of Expansions of Alloy 800 Sleeves in .75 inch O.D. x .042/.043 inch Wall Steam Generator Tubes."

9.5.6 Report No. 00000-OSW-034, "Test Program for Particle Removal Prior to Sleeve Installation."

9.5.7 Report No. 00-TR-FSW-008, "Test Report to Determine Tube Surface Roughness After Tube Conditioning Using the Burnishing Tool."

9.5.8 Report No. 00000-NOME-TR-0091, "Test Report for the Qualification of the Alloy 800 Sleeve Rolling Operation for Combustion Engineering 0.75 inch OD x .048 inch Wall Steam Generator Tubes".

9.5.9 Report No. 00000-NOME-TR-0100, "Test Report for the Qualification of the Alloy 800 Sleeve Rolling Operation for Combustion Engineering 0.75 inch OD x .042 inch Wall Steam Generator Tubes."

9.5.10 Report No. 00000-NOME-TR-0101, "Test Report for the Qualification of the Alloy 800 Sleeve Rolling Operation for Westinghouse D2, D3, D4, D5, and E 0.75 Inch OD x .043 inch Steam Generator Tubes."

10 EFFECT OF SLEEVING ON OPERATION

Multiple plant specific analyses have been performed to determine the effects of installation of varying lengths and combinations of TZ and TS sleeves. Sleeve lengths and various combinations of installed sleeves were used to evaluate the effect of sleeving on the hydraulic characteristics and heat transfer capability of steam generators. Using the head and flow characteristics of the pumps, in conjunction with the primary system hydraulic resistances, system flow rates have been calculated as a function of the number of sleeved tubes and the types of sleeves installed. Similarly, curves are generated from calculations that show the percent reduction in system flowrate as a function of newly plugged tubes (per steam generator). These curves are derived from plant specific information based on the following steam generator conditions:

- Number of Open Tubes Per Steam Generator
- Number of Tubes Sleeved
- Primary System Flowrate
- Primary Coolant Temperature

This information has been used to generate tables, such as Table 10-1, that provide hydraulic equivalency of plugs and installed sleeves, or the sleeve/plug ratio. Table 10-1 is provided as an approximation only and is based on assumed operating parameters and sleeve types for steam generators with 7/8" O.D. tubes. It must be assumed that some variations in the sleeve/plug ratio will occur from plant to plant based on operating parameters and steam generator conditions.

The overall resistance to heat transfer between the primary and secondary side of the steam generator consists of primary side film resistance, the resistance to heat transfer through the tube wall, and the secondary side film resistance. Since the primary side film resistance is only a fraction of the total resistance and the change in flow rate is so small, the effect of this flow rate change on heat transfer is negligible.

When the sleeve is installed in the steam generator tube there is an annulus between the sleeve and tube except in the sleeve-tube expansion regions. Hence, there is effectively little primary to secondary heat transfer in the region where the sleeve is installed. The loss in heat transfer area associated with sleeving is minimal when compared to the overall length of the tube.

In summary, installation of sleeves does not substantially affect the primary system flow rate or the heat transfer capability of the steam generators.

10.1 REFERENCES FOR SECTION 10

10.1.1 "Calculation of Alloy 800 Sleeve Hydraulic Resistance in Westinghouse 7/8 Inch Model Steam Generators," NSD-ENG-CALC-310, August 2003.

Table 10-1 Typical Sleeve to Plug Equivalency Ratio

Case	Configuration	Ratio (Sleeve/Plug)*
1	TZ (1)	[ ]b
2	TZ (1) and TS (1)	
3	TZ (1) and TS (2)	
4	TS (1)	
5	TS (2)	

Note:
* This ratio should be considered approximate due to plant to plant variation

Enclosure D

FENOC-08-148

(Non-proprietary)

Westinghouse

Westinghouse Electric Company
Nuclear Services
P.O. Box 355
Pittsburgh, Pennsylvania 15230-0355
USA

Mr. Gary Alberti
FirstEnergy Nuclear Operating Co.
Beaver Valley Power Station
P. O. Box 4
Shippingport, PA 15077

Direct tel: 412-374-5216
Direct fax: 412-374-2252
e-mail: blanchk@westinghouse.com

Our ref: FENOC-08-148

September 26, 2008

FirstEnergy Nuclear Operating Company
Beaver Valley Power Station Unit 2
Summary of Alloy 800 Sleeve Parent Tube Eddy Current Test Results

Dear Gary,

Attached is a summary of eddy current test results related to the ability to detect parent tube degradation in tubes repaired using Alloy 800 sleeves.

If you have any questions, please contact Bill Cullen at 724-722-5314 or me.

Regards,
WESTINGHOUSE ELECTRIC COMPANY

Jason A. Brown for

Kenneth Blanchard
Customer Project Manager

with attachment

cc: K. Blanchard – Energy Center
R. Jewell – Energy Center
S. DiTommaso – Beaver Valley Site
W. K. Cullen – Waltz Mill
R. J. Pocratsky – Waltz Mill
J. A. Brown – Energy Center

Alloy 800 Sleeve-Parent Tube Eddy Current Testing Results

Background:

The industry has long advocated that standard eddy current techniques would adequately detect parent tube degradation in tubes adjacent to the nickel band region of Alloy 800 and TIG sleeves. However no formal qualification exists for this condition. This position was discussed in WOG-04-518. Eddy current standards for TIG sleeve installations at one plant included 50%, 70%, and 100% through wall axial ID EDM notches in the parent tube adjacent to the sleeve nickel band region. These notches are readily detectable with the Plus Point probe using both 75 and 150 kHz, however the ability to detect true SCC flaws and EDM notches can be different, due primarily to the signal amplitude response. As the TIG (Alloy 690) and Alloy 800 sleeve materials are similar with similar eddy current characteristics the observations from the standards using TIG sleeves are considered applicable to Alloy 800 sleeves.

Eddy Current Test Results for Laboratory Generated Parent Tube SCC:

To assess detection capabilities for true SCC flaws, a section of mill annealed Alloy 600 tubing with laboratory (doped steam) generated flaws was used. The nominal tube dimensions were ¾ inch OD x 0.043 inch wall thickness. This specimen contained four, axially oriented, OD initiated flaws all at the same approximate elevation. The four flaws are equally spaced around the tube circumference. The residual stresses required for crack initiation were applied by use of a clamp device which acted across one axis of the tube. The device was then removed and applied perpendicular to the first axis of application. The resulting tube condition was essentially round, with no apparent ovalization. Due to the generation of 100%TW flaws this specimen was not used in the original program (a bobbin coil based detection program) under which it was developed.

A carbon steel simulating tubesheet collar was prepared with the tube hole ID resulting in a slip-fit condition between collar and tube. The slip-fit condition was used to limit the radial expansion of the tube, thus minimizing the impact upon flaw eddy current signal amplitude response due to radial expansion. The tube was then hydraulically expanded into the collar. Plus Point eddy current data was collected for the parent tube prior to and after expansion into the collar. For the prior to expansion condition a TSP simulating ring was located over the flaws so that both the pre and post expansion conditions included carbon steel at the tube OD. The Plus Point data prior to expansion suggests that based on flaw amplitude, two of the four flaws had 100%TW penetration for a limited axial length (less than the total flaw length), one possibly had 100%TW penetration, and one had less than 100%TW penetration. The flaw amplitudes ranged from 0.86 to 4.65 volts in 300 kHz

For PWSCC, 100%TW flaw penetration has a 300 kHz Plus Point amplitude of approximately 4 volts. As the 100%TW length is increased the flaw amplitude will also increase. Only the 4.65 volt signal exceeds this value. The slip-fit condition between collar and tube included only a few mils of diametrical clearance; thus the introduced radial expansion was not sufficient to result in flaw tearing of existing 100%TW areas or <100%TW areas. Any flaw amplitude increases are associated with a disruption of the crack faces or flaw width increase at the tube ID surface. This flaw amplitude increase (without flaw tearing) can result in overestimation of flaw depth using amplitude based sizing methods. After expansion of the tube into the collar the 4.65 volt increased was increased to 7.25 volts while the other flaws experienced much smaller increases and remained below 4 volts. The 0.86 volt signal was increased to only 1.25 volts.

An Alloy 800 sleeve was then roll expanded (within procedure specifications) into this assembly with the sleeve nickel band placed adjacent to the parent tube flaws. Plus Point eddy current data was collected after sleeve installation.

The main sleeve analysis frequency is 75 kHz. This frequency is selected to provide for detection of flaws in the parent tube. The result of this analysis showed that all four parent tube flaws were detectable. The responses produced both visual response (from the terrain plot) and signal response (measurable amplitude and phase angle in the flaw plane). Thus it can be concluded that for the case of parent tube degradation existing prior to sleeve installation, that <100% through-wall and 100% through-wall degradation would be readily detectable with the Plus Point coil in 75 kHz. Good flaw detection capabilities were also provided for 150 kHz; all four flaws were also detected using 150 kHz. The amplitude responses for all flaws in the respective frequencies are essentially equal (5 to 6 volts in 75 kHz, 4 to 5 volts in 150 kHz), suggesting that the eddy current penetration into the parent tube extends well into the tube wall. This observation (of equal flaw amplitudes for all flaws) also suggests that the direction of flaw initiation will not significantly affect detection. That is, whether the flaws are initiated from the OD or ID, as long as the crack face extends through the depth of eddy current field penetration, the flaw should be detectable. The observation that the EDM notches of the standard discussed above were detectable in both 75 and 150 kHz suggests that for the nickel band configuration, that the influence of the nickel band on these frequencies is limited, and that flaw penetration beyond this influence would result in a high probability of detection. Thus, for the nickel band configuration, the amplitude response difference between EDM notches and SCC upon detection capabilities is not as pronounced as for non-nickel band situations. For the range of available frequencies, 50, 75, 150, and 300 kHz, the phase responses are described by eddy current theory. That is, as inspection frequency is increased the phase response of the flaw rotates towards larger phase angles. Figures 4, 5, 6, and 7, present the Flaw 1 +Pt analysis responses for the analysis frequencies (50, 75, 150, and 300 kHz). In 300 kHz, no flaws are detected; this is an expected result for this analysis frequency and indicates why the 75 kHz frequency is used.

The pre-sleeve installation and post-sleeve installation flaw length values were compared. The total flaw length values were similar for three of the four flaws. The post sleeve installation length for Flaw 1 was reduced from 0.73 to 0.38 inch, however, destructive examination would show that the post sleeve installation length is actually closer to the true length. Figure 2 presents the destructive examination depth profile of Flaw #1 and Figure 3 presents the destructive examination depth profile of Flaw #4.

PWSCC typically exhibits minimal taper due to the highly stress dependent nature of the mechanism. Thus flaw length at the tube ID and OD (for 100%TW degradation), or at the crack front for part throughwall flaws should be similar. As such, any influence upon detection capability at the tube-sleeve interface due to the nickel band will not adversely affect detection as sufficient flaw length at the crack front would permit detection.

The most recent, and future, Alloy 800 sleeve installations will include Plus Point (or equivalent) inspection of the parent tube in the tube-sleeve hardroll joint region prior to sleeve installation. The Plus Point probe in this condition is qualified for detection according to Appendix H of the EPRI PWR Steam Generator Examination Guideline Revision 7 (EPRI 1013706). Thus PWSCC in the parent tube would be identified prior to sleeve installation. If degradation of the parent tube in this region is observed the tube is not a candidate for repair by sleeving. Once the sleeve is installed, one element required for flaw initiation, the environment, would be eliminated, and flaw initiation or growth, after sleeve installation, would not occur.

Destructive examination (DE) of the parent tube was performed to compare NDE reported flaw length against truth. Prior to disassembly of the specimen a notch was placed on the parent tube at a location judged to be in-line with one of the suspected eddy current flaw signals. Upon destructive examination this notch was confirmed to be in-line with a flaw, thus confirming that the suspected flaw signals truly were generated by the ODSCC. The prior to expansion flaw lengths were compared against the DE data. For Flaws 1, 2, and 3, the NDE length exceeded the DE length. For Flaw 4 the NDE length underestimated the DE length by 0.05 inch. Destructive examination showed that Flaw 4 had a local maximum depth of approximately 85%TW with an average depth of 54%TW over the length of the flaw (0.36 inch). Flaw 4 also had the shortest overall flaw length by DE and by NDE.

The flaws were found to be initiated at multiple axial elevations with linking of some of the segments. Figure 8 presents a magnified photograph of the OD surface of Flaw 4; Figure 9 presents a magnified photograph of the OD surface of Flaw 1.

<u>Eddy Current Test Results for OD EDM Notch Specimen:</u>

An additional specimen was prepared using a tube specimen from the structural and leakage integrity testing program described by WOG-06-23. The tube contained 6 axial OD EDM notches, equally spaced around the tube circumference, each with a nominal depth of 80%TW. The EDM notch length was 0.48 inch. An axially oriented, 40%TW OD milled slot, using a 1/16th diameter end mill cutter was applied to the tube. The milled slot total length was 0.43 inch, and was located such that the axial center of the milled slot was adjacent to the upper edge of the EDM notches. Thus approximately ½ of the milled slot length extended above the EDM notches. The slot was radially located between two of the axial EDM notches. Figure 1 presents a schematic of the tube flaws. This tube was tack rolled into a carbon steel split collar. The tube hole diameter in the split collar is 0.756 inch, thus the amount of radial expansion applied to the tube was minimal. RPC eddy current data was collected prior to tube tack rolling and after tack rolling. As expected, the prior to rolling signal amplitudes for the EDM notches were similar, about 2.5 volts in 300 kHz. However, the 300 kHz flaw responses for the expanded tube in collar condition shows the flaw amplitudes were actually reduced to about 1.o to 2.0 volts. This is likely due to compression of the EDM width nearer to the tube ID surface due to roll expansion. An Alloy 800 sleeve was installed such that the microlok to nickel band interface was adjacent to the axial center of the milled slot.

Results of the eddy current analysis of the installed sleeve-tube combination indicate that all of the tube 80%TW axial OD EDM notches and the 40%TW axial milled slot are detectable through the nickel band. As the 1/16th diameter milled slot extends above the EDM notches into the microlok band, detection was readily apparent in this area. In the nickel band area the proximity of the EDM notches and milled slot make distinguishing of the signals difficult, but still, the milled slot is judged detectable in the nickel band region and at the microlok to nickel band interface. Starting in the microlok area, each scan line at the axial slot was interrogated; the axial slot produced a signal response for each scan line well into the nickel band region. Detection of the axial slot and all EDM notches is evident in both the 75 and 150 kHz channels. In 300 kHz only three of the six axial EDM notches produce a signal response, however, this signal response is judged not reliably detectable. The 0.052 inch diameter, 100%TW hole in the parent tube located approximately 3 inches above the axial slot is also not detectable through the sleeve in the 300 kHz channel. This is expected as the lower frequencies will project the eddy currents farther into the parent tube. One interesting artifact of the inspection was that the axial seam between the two halves of the carbon steel split collar can be observed in both 75 kHz and 150 kHz through the microlok band also possibly through the nickel band.

The +Pt amplitude in 300 kHz of the axial milled slot without the sleeve was small, only about 1.02 volts. The detection of the milled slot through the nickel band shows that the 75 kHz analysis channel provides good penetration of eddy currents into the parent tube. Using a regression of +Pt amplitude on maximum depth for laboratory generated flaws and pulled tubes, a 60%TW axial PWSCC indication would produce an amplitude response of 1.3 volts. Thus as the 40% OD slot was judged detectable in the 75 kHz channel, a 60% ID flaw would also be judged detectable as the amplitude of the axial ID crack exceeds the amplitude response of the 40% OD slot.

As the EDM notch depth is uniform over the axial length, this test can be used to assess the impact of the edge effects of the nickel band. The NDE total reported EDM flaw length prior to sleeve installation was 0.53 inch, compared to the actual length of 0.48 inch. A near uniform 300 kHz amplitude response is measured for approximately 0.35 inch at the center of the notch. After sleeve installation the total flaw length is slightly reduced, and the length at the center of the flaw with near uniform amplitude response (in 75 kHz) varies from 0.16 to 0.25 inch. At the center of the nickel band the eddy current effects are minimized due to the design of the +Pt coil. Locally (at the center of the nickel band) there is a limited differential response available to the coil and thus the effect of the nickel is reduced. In essence, the coil "nulls" itself within the nickel band. This phenomenon is observed with volumetric signals. At the edge of the volumetric signal the Plus Point amplitude response is larger than at the center of the volumetric degradation as the Plus Point coil has a limited differential response at the center of the volumetric degradation. At the edges of the nickel band the flaw amplitude response is decreased (as the coil is experiencing a differential response), but still produces a reportable flaw-like signal. The 40% OD axial slot was detectable across the microlok to nickel band interface. Figure 10 presents the +Pt 75 kHz response for the 40%TW axial milled slot at the microlok to nickel band interface, which represents the limiting condition with regard to detection capabilities.

An artifact of the test configuration was that a simulated circumferential separation of the parent tube was inherently developed. From Figure 1 the distance from the center of the 0.052 inch diameter drill hole to the end of the tube is 3.00 inches. Once the tube with EDM notches was rolled into the tubesheet collar, a second tube was then abutted against the first and rolled in place. To assess how well this fit was created, the axial length involvement of the tube to tube fitup was compared with the circumferential EDM notch of the EP5 standard. The axial length involvement of the 100%TW circumferential notch of the EP5 standard was 0.38 inch, while the axial length involvement of the tube to tube fitup was measured at 0.31 inch. The length of the sleeve hardroll flat is 1.1 inch. Figure 11 presents a terrain plot of the sleeve-tube assembly. The top of the hardroll flat was defined as the 0.00 elevation point. The cursor is located at 1.1 inch below the reference elevation, or the bottom of the sleeve hardroll flat and shows the bottom of roll position. Immediately below this point, a large differential signal is noted, and is located at 3 inches below the parent tube drill hole, coinciding with Figure 1. Thus the tube to tube fitup condition is detected through the sleeve, and it can be judged that a postulated circumferentially separated tube condition below the sleeve to tube hardroll joint would be detectable.

<u>Conclusion:</u>

Eddy current examination of installed Alloy 800 sleeves with parent tube OD flaws adjacent to the sleeve nickel band shows that all flaws, ranging in depth from 40% to 100%TW from the OD were detectable in the 75 kHz channel. The readily detectable condition for the OD initiated SCC suggests that 100% through-wall and part through-wall PWSCC degradation approaching 100% through-wall will be readily detectable using the current examination techniques.

The mechanical and leakage testing program described by WOG-06-23 has established that degradation of the parent tube adjacent to the nickel band will not prevent the sleeve from satisfying its design function. WOG-06-23 concludes that NDE of the parent tube adjacent to the nickel band region is not required to satisfy the tube-sleeve system integrity requirements. The results of this eddy current testing program have established that both part throughwall and 100%TW degradation of the parent tube will be readily detectable using standard eddy current techniques and thus provides a defense in depth approach to the position established by WOG-06-23.

Figure 1

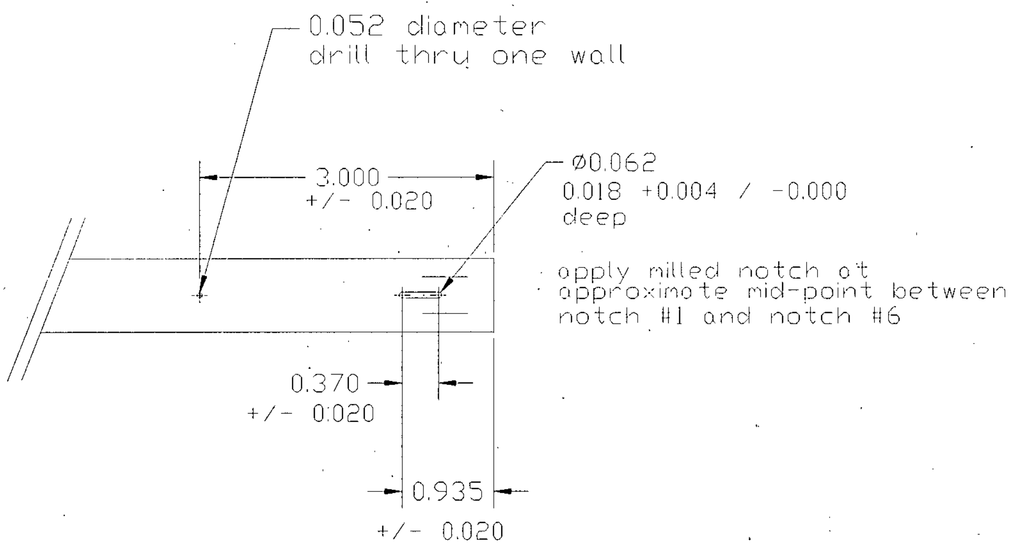

0.052 diameter
drill thru one wall
3.000
+/- 0.020
Ø0.062
0.018 +0.004 / -0.000
deep
apply milled notch at
approximate mid-point between
notch #1 and notch #6
0.370
+/- 0.020
0.935
+/- 0.020

Figure 2

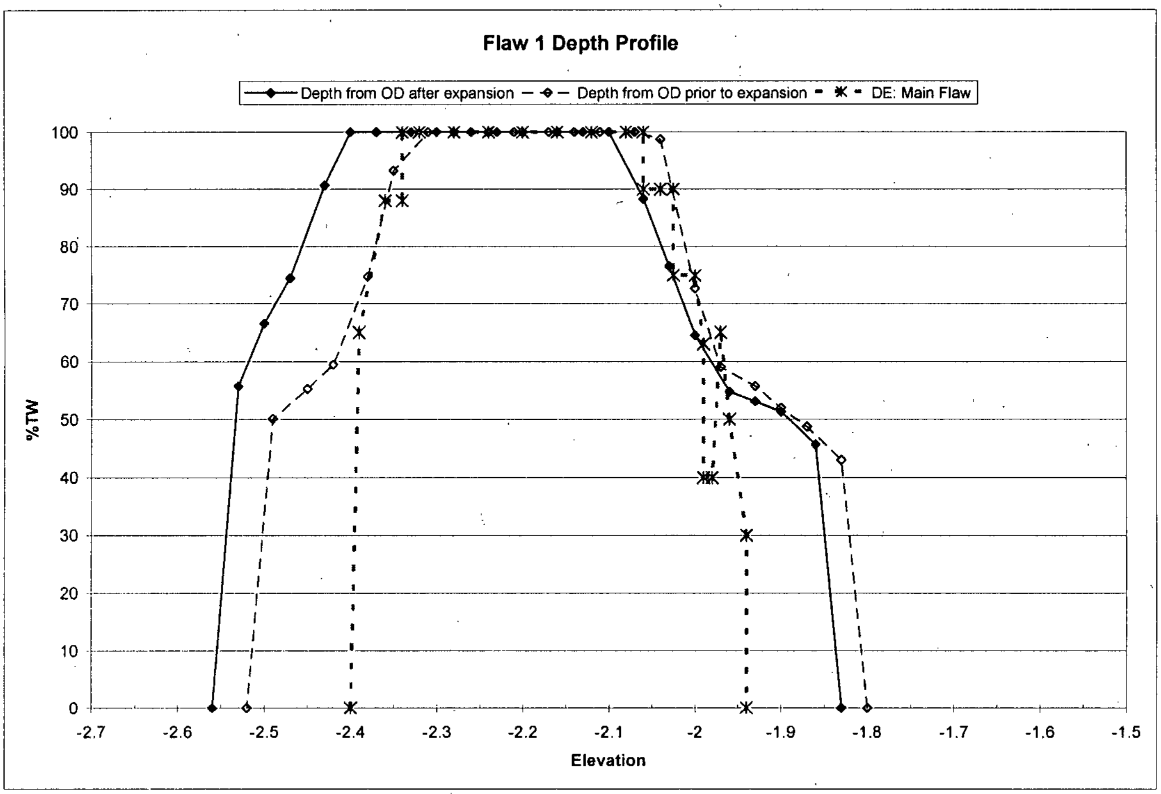

Flaw 1 Depth Profile
Depth from OD after expansion
Depth from OD prior to expansion
DE: Main Flaw
100
90
80
70
60
50
40
30
20
10
0
%TW
-2.7
-2.6
-2.5
-2.4
-2.3
-2.2
-2.1
-2
-1.9
-1.8
-1.7
-1.6
-1.5
Elevation

Figure 3

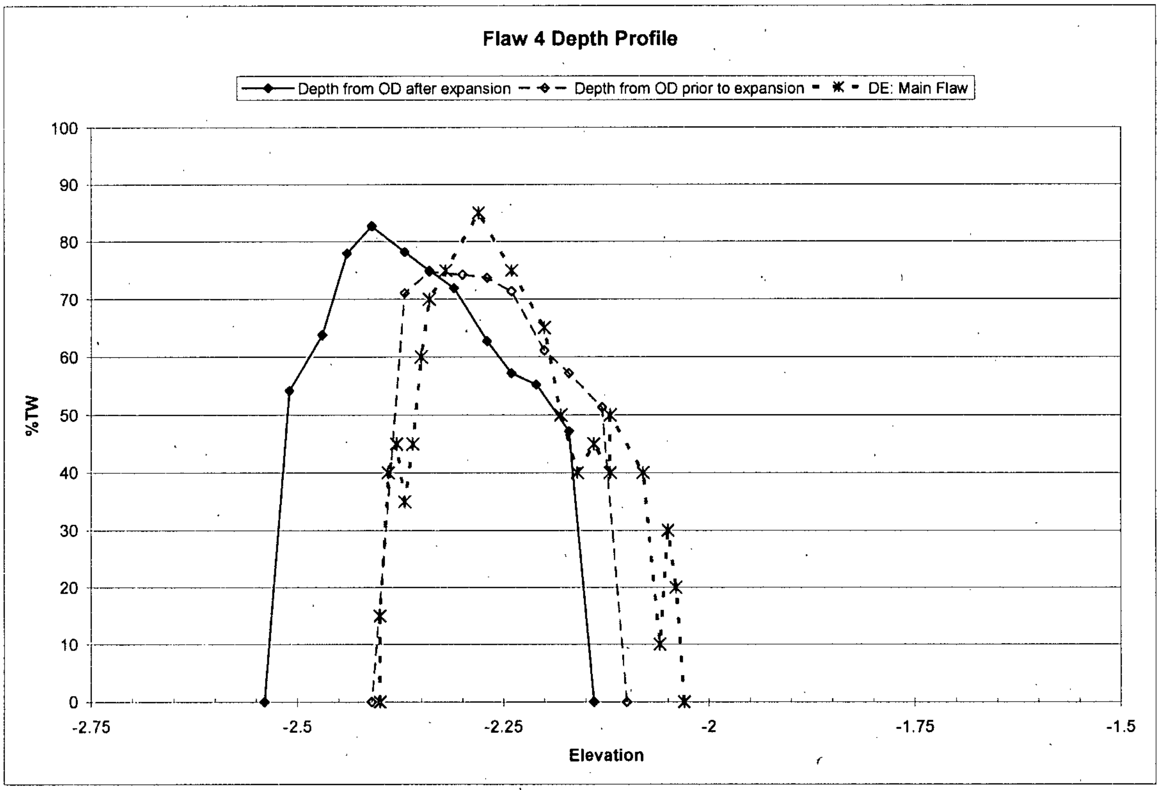

Flaw 4 Depth Profile
Depth from OD after expansion
Depth from OD prior to expansion
DE: Main Flaw
100
90
80
70
60
50
40
30
20
10
0
%TW
-2.75
-2.5
-2.25
-2
-1.75
-1.5
Elevation

Figure 4

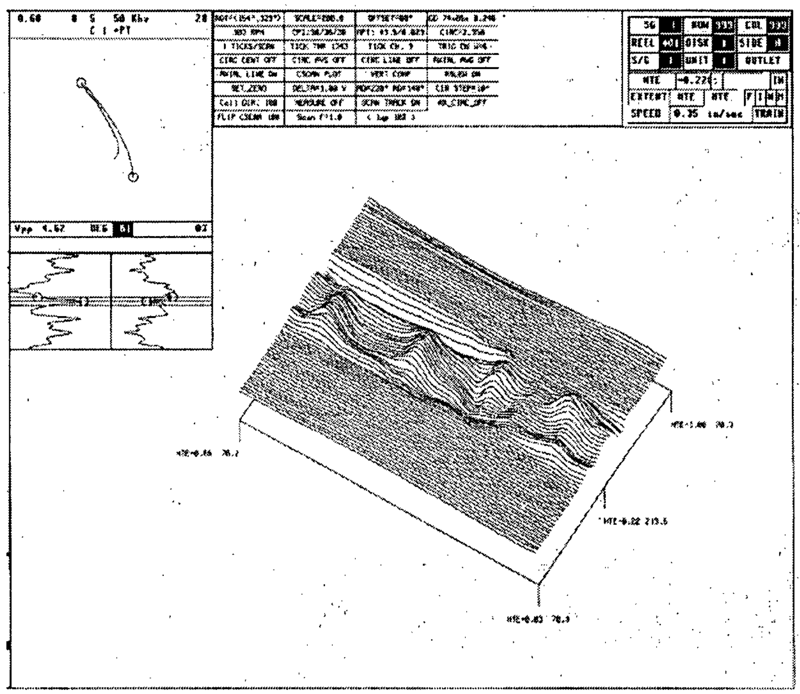


Figure 5

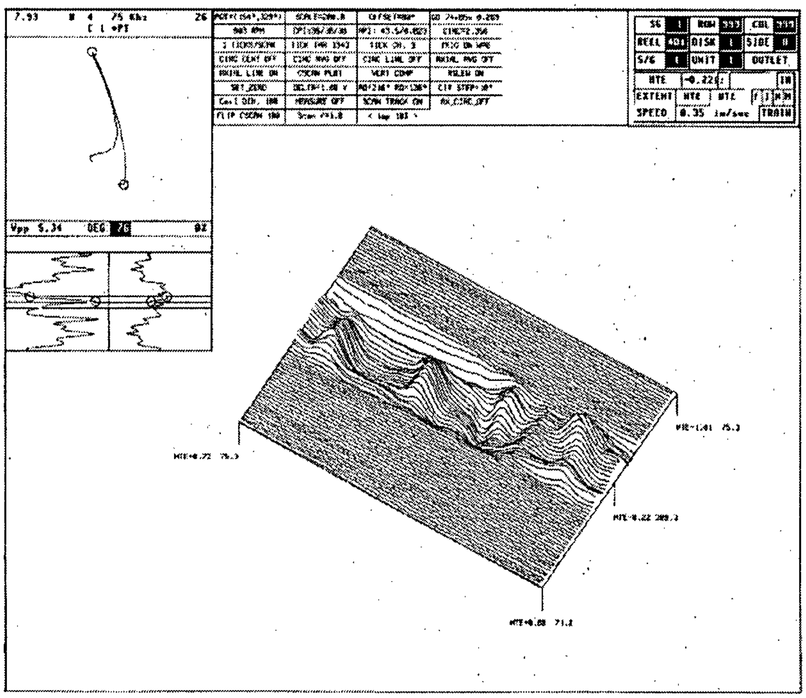


Figure 6

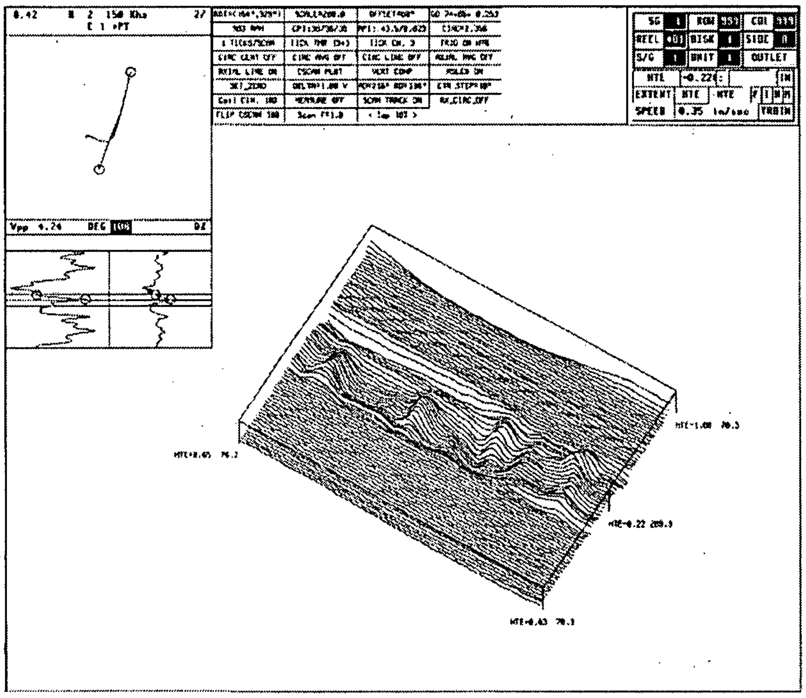


Figure 7

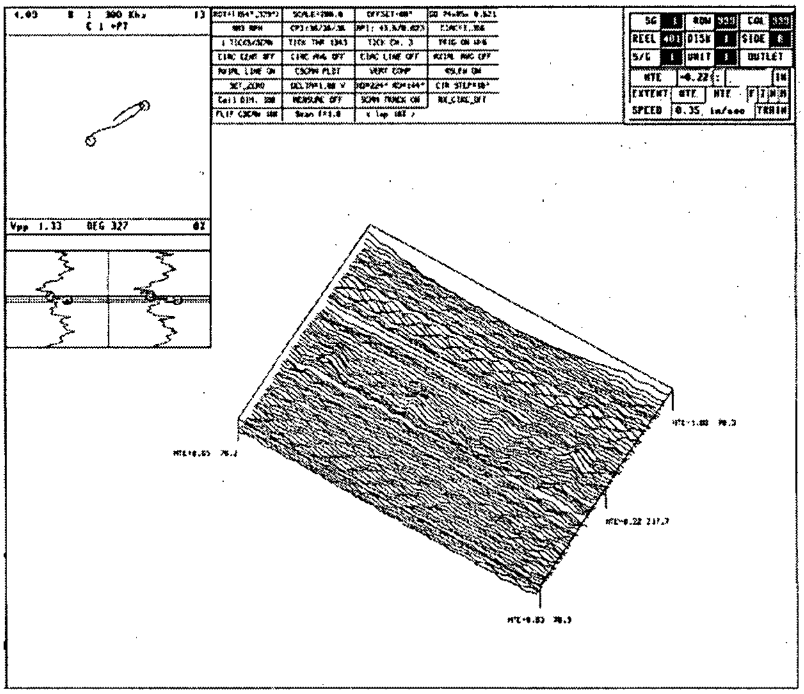


Figure 8

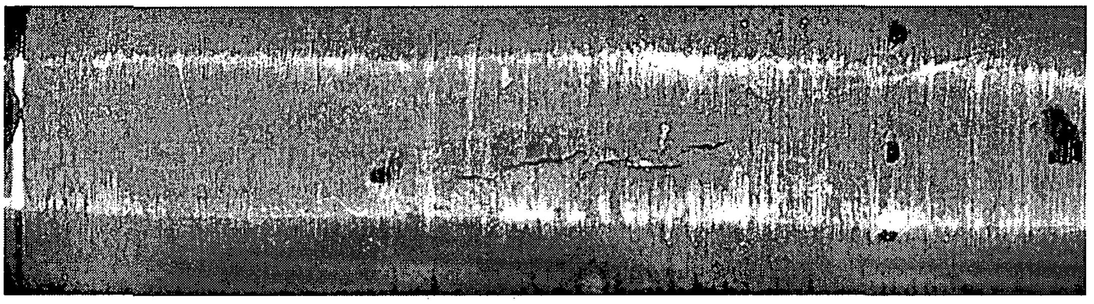


Figure 9

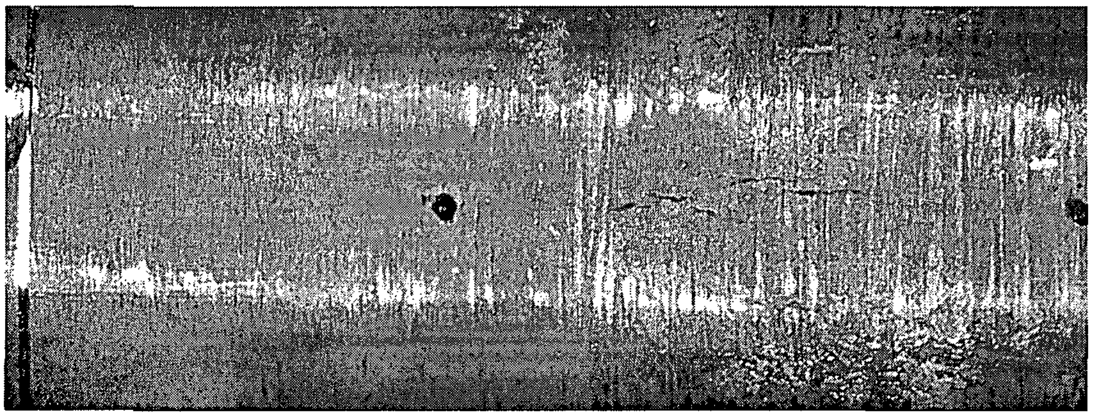


Figure 10

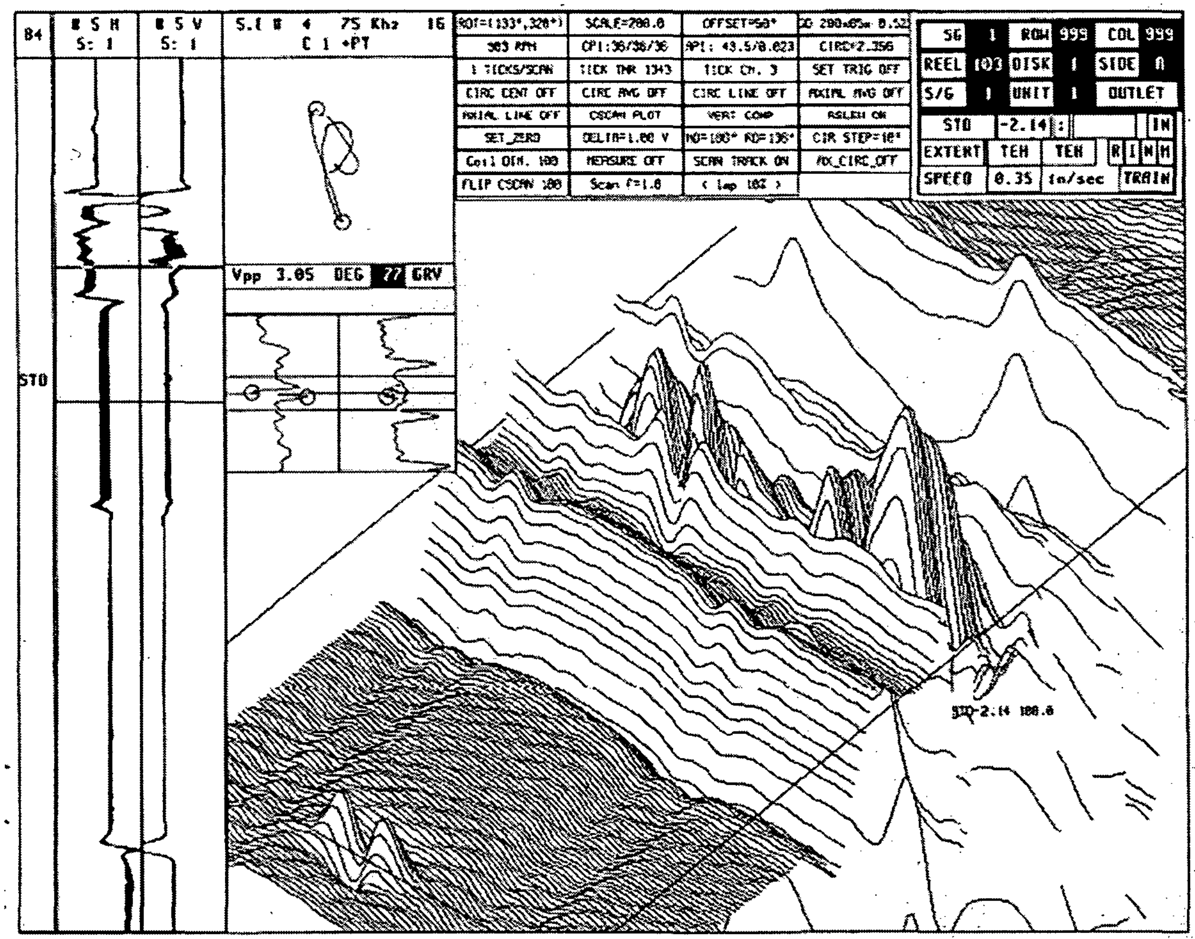
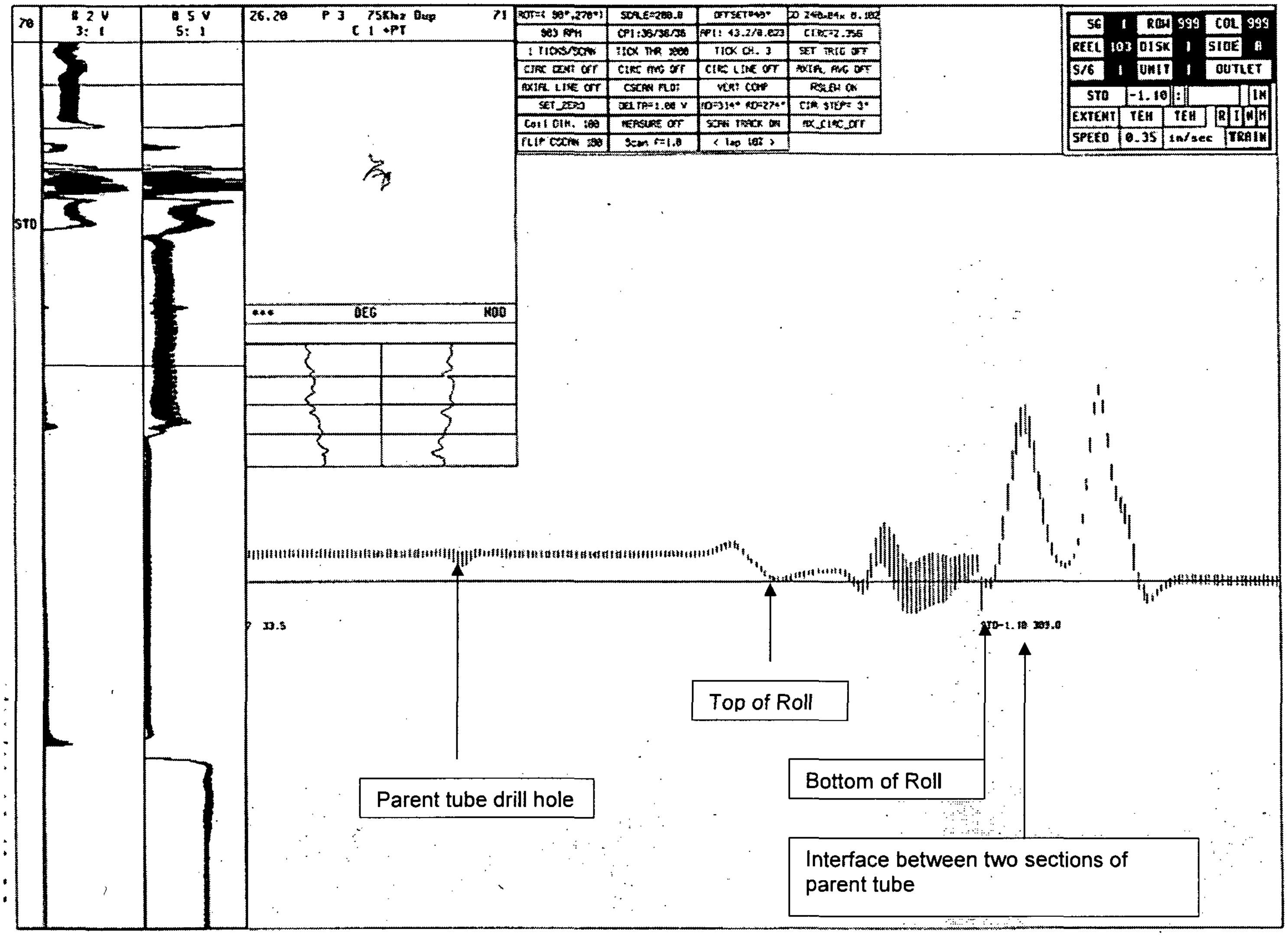

SG 1 ROW 999 COL 999
REEL 103 DISK 1 SIDE A
S/G 1 UNIT 1 OUTLET
STD -2.14 IN
EXTENT TEH TEH
SPEED 0.35 in/sec TRAIN
Vpp 3.05 DEG 77 GRV
STD

Figure 11


Top of Roll
Bottom of Roll
Parent tube drill hole
Interface between two sections of
parent tube