BAW-10219
REV. 01
MARCH 1996

ELECTROSLEEVING QUALIFICATION FOR PWR RECIRCULATING STEAM GENERATOR TUBE REPAIR

NON-PROPRIETARY

FRAMATOME TECHNOLOGIES, INC.
P.O. BOX 10935
LYNCHBURG, VA 24506-0935

COPY NO. 1

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RECORD OF REVISION

Revision	Date	Section	Description
00	11/95	All	Original Issue
01	03/96	All	Complete revision.

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GLOSSARY OF TERMS

AECB	Atomic Energy Control Board
ANSI	American National Standards Institute
ASTM	American Society of Testing Materials
ASME B&PV	American Society of Mechanical Engineers, Boiler and Pressure Vessel Code
AVT	All Volatile Treatment
BOL	Beginning of Life
FTI	Framatome Technologies, Inc.
CBH	Contoured Bottom Hole
CE SYS 80	Combustion Engineering System 80 RSG
CSA	Canadian Standards Association
DBE	Design Bases Event
EC	Eddy Current
ECT	Eddy Current Testing
EDM	Electrode Discharge Machining
EOL	End of Life
FBH	Flat Bottom Hole
FIV	Flow-Induced Vibration
FSM	Fluid-elastic Stability Margin
FTI	Framatome Technologies incorporated
gpd	Gallons Per Day
HMA	High Temperature Mill Annealed
ID	Inside Diameter
IGA	Intergranular Attack
IGSCC	Intergranular Stress Corrosion Cracking
LL	Lower Loop (B&W Plant Design)
LMA	Low Temperature Mill Anneal
LOCA	Loss of Coolant Accident
LOW	Lake Ontario Water
MCCR	Ministry of Consumer and Commercial Relations
$MgCl_2$	Magnesium Chloride
MSLB	Main Steam Line Break
NaOH	Sodium Hydroxide
NDE	Nondestructive Examination
NDD	No Detectable Degradation
NGS	Nuclear Generating Station
nm	nano-meter (10^{-9} meter)
OBE	Operational Base Earthquake

GLOSSARY OF TERMS (Cont'd)

OD	Outside Diameter
OTSG	Once-Through Steam Generator
P	Phosphorous
P_{burst}	Internal Burst Pressure
$P_{collapse}$	External Collapse Pressure
PVT	Process Verification Tube
Pump Curve	Relationship of Pump Volumetric Flow Rate and Discharge Head
PWR	Pressurized Water Reactor
PWSCC	Primary Water Stress Corrosion Cracking
RL	Raised Loop (B&W Plant Design)
RPC	Rotating Pancake Eddy Current Inspection Coil
RSG	Recirculating Steam Generator
RT	Room Temperature
SCC	Stress Corrosion Cracking
SI	Safety Injection
S_m	Allowable Stress Intensity
SSE	Safe Shutdown Earthquake
S_U	Ultimate Tensile Strength
S_Y	Yield Strength
SPS	Sleeve Procedure Specification
TS	Tubesheet
TW	Throughwall
TSP	Tube Support Plate
TTS	Top of Tubesheet
UT	Ultrasonic Testing
W-D	Westinghouse Model D RSG
W-E	Westinghouse Model E RSG
WT	Witness Tube
%TW	Percent Through Wall

1.0 INTRODUCTION

The qualification program of an electroformed sleeve for the repair of PWR Recirculating Steam Generators (RSGs) with degraded Alloy 600 tubing is described in this report. The Electrosleeve™(1) has been qualified for the major RSG designs, including Westinghouse Models D, E, F, 33, 44, and 51, and Combustion Engineering RSGs. This report documents the design analyses, mechanical testing, corrosion evaluation, nondestructive examination, installation process, and ALARA aspects of the sleeve design.

Sleeving is a method used to repair defective steam generator tubes and thus keep the tubes in service. Typically, sleeves have been designed with welded, brazed, rolled, and/or hydraulically expanded sleeve-to-tube joints. The design emphasis for sleeves is now focused on repair methods that impart minimal residual effects on the parent tube. The electroformed sleeve is the next generation of SG repair which requires no "welding" or deformation of the parent tube, while providing the benefits of previous sleeve repair options.

The nickel utilized in the repair process, once deposited, is referred to as a nanostructured material. Nanostructured sleeve material consists of a grain structure having mean diameters less than 300 nm, and as a result possesses unique properties, including enhanced corrosion and wear properties, along with enhanced hardness, strength and ductility. The ultra-fine [ ]^{c,e} microalloyed grain structure of the (>99.5% pure) electroformed nickel provides outstanding mechanical properties that exceed conventional nickel plating.

An electroformed sleeve generically refers to the electrochemical deposition of ultra-fine grained nickel on the inner surface of a tube to form a structural repair of the degraded tube. The electrodeposition of nickel provides a continuous metallurgical bond between the tube and sleeve that eliminates all leak paths and macro-crevices. The electroformed sleeve provides a structural, leak tight seal, while minimizing residual stresses in the parent tube. It results in no parent tube deformation or microstructure changes. Thus, the design does not require a post-installation stress relief. Since the electroforming of the nickel imparts very low stresses on the parent tube, there is no need for stress relief, therefore installation into locked steam generator tubes is not a concern.

(1) Electrosleeve™ is a registered trademark of Ontario Hydro Technologies.

Revision 01 of this document (this revision) is being issued to include qualification data on RSGs with 11/16" OD x 0.040" wall tubing. This revision also incorporates the latest testing and analysis information available on the Electrosleeve™.

2.0 EXECUTIVE SUMMARY

The material properties of the ultra-fine grained nickel sleeve have been characterized by testing as described in the ASME Section III Appendices and ASTM specifications. The material properties established include tensile, yield, modulus of elasticity, thermal stability, creep, ductility, and fatigue. These properties were utilized during the sleeve analyses and mechanical qualification tests.

Mechanical testing was performed on the sleeve design to demonstrate its structural adequacy. This testing included axial fatigue, pressure, thermal, tensile tests, and primary hydrotests to burst pressure. In addition, sleeves with machined defects were put through fatigue tests and burst tests to show that a degraded sleeve still maintains structural integrity as a replacement for the parent tube.

Structural analyses performed included fatigue test loads (uniaxial and bending), ASME B&PV Code stress analysis, plugging criteria analysis, flow induced vibration analysis, thermal/hydraulic analysis, and creep analysis.

Corrosion tests have been performed to evaluate the Electrosleeve™ material's performance in primary and secondary water environments. Nickel plating has been utilized in operational applications as a means to repair and prevent PWSCC. Inservice experience in steam generators in Belgium, Sweden, and Canada, and in the pressurizer heater nozzles at Calvert Cliffs [12.37] reinforce the basis that electrodeposited nickel is resistant to corrosion and degradation in actual service environments.

Based on the testing and analysis documented in this report, the electroformed sleeve has been structurally qualified for application in PWR recirculating steam generator designs. Section 8.7 of this report provides a summary of key design aspects of the sleeve.

3.0 BACKGROUND

Most early design PWR steam generators were fabricated with tubing made of Ni-Cr-Fe Alloy 600. In general, the tubing in these steam generators is low mill annealed (LMA). The tubes are typically expanded for lengths ranging from 2" to the full thickness of the tubesheets (TS).

The cracking of LMA tubes due to high tensile stresses was identified in the late 1970s and early 1980s. Intergranular stress corrosion cracking (IGSCC) has occurred in Row 1 U-bends and in the expansion roll transitions of tubing expanded into the tubesheet. Shot peening [12.8] and U-bend stress relief [12.9] were developed as corrective measures for plants characterized as having high potential for IGSCC. The French and Belgians were the first to report that shot peening, as a corrective measure, was less effective on plants which had been in operation [12.10]. This was attributed to the presence of small cracks (below the NDE detection capabilities) that had initiated prior to the peening operation. Thus, other repair methods are required to keep tubes in service.

Subsequent to this, plants began experiencing degradation by ODSCC at both roll and explosive expansion transitions. There has also been the emergence of secondary side corrosion at the TSP intersections. The various degradation modes have expanded to now include high mill annealed (HMA) tubes as well.

These degradation mechanisms led to the development of numerous types and designs of sleeves in the industry. The overall objective of these designs is to provide a structural repair to the tube, spanning the degraded region of the tube. The typical sleeve design has been the tube-within-a-tube concept, with structural joints formed by various means at each end of the sleeve. Joints have been both mechanical (leak limiting) and welded (leak tight) in these types of sleeves.

Since the original installation of many of these sleeves, tubes have been found to be locked at the tube support plates, in some plants, due to the buildup of corrosion products or other mechanisms. This locked tube condition severely impacts the ability to perform an effective stress relief of tube-sleeve joints that have high installation residual stresses, and may lead to severe local yielding or buckling of the tube or a redistribution of residual stresses without expected reduction.

FTI, in cooperation with Ontario Hydro Technologies, has now developed an electroformed sleeve which offers an alternative solution to repairing Alloy 600 tubes experiencing degradation at the top of the TS, as well as the TSPs. This process deposits a layer of electroformed nickel on the inside diameter of degraded tubes in order to provide a structural, leak tight repair option that is simple to install and requires no stress relief. This sleeve will span defects within the tube at the baffle plates, the tube support plates, at or near the secondary face of the tubesheet and in freespan regions in PWR steam generators.

This repair process builds on previous experience with nickel plating and Electrosleeving. Framatome (Europe) has been using nickel electroplating as a remedial technique for the repair of primary stress corrosion cracking (PWSCC) of steam generator tubing since 1985. The primary goal of this technique is to deposit a layer of nickel plating capable of bridging SCC in a SG tube, thereby arresting the degradation process of the tube wall. This process has also been used to seal the roll transition area and thereby prevent the initiation of PWSCC; some of these repairs were performed over through wall flaws. EPRI has documented this successful repair of European steam generator tubes affected by PWSCC with electroplated nickel [12.12]. Since 1985, Framatome has successfully installed electroplated nickel in more than 1,000 tubes at various plants in Europe. As of today, over 95% of these electroplated nickel sleeves are still inservice and exhibit no compromising degradation or cracking. A small percentage of tubes have been plugged since the first large commercial application in 1988 at Doel-2, but none were due to any defect or degradation of the nickel sleeving.

Ontario Hydro (OHT) has also successfully installed Electrosleeves into various steam generators in the Pickering plants. Initially, sleeves were installed as part of the development phase and were either plugged or the tubes pulled for evaluation. In May 1994, fourteen Electrosleeves™ were installed in Pickering Unit 5 and left in service. Subsequent inspection has indicated no degradation in these sleeves. Refer to Table 3.1 for a summary of Framatome nickel plating and Ontario Hydro Electrosleeving experience in operating steam generators.

In 1995, FTI installed 8 Electrosleeves™ in one steam generator at Oconee Unit 1. These sleeves were installed as part of the development program to gain experience with the sleeving equipment and field procedures. All of the sleeves were successfully installed. These tubes were subsequently plugged since the Electrosleeve™ was not licensed at that time.

In regards to terminology, Electrosleeve™ specifically refers to nanocrystalline microalloyed nickel electrochemical deposited sleeve material. Electrosleeving material has the high strength and thermal stability to qualify as a structural repair. Nickel plating refers to the process currently being used in Europe which utilizes a thin (~ 0.004 inch) layer to either prevent PWSCC or form a protective layer over existing PWSCC to inhibit further growth. Nickel plating is also high purity nickel, but is not nanocrystalline in nature, nor is it microalloyed for thermal stability. Nickel plating as currently used in Europe is not used for a structural repair.

Table 3.1

Steam Generator Nickel Plating and Electrosleeving Experience

PLANT/VENDOR	YEAR	TUBE NI-PLATED	TUBES STILL IN-SERVICE	ACTIONS TAKEN	COMMENTS
Doel-2 (Framatome)	1985	10	1	3 plugged, 3 pulled, and 3 repaired (1990)	R&D field baseline program; large throughwall cracks; some leaked due to micro nickel pits; lab exam results: bridged cracks, no internal corrosion
Doel-2 (Framatome)	1986	81	56	13 plugged, 3 pulled, and 9 repaired (1990)	R&D field baseline program; large throughwall cracks; some leaked due to nickel hardness (nickel cracked over Alloy 600 cracks > 0.39 inch)
Doel-2[1] (Framatome)	1988	33	33		First commercial application; large throughwall cracks; visual inspections in 1988, 1989, and 1990 with a 40X baroscope; conclusions: no leaks, no visible corrosion, no erosion
Doel-3[2,6] (Framatome)	1988	11	11		Large throughwall cracks in parent tubing; UT inspected in 1988 (baseline), 1989, 1990, and 1991; conclusion: cracks have not propagated into nickel plating
Ringhals-3[3,6] (Framatome)	1990	10	10		UT (long. and circum.) baseline in 1990 to qualify UT relative to ET; UT 1991 and 1992; conclusion: cracks have not propagated
Doel-2[4] (Framatome)	1990	345	337	8 plugged (not related to nickel plating)	Local re-expansion (2 inches) in the tubesheet entirely protected by Ni-plating on 4 inches (2 mils thick); visual and ET inspected in 1990 (baseline)
Tihange-2[5] (Framatome)	1992	602	602		Plating in parallel on all three S/Gs
Pickering-6 (OHT)	May 1993	1	0		Trial run of Electrosleeve™. Process not approved yet by AECB and MCCR so tubes plugged.
Pickering-8 (OHT)	October 1993	9	0		9 Electrosleeves™ installed in BO5 and B011, Process not approved yet by AECB and MCCR so tubes plugged.
Pickering-1 (OHT)	Nov 1993	8	0		6 Electrosleeves™ installed in 3 tubes, 3 sleeves unacceptable due to disbonded areas. Process not approved yet by AECB and MCCR so tubes plugged.
Pickering-5 (OHT)	May 1994	48	14	4 tubes pulled	> 90% Electrosleeves™ acceptable. 30 of 48 sleeves installed in mockup located on SG platform.
Tihange-2 (Framatome)	1993 1995	~600	Exact number not available		On all three S/Gs. More than 500 tubes in 1993 + some repairs and new tubes in 1995.
Tihange-2 (Framatome)	1996 (planned)	600			Preparation/planning for May 1996 outage.
Oconee-1	1995	9	0	All 9 plated, then plugged	9 Electrosleeves™ installed, process not yet approved by NRC, 9 tubes plugged.

1 Crack sizes at Doel-2: 0.2 to 0.3 inch; frequently up to 0.5 inch
2 Crack sizes at Doel-3: 0.4 inch
3 Crack sizes at Ringhals-3: 0.1 to 0.2 inch
4 No cracks; high work hardened area
5 Crack sizes at Tihange-2: 0.35 to 0.47 inch
6 Steam generator replacement was made at Doel-3 in 1993 and in Ringhals-3 in 1995.

4.0 DESIGN CRITERIA

4.1 Qualification Methodology

The first step in the qualification of the Electrosleeve™ for use in repairing degraded PWR steam generator tubing consists of specifying the requirements, regulatory or others, that are imposed upon the sleeve in the installed condition. If the current standard does not explicitly apply to the Electrosleeve™, then it was still followed as a guideline. Next the material properties of the Electrosleeve™ were determined per ASME and ASTM guidelines.

The following methodology was used to qualify the Electrosleeve™:

- o Define the design requirements for the steam generator tube repair.
- o Develop the applicable material properties per the requirements of the ASME Code, Section III [12.2].
- o Prepare a design analyses of the tube repair per the requirements of the ASME Code, Section III [12.2].
- o Evaluate the tube repair to the requirements of NRC Regulatory Guide 1.121 [12.6].

The design requirements for the Electrosleeve™ are defined in Section 4.2.

The determination of material properties is presented in Section 6.0. The material properties were developed per the following methodology:

- o Determine the design stress intensity value (S_m) per the methodology of ASME Code, Section III. Appendix III-2110(b).
  - Perform tensile testing per ASTM E8 and E21, [12.13. 12.14].
  - Perform creep testing per ASTM E139 [12.22].
  - Perform bend testing per ASTM E290 [12.20].

[

]c

c

The design analyses for the Electrosleeve™ was performed using ASME Code, Section III as a guideline. The following methodology was used:

- Determine the minimum required sleeve thickness using ASME Code, Section III, Subsection NB as a guide. The design stress intensity value determined in Section 6.0 will be used.
- Determine the structural loading associated with the tube repair including repair of locked tubes and tubes with 100% through wall defects. Evaluate the structural loads and installed sleeve configurations per the stress and fatigue limits in ASME Code, Section III.

c

Additional qualification evaluations included:

- Flow induced vibration
- Corrosion (Primary and Secondary Side Environments)
- Nondestructive Evaluation Techniques
- Regulatory Guide 1.121 evaluation.

The purpose of this report is to show that the Electrosleeve™ is qualified for the structural repair of the three major sizes of steam generator tubing (11/16", 3/4", and 7/8") that are in most RSG designs in service today. Qualification testing and/or analysis was performed on all three of the sizes of tubing. In the cases where a bounding condition and size was determined, the results were expanded to envelope the other sizes of tubing. Material test results are also presented for 5/8" OD (OTSG) size tubing.

4.2 Qualification Requirements

The electroformed sleeve is designed for application in PWR steam generators with nominal 3/4 inch OD x 0.042/0.043/0.048 inch walls, 11/16 inch OD x 0.040 inch wall, 7/8 inch OD x 0.050 inch wall tubing. The operating conditions of these steam generators form the design basis for the sleeve operating conditions. Design requirements for the sleeve are:

- Span defects in the parent tube at TTS and TSP locations in both the HL and CL regions of RSG's while maximizing tube access,
- Provide a structural repair for the parent tube at these locations,
- Provide a leak tight seal for primary to secondary side water,
- Minimize residual stress in the parent tube in order to minimize the possibility of primary and secondary side IGSCC.

The design and qualification of the sleeve utilized applicable industry codes and standards as summarized in Table 4.1.1. The ASME B&PV Code is the basic governing document for numerous aspects of the design, including determining test loads, performing structural analyses, procuring material, establishing the sleeve procedure qualification, and preparing the Sleeving Procedure Specification.

At present, nickel is not identified as an approved material in the Code for ASME Section III Class I systems. Also, electroformed sleeves are not identified in ASME Section XI as a sleeving method. Therefore, material testing has been performed per the guidance of ASME Section III and ASTM to establish material design properties. Similarly, the sleeve procedure qualification has been performed following the guidance of ASME Section XI for steam generator sleeving.

4.3 Sleeve Design Conditions

The design and operating conditions for the steam generator become the design and operating conditions imposed on the sleeves. The Tables contained in Appendix A detail the operating conditions for which the sleeve has been designed. Analysis and testing were performed to the worst case bounding conditions. The sleeve was designed to encompass the following types of steam generators in service: Westinghouse Models D, E, F, 33, 44, 51, CE Models 67, 80, 3410, and ANO-2, Ft. Calhoun, and Maine Yankee.

Steam generator design transients were used to establish sleeve loading transients. Section 3 discusses how these transients were used to establish the sleeve loading transients and cycles. Operating pressure and thermal loading ranges were used to establish the worst case conditions. Both unlocked and locked tube conditions were considered. For the locked tube condition, the conservative assumption that the tubes are locked at all tube support plates was utilized.

TABLE 4.1.1
SUMMARY OF APPLICABLE CODES AND STANDARDS [1]

Application	Criteria
Structural Design of the Sleeve - Sleeve/Tube Loads - Analyses	ASME B&PV Code, Section III [12.2]
Sleeve Plugging Limit	NRC Reg. Guide 1.121 [12.6]
Material Procurement	ASME B&PV Code, Sections II and III [12.1,12.2]
Electroformed Sleeve Qualification	ASME B&PV Code, Section XI [12.4] ASTM Standards [12.13-12.28]
Sleeve NDE	ASME B&PV Code, Sections V and XI [12.3,12.4] Code Case N-504-1 [12.7]
Qualification	EPRI Checklist [12.11]

NOTES: [1] The ASME B&PV Code currently does not specifically identify electrochemical deposition of material for steam generator tube repair, nor nanocrystalline nickel material. Therefore, these Code sections were followed as a guideline for the development of the Electrosleeve™.

5.0 SLEEVE DESIGN

5.1 Design Description

An electroformed sleeve is an electrochemical deposition of ultra-fine grained nickel material on the inside diameter of a degraded steam generator tube that requires repair. Table 5.1.1 contains a summary of the dimensions of an installed Electrosleeve™ in each of the steam generator designs. The approximate axial length for all sizes of RSG tubing is 8" at the TTS, and 4" at a TSP intersection (based on a 3/4" TSP). The actual sizes of an installed sleeve may vary. If a size change affects any of the structural properties of the sleeve, justification or testing will be performed, as required. For the purposes of the qualification of this repair process, any reference to the length of a sleeve refers to the length between the tapered edges, including the minimum bond lengths, but not including the tapered edges. The tapered transitions are not considered part of the pressure boundary region of the sleeve.

Figure 5.1.1 depicts a typical RSG Electrosleeve™ arrangement. The sleeve is designed to repair degraded tubes by axially spanning the degraded region in order that they may remain in service. The sleeve is designed to be installed at any straight section of tubing, including the top of the TS, all TSP intersections, and freespan areas. The electroformed repair is 100% leak tight because the nickel is bonded to the tube.

The material used for the sleeve is high purity nickel (>99.5%). Nickel is deposited relatively easily with excellent bonding characteristics to the alloy 600 base metal. The Electrosleeve™ composition does not release activated species such as Cobalt. It also has excellent material properties and ductility as shown in Section 6 of this report.

The design of the sleeve is such that it acts as the primary pressure boundary and maintains its structural integrity in the event of a MSLB, OBE, or DBE. Installation of the sleeve has no effect on the parent tube material microstructure. Residual stresses generated in the tube are very low, such that post-installation stress relief is not required.

5.2 Process Description

The operations required for Electrosleeve™ installation are:

- Mechanically clean tube regions to be repaired
- Install electroforming probes into tubes

[

]^{e}

[ ]^{e}

- Remove electroforming probes from tubes
- Post-installation sleeve/tube NDE inspection

[ ]^{e}

[ ]^{c,e}

FIGURE 5.1.1
TYPICAL RSG TSP and TS SLEEVE ARRANGEMENT

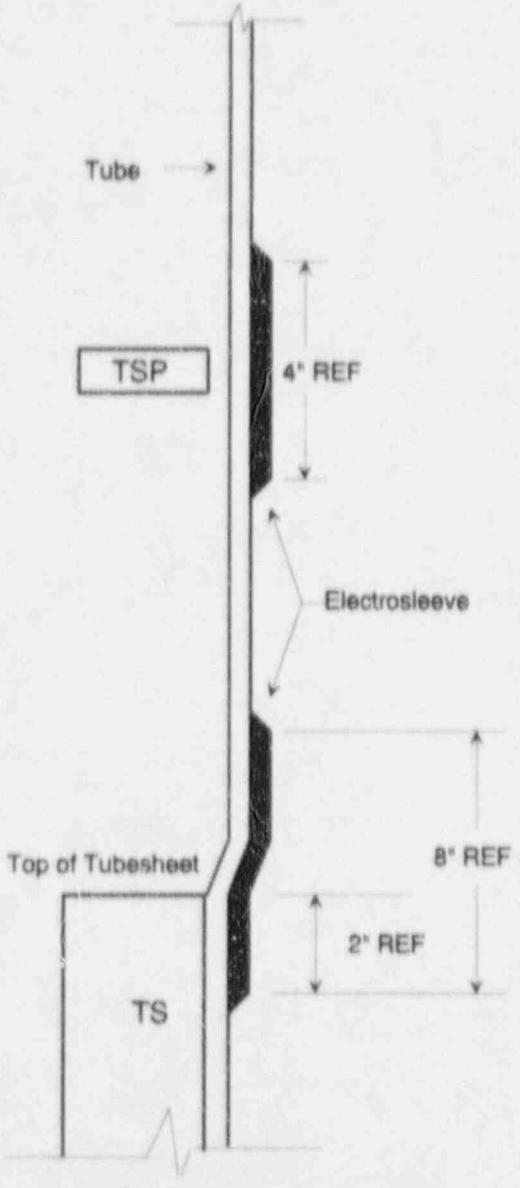


TABLE 5.1.1
STEAM GENERATOR TUBE AND ELECTROSLEEVE™ NOMINAL DIMENSIONS

Steam Generator	Tube OD (inch)	Tube Wall (inch)	Nominal Slv Wall (inch)	Sleeve Location	Sleeve Length (inch)
W D2,D3,D4,D5,E and CE Sys-80	0.750	0.043	[ ]^{d}	TS	8.0
W D2,D3,D4,D5,E and CE Sys-80	0.750	0.043	[ ]^{d}	TSP	4.0
CE 67, 3410 ANO-2, Ft Calhoun, Maine Yankee	0.750	0.048	[ ]^{d}	TS	8.0
CE 67, 3410 ANO-2, Ft Calhoun, Maine Yankee	0.750	0.048	[ ]^{d}	TSP	4.0
W 33,44,51	0.875	0.050	[ ]^{d}	TS	8.0
W 33,44,51	0.875	0.050	[ ]^{d}	TSP	4.0
W F	0.688	0.040	[ ]^{d}	TS	8.0
W F	0.688	0.040	[ ]^{d}	TSP	4.0

6.0 DESIGN VERIFICATION - MATERIAL PROPERTIES

The Electrosleeve™ is a nanocrystalline material installed "in-situ" on the tube inside surface using an electrochemical deposition process. The properties of the nanocrystalline nickel material are superior to those of regular nickel. This section describes the tests performed to establish the properties of the Electrosleeve™ material. ASTM and ASME standards were utilized in the development and qualification of the material. For the purposes of this section and other design verification sections of this report, a specimen is defined as a tube with an Electrosleeve™ installed on the inside diameter of the tube.

The material properties of the electrochemical deposited nickel material are independent of the host tube inside diameter and thickness. The supporting data is presented in the following sections.

6.1 Tensile Strength

Tensile tests were performed to document yield strength, ultimate strength, and elongation of the electrochemical deposited nickel material. More than [ ]^{d} specimens were tested in order to insure statistically significant results. [ ]^{d} alloy 600 tube sizes with an installed Electrosleeve™ were tested by FTI:

[ ]^{d}

The tensile tests were performed at the following temperatures: RT, [ ]^{d} Additionally, OHT performed tensile tests of ultra-fine grained nickel material installed into [ ]^{d}

The test specimens were fabricated as shown in Figure 6.1.1 and ASTM procedures [12.13, 12.14] were utilized to perform the testing. The results of the tensile tests were tabulated for the each of the [ ]^{d} temperatures tested by FTI and combined with the results of OHT test specimens. This data was evaluated per the ASME Code to establish the design properties for the nanocrystalline nickel material at the Electrosleeve™ design temperature of 650°F.

The ASME Code minimum design strength values at the design temperature are tabulated in Table 6.1.1. The typical yield and ultimate strength versus temperature is shown in Figure 6.1.2.

6.2 Modulus of Elasticity

[ ]^{d} specimens were utilized in testing to determine the modulus of elasticity for the material per ASTM procedure [12.15]. The specimens were fabricated from;

[ ]^{d}

Electrosleeved tubes. The specimen design is illustrated in Figure 6.1.1.

[ ]^{d}

The results of the testing show the modulus of elasticity for the electrochemical deposited nickel material is independent of tube size. Figure 6.1.2 shows the design value for Young's Modulus versus temperature for all tube sizes.

6.3 Ductility/Adhesion

[ ]^{d} specimens were tested per ASTM procedure [12.20, 12.21] in order to verify the ductility and adhesion of the electrochemical deposited nickel material. Specimens were fabricated by Electrosleeving a tube then splitting it longitudinally in half. The specimens were then bent with the nickel sleeve outside diameter in tension over a 1/4" mandrel as shown in Figure 6.3.1.

[ ]^{d}

The ductility of the electrochemical deposited nickel material is further demonstrated by the ductile failures the material exhibited during the tensile tests (Section 6.1), creep tests (Section 6.6) and burst tests (Section 6.7).

6.4 Fatigue Life

With the exception of the work presented in this document, there has yet to be undertaken a systematic study of the fatigue performance of nanostructured materials. A comprehensive review [12.45] of the literature regarding the effect of grain size (i.e., $\geq 10\mu m$) on the fatigue performance of conventional nickel and nickel-based alloys shows that in general, decreasing grain size results in;

[ ]^{c,e}

Fatigue testing was performed on over [ ]^{d} specimens in order to establish a design fatigue curve. [ ]^{d} electrosleeved alloy 600 tube sizes were tested by FTI:

[ ]^{d}

In addition, OHT performed fatigue testing on [ ]^{d} electrosleeved tube specimens using [ ]^{d}

[ ]^{d}

[ ]^{d}

[

]^{d} specimens were fitted to a curve, obtained by applying a least squares fit. ASME Code safety factors were applied to the normalized data. The bounding design fatigue curve is made by combining the results of both of these adjusted curves into a single bounding curve. Figure 6.4.1 illustrates the fatigue data for the electrochemical deposited nickel material.

Fatigue testing of the Electrosleeve™ material has been conducted at both room and elevated temperatures. The results show that the material maintains its fatigue resistance in the temperature region tested.

[ ]^{d}

[ ]^{d}

6.5 Thermal Stability

[ ]^{d} test specimens were utilized to verify the thermal stability of the electrochemical deposited nickel material. The specimens were fabricated as shown in Figure 6.1.1. Vickers hardness measurements were performed in accordance with ASTM procedures [12.23].

[ ]^{d}

The results of the testing at the design temperature of 650°F are shown in Figure 6.5.1. This graph shows that hardness of an electroformed sleeve at the design temperature is stable, and thus the thermal stability of the material at lower operational temperatures is verified. The results from the testing performed at [ ]^{d} also show that the material maintains thermal stability at that elevated temperature.

Resistance to Strain-Induced Recrystallization

As a result of the stored energy of cold-work, strained materials tend to undergo recrystallization accompanied by a commensurate decrease in mechanical strength, at temperatures well below those required for the onset of normal grain growth. In order to assess the susceptibility of Electrosleeve™ material to strain induced recrystallization, [

]^{d}

[

]^{d}

[ ]^{d}

As summarized in Table 1, there is no evidence that recrystallization has taken place in any of the specimens, since the hardness of recrystallized nickel would be expected to be less than [ ]^{d} The hardness values shown are consistent with the normal variance in hardness noted with as-plated material.

6.6 Creep Properties

The effect of decreasing grain size on creep deformation has been well documented, with steady state creep rates generally increasing with decreasing grain size; however, with the exception of the work presented herein, to date, there have only been a few studies on the creep performance of nanostructured materials. [

]^{c}

Intrinsic intergranular creep cracking is the predominant mode of premature creep failure for engineering materials. [

]^{d}

[

]^{d}

A series of constant load creep tests were performed using ASTM E139 [12.22] as a guideline to determine the creep behavior of the Electrosleeve™ material. Creep testing is a determination of deformation as a function of time and the time to fracture at an elevated temperature when sufficient load is present. Constant load creep testing is performed in a controlled environment at constant temperature. In the defined gauge length the strain versus time data presents the challenge of representing the creep phenomena by a mathematical equation. The literature on creep presents many options to model creep [12.30, 12.31, 12.38] and finite element codes [12.32] have creep calculation capability for analysis. Evaluation of data and analysis is presented in Section 8.6. The test specimens for creep testing were fabricated as shown in Figure 6.1.1.

[

]^{d}

[ ]^{d}

Table 6.6.1 lists the creep test specimens. Note that due to the long term nature of creep tests, some specimens have not failed but the duration of test and strain value are reported as status. [ ]^{d}

Figure 6.6.1 presents typical creep test results [ ]^{d}

The failures of the standard specimen geometries have been observed to be ductile, [ ]^{d}

[ ]^{d}

The creep fracture faces examined have some unique differences in loading conditions:

[ ]^{d}

Photomicrographs recorded [ ]^{d} show the fracture-face features of all specimens examined to be entirely ductile in nature and possessing classical microvoid coalescence features. Inspection at [ ]^{d}

In summary, fractographic analysis of specimens [ ]^{d} demonstrate the creep failures to be entirely ductile in nature with no evidence of operative intergranular failure mechanisms.

[ ]^{c,d}

6.7 Burst Strength

Burst tests were performed on [ ]^{d} sleeve specimens fabricated per Figure 7.1.1. Each specimen had a machined gauge length in order to accurately test the burst characteristics of the electrochemical deposited nickel material.

The specimens were pressurized using a hydraulic pressure generator at room temperature. The specimens were internally pressurized at a rate of 200 to 2000 psi per second, per EPRI guidelines. The data for the different sizes of specimens tested is contained in Table 6.7.1. For supplemental information, Table 6.7.2 also contains [ ]^{d} The data shows that the electroformed sleeve material burst pressure may be calculated by [ ]^{c,e}

[ ]^{c,e}

6.8 Thermodynamic Properties

[ ]^{c,e}

TABLE 6.1.1
ASME CODE, SECTION III, DESIGN VALUES

[ ]d

TABLE 6.6.1
CREEP TEST SPECIMENS

[ ]^d

TABLE 6.6.1 (Cont'd)
CREEP TEST SPECIMENS

d

TABLE 6.7.1
FTI BURST TEST RESULTS at ROOM TEMPERATURE

[ ]a

TABLE 6.7.2
OHT BURST TEST RESULTS at 581°F

d

FIGURE 6.1.1
MATERIAL TEST SPECIMEN DESIGNS
TENSILE, FATIGUE, YOUNG'S MODULUS SPECIMENS

[ ]d

FIGURE 6.1.1 (Cont'd)
MATERIAL TEST SPECIMEN DESIGNS
CREEP SPECIMENS

[

]d

FIGURE 6.1.1 (Cont'd)
MATERIAL TEST SPECIMEN DESIGNS
THERMAL STABILITY SPECIMENS

[ ]d

FIGURE 6.1.2
TYPICAL TENSILE PROPERTIES v/s TEMPERATURE

d

FIGURE 6.3.1
REVERSE BEND SPECIMEN

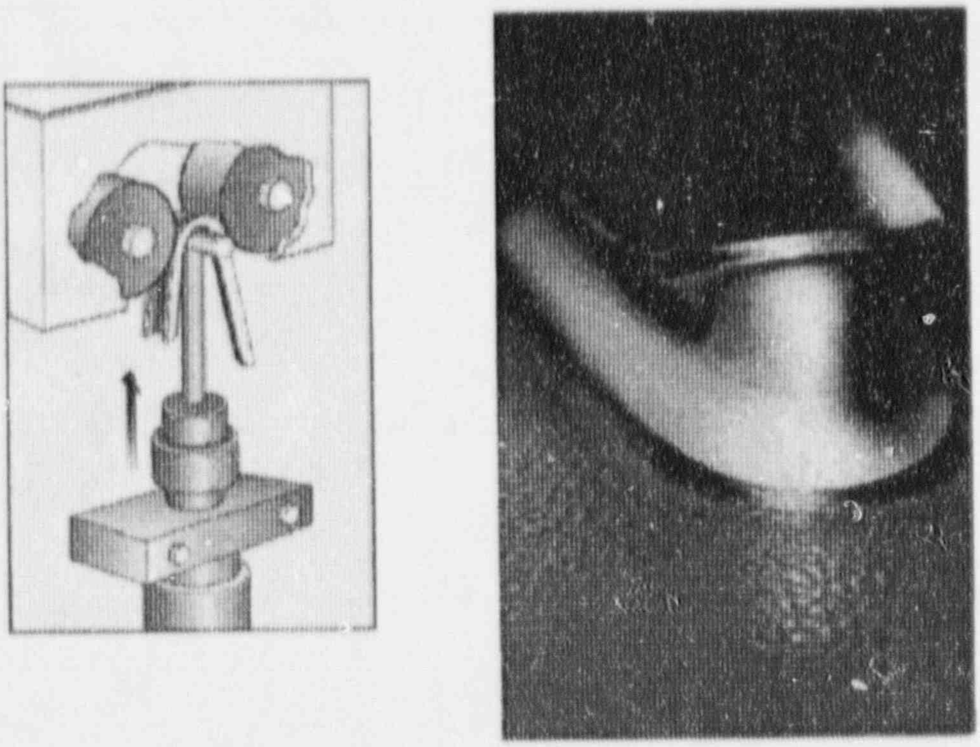


FIGURE 6.4.1
FATIGUE TEST DATA

[ ]d

FIGURE 6.5.1
<u>THERMAL STABILITY TEST RESULTS</u>

[ ]^{d}

FIGURE 6.6.1
CREEP TEST RESULTS

FIGURE 6.6.2

TYPICAL CREEP FRACTURE SURFACE FRACTOGRAPHY

[ ][a]

7.0 DESIGN VERIFICATION - MECHANICAL TESTING

The Electrosleeve™ qualification program combined analysis and mechanical testing to meet the sleeve qualification requirements presented in Section 4.0. The mechanical testing is summarized in this section and the analysis results are presented in Section 8.0. Sections 7.0 and 8.0 together demonstrate that the installed Electrosleeve™ is qualified for all RSG designs and their operating conditions.

7.1 Locked Tube Testing

Locked tube testing was performed in order to measure the loads induced on a locked parent tube as a result of the electrosleeving process.

The testing was performed on [ ]^{d} mockups. Each of the mockups had tubes that were roll expanded and welded into the TS and TSP, reinforced into place with tie rods, instrumented with strain gages and thermocouples, and sleeved in the TS and freespan. Figure 7.2.1 depicts a typical mockup that was utilized in the locked tube testing.

The results of the testing are summarized below for a 4" sleeve installation completely within the tube span:

^{d}

[ ]

[ ]^{d}

Note that the axial load and associated axial stress [ ]^{d} decreased as a result of the increased span. This effect would be observed for all tube sizes for any change in span length. The axial span load and stress may be ratioed by the actual length of the installed sleeve(s) within a particular tube span v/s the [ ]^{d} length used to determine the effect of a differing sleeve length or numbers of installed sleeves within a particular span.

The axial tube stress is present in the parent tube after sleeving prior to startup. These stresses are considered extremely low and thus not significant.

7.2 Fatigue Testing

Section III of the ASME B&PV Code does not provide design rules for sleeves fabricated "in-situ" by electrochemical deposition of material. In such cases, the ASME B&PV Code, Section III, Appendix II [12.2] allows the use of experimental stress analysis to substantiate the critical, or governing stresses. The adequacy of the installed material and its bond to the tube to withstand operational pressure and thermal cyclic loadings was demonstrated by means of fatigue testing per the ASME B&PV Code, Section III, Article II-1500 [12.2].

The Electrosleeve™ is designed to accommodate all loads that any steam generator tube may experience due to normal plant conditions and all anticipated transients specified for the steam generator. Appendix A summarizes the expected transient conditions which were used to qualify the Electrosleeve™ design. The fatigue testing loads associated with those transients are developed in Section 8.2. The following is a discussion of the fatigue testing performed to qualify the Electrosleeve™.

The minimum bond specimen illustrated in Figure 7.1.1 addresses the situation where significant degradation and metal loss of the parent tube occurs (wastage, gross IGA, etc.). [

]^{d} The testing described below verifies that the Electrosleeve™ and the minimum bond length will carry the loads imposed in service for the various steam generator designs.

[

]^{d}

The minimum bond fatigue test specimens were tested with loadings that represent the design life of an installed sleeve. The loads are given in Table 8.2.1.

In accordance with the methodology [

]^{d} The sleeve-to-tube joint was monitored after test completion by UT examination to verify de-bonding did not occur.

[

]^{d}

The acceptance criteria [

]^d

This criteria applies to the exposed Electrosleeve™ material as well as the sleeve/tube bond.

At the conclusion of the fatigue tests, the specimens were visually and UT examined for bond or sleeve failure. All [ ]^d specimens were acceptable with no evidence of degradation.

7.3 Testing of Degraded Sleeves

A series of fatigue tests were performed on mechanically degraded sleeves in order to establish a plugging criteria per the guidelines of the NRC draft Regulatory Guide 1.121 [12.6]. [

]^d

This testing was done in conjunction with a plugging criteria analysis as discussed in Section 8.5. [ ]^d

7.3.1 Plugging Criteria Fatigue Tests

[ ]^d

The test loads were developed to allow testing to proceed in steps, with each step representing 2 years of operating life. The test steps were repeated until the specimens failed or until 40 years of service life was reached. The failure point can thus be used to define the inspection interval for the defective sleeve. [

]^d

The results of the defective sleeve fatigue tests showed that an Electrosleeve™ with a [ ]^d has a maximum inspection interval of:

Tube Size	Defect Type	Fatigue Inspection Interval

[

]^d

7.3.2 Plugging Criteria Burst Testing

Regulatory Guide 1.121 [12.6] requires that 3 times normal operating differential pressure or the worst case faulted differential pressure be less than the tube burst pressure. Burst tests were performed on sleeved tubes in order to demonstrate that this margin is available in sleeves with defects.

[

]^d

The specimens, along with burst test results, are listed in Table 7.3.2.

7.4 Creep-Fatigue Experimental Analysis

Testing was performed to determine the effect of creep-fatigue interaction. [ ]^{d} were tested with the following results:

[

]^{d}

7.5 Mechanical Testing Summary

The mechanical design verification tests were performed to show that the Electrosleeve™ is structurally capable of withstanding actual in-service loading conditions. The tests were performed conservatively, in order to envelope worst case conditions.

The burst tests demonstrate that the Electrosleeve™ is ductile [ ]^{d} The burst tests also show that a sleeved defective tube with a [ ]^{d} throughwall defect in the sleeve will withstand faulted condition loadings.

The locked tube tests show that the electrosleeving process is unaffected by locked tubes. Further, no significant loads are generated in the parent tube from the installation process.

The series of experimental fatigue tests confirm the structural integrity of the electrochemical deposited nickel sleeve material:

[ ]^{d}

TABLE 7.3.1
PLUGGING CRITERIA FATIGUE TEST SPECIMENS

d

TABLE 7.3.2

PLUGGING CRITERIA BURST SPECIMENS

[

]b

FIGURE 7.1.1

MECHANICAL TEST SPECIMEN DESIGNS

MINIMUM BOND FATIGUE AND BURST SPECIMENS

[d]

FIGURE 7.1.1 (Cont'd)
MECHANICAL TEST SPECIMEN DESIGNS

PLUGGING CRITERIA FATIGUE SPECIMENS

[ ]^{d}

FIGURE 7.1.1 (Cont'd)

MECHANICAL TEST SPECIMEN DESIGNS

PLUGGING CRITERIA BURST SPECIMENS

d

FIGURE 7.2.1

TYPICAL LOCKED TUBE MOCKUP TEST RIG

[ ]^{d}

8.0 DESIGN VERIFICATION - ANALYSES

Design analyses were performed for the Electrosleeve™ to verify it conforms to the qualification requirements identified in Section 4.0. The design analyses consist of;

- o pressure boundary minimum thickness calculation;
- o analyses to support fatigue testing per Appendix II of the ASME Code;
- o analyses of flow-induced vibration of sleeved tubes;
- o analyses of the effect of a sleeve on heat transfer and primary fluid flow;
- o analyses of a degraded sleeve for plugging criteria; and
- o analysis of creep.

The analyses were performed on the different sizes of steam generator tubing outlined in Section 4.0. The results are presented in Sections 8.1 through 8.6.

8.1 Pressure Boundary Thickness

The Electrosleeve™ pressure sizing calculation used the allowable stress based on the strength properties derived from the material testing of the electrochemical deposited nickel material. [ ]^d

The structural adequacy of the various sizes of electroformed sleeves was evaluated for pressure thickness and external pressure in accordance with the ASME B&PV Code. The minimum sleeve wall thicknesses per NB-3324 [12.2] for the sleeve, based on the primary side design pressure, are:

Tube Size	Electrosleeve™ Nominal OD (inches)	Electrosleeve™ Min. Thickness (inches)	Electrosleeve™ Nom. Thickness (inches)
11/16" OD x 0.040"wall	0.608	[ ]^c	[ ]^c
3/4" OD x 0.042" wall	0.666	[ ]^c	[ ]^c
3/4" OD x 0.043" wall	0.664	[ ]^c	[ ]^c
3/4" OD x 0.048" wall	0.656	[ ]^c	[ ]^c
7/8" OD x 0.050" wall	0.775	[ ]^c	[ ]^c

The allowable external pressure for the sleeve and tube was calculated per classical collapse pressure equations for each of the sizes of tubes/sleeves. The results of the calculations show that the sleeve [

]^{d}

The design primary stress intensity was calculated for the case of a tube completely removed from the sleeve. Stresses were calculated for each of the steam generator designs. All stresses in the sleeve satisfy the primary stress limits. The maximum stress intensities are listed in Table 8.1.1.

8.2 Fatigue Test Loads

Section III of the ASME B&PV Code does not provide design rules for sleeves fabricated by electrochemical deposition of material. In such cases, the ASME B&PV Code, Section III, Appendix II [12.2] allows the use of experimental stress analysis to substantiate the critical, or governing stresses. The adequacy of the installed material and its bond to the tube to withstand operational pressure and thermal cyclic loadings was demonstrated by means of fatigue testing per the ASME B&PV Code, Section III, Article II-1500 [12.2].

[ ]^{d} different fatigue test specimens were used to demonstate the fatigue life of the Electrosleeve™ for the steam generator design transients listed in Appendix A. The specimens tested are:

[

]^{d}

[

]^{d}

[

]^d

[

]^d

The Electrosleeve™ is designed to accommodate all loads that the steam generator tube may experience due to normal plant conditions and all anticipated transients specified for the steam generator. The tables presented in Appendix A summarize the expected transient conditions which were used in the design of the sleeves for the different sizes of tubes.

Calculations were prepared for each sleeve design to determine a conservative maximum loading for a sleeve in any steam generator tube based on the transients listed in Appendix A. These calculations include both pressure and thermal gradient loading.

The loadings were evaluated for tubes either locked or unlocked at the tube support plates. The tube loading calculated for a locked tube enveloped the tube loads calculated for a tube in the unlocked condition. As a result, the fatigue loading evaluation considered the tubes to be locked at all tube support plates. Loads due to thermal and pressure transients were calculated for [ ]^d cases using the transients listed in Appendix A. Where possible, transients were grouped together and the number of cycles adjusted accordingly. The structural model for each of these cases considered a tube with a sleeves installed at the [

]^d The sleeved tube conditions considered are:

[

]^d

The loading analysis model for the periphery tube case considered the following boundary conditions:

[

]^{d}

The loading analysis model for the interior tube case considered the following boundary conditions:

[

]^{d}

The specific combination of geometry and operating conditions which resulted in the highest load for a given transient grouping was used in the mechanical test program.

The load ranges were calculated based on the following conditions:

[

]^{d}

The calculated axial tube loads for all transients were combined into a set of test load ranges. The required number of test cycles was determined per [12.2] Appendix II, and was based on the number of test assemblies and various factors relating the test conditions to the actual operating conditions.

The fatigue load testing sequence for specimen 1 is shown in Table 8.2.1 for the recirculating steam generators considered. The load testing sequences were utilized in the tests described in Section 7.2.1.

Fatigue testing was performed in Section 7.2.2 to determine the life of an Electrosleeve™ [

]^{d} These specimens were subjected to testing representative of the design life of the Electrosleeve™.

Fatigue test loads were calculated for these test specimens to represent the operating pressure and thermal stress ranges the sleeve would be subjected to over its life. [

]^{d} sleeved tube specimens were tested. The test loadings and total cycles required in the fatigue tests in Section 7.2.2 are listed in Tables 8.2.2 and 8.2.3.

8.3 Flow-Induced Vibration

The flow-induced vibration (FIV) analyses evaluated fluidelastic stability margins (FSM) and random vibration response for the nickel sleeve. [

]^{c} The Fluid-elastic Stability Margins and the responses to small scale turbulence were examined. [

]^{c} The FIV analyses were performed using Conner's Constants, % damping and added mass coefficient as listed in Table 8.3.1.

]^{e}

The FIV tube model included the hot leg, U-bend, and cold leg tubing from tubesheet to tubesheet. This model allows cross flow loads to be applied to the U-bend tubing for evaluating the tube support plate sleeves. The cases considered are for virgin and sleeved tubes. The results of all of the FIV analyses are presented in Table 8.3.1. The bounding cases for each similar design is presented in the table. [

]^{d}

bound all CE RSG designs. The analyses indicate that the Electrosleeve™ is acceptable for installation in RSGs based on FIV considerations.

8.4 Thermal/Hydraulic

The effect of an Electrosleeve™ installation on steam generator performance was analyzed for heat transfer, flow restriction, and steam generation capacity. Several cases were considered in the evaluation, consisting of a single sleeve in a tube, as well as multiple sleeves in a single tube. All designs of steam generators were considered in these analyses. In addition, cases in which the sleeved tubes were distributed asymmetrically among the RSGs were considered.

The analyses show that the heat transfer affects of electrosleeving are minimal. The affects of installed Electrosleeves™ on primary flow are presented in Table 8.4.1 for each of the steam generator designs. The results are presented as an equivalency number of sleeves installed having the same impact as plugging one tube. The results show that the installation of an Electrosleeve™ has minimal affects on plugging margin and RCS flow.

In summary, the thermal/hydraulic analyses show the advantages of an Electrosleeve™ over previous sleeve designs as;

- o a smaller unrecoverable pressure drop from a larger ID of the sleeve, and
- o the negligible loss of heat transfer area since the sleeve is in direct contact with the tube.

8.5 Sleeve Plugging Criteria

NRC Regulatory Guide 1.121 [12.6] provides guidelines for determining the degradation limits for PWR steam generator tubes. Since the sleeve replaces a portion of the original tube, these guidelines are used to determine the plugging limits for the sleeve.

Three criteria for normal operating conditions (level A) and four criteria for faulted conditions (level D) were evaluated in the sleeve/tube bonding joint and in the straight sleeve section. The burst plugging limits are based upon test results performed as part of the Material Properties verification (Section 6.7).

The required minimum sleeve wall thicknesses were calculated for the defined sleeve length only. The tapered sections of the sleeves are not included in the structural assessments. The allowable part throughwall defect in each of the sleeve sizes is summarized in Table 8.5.1. The analysis results presented in Table 8.5.1 show that any sleeve [

]^{e}

The fatigue testing results from Section 7.3 show that any sleeve exhibiting a crack-like flaw [ ]^{d} at a location where the tube also shows a defect greater than 100% throughwall meets the RG 1.121 criteria.

The plugging limits were also evaluated for the tube in the sleeve/tube joint region. The existing tube plugging criteria for the tube still applies to this region [

]^{d}

The results of the analyses and fatigue testing of the sleeve and tube with 100% throughwall defects in the tube and [

]^{d,e}

8.6 Creep Analysis

ASME Code Case N-47 [12.5] established design rules for Section III, Class 1 components for the conditions when the metal temperature exceeds those established by Section III. The design rules in the code case are designed to guard against:

a) ductile rupture from short term loadings
b) gross distortion
c) creep rupture from long term loadings
d) creep fatigue failure

The analysis results presented in Section 8.1 and the mechanical testing in Section 7.0 demonstrate that ductile rupture from short term loadings are not a concern. The other design aspects are discussed below.

8.6.1 Gross Distortion

During creep, a specimen under load will undergo permanent deformation over time. The amount of deformation will vary based on stress, time, and temperature. [

]^{d}

The creep response of the Electrosleeve™ material was modeled using an equation [

]^{b,c,e}

[

]^{b,c,e}

The material constants for the creep equation were determined by fitting the curve to the results from constant load tests (Figure 8.6.1). [

]^{b,c,e}

ANSYS was then used to create a finite element model Figure 8.6.3 of various tube/defect geometries and the total creep strain calculated. The following cases were considered and are illustrated in Figure 8.6.2:

[

]^{c}

With the exception of cases [

]^{c}

The finite element analysis imposed the steady state loads generated during 100% power as well as transient fatigue loads. The transient loads included the loads generated under worst case locked tube scenario.

The analysis results for various times are summarized in Tables 8.6.1 and 8.6.2. Converting the calculated creep strains into expected deformations in the steam generator demonstrates that the Electrosleeve™ is not subjected to any gross distortions.

8.6.2 Creep Rupture

Considerable research and effort has been spent over the last half century developing methods to predict creep rupture. Many of these techniques involve time-temperature parameters whereby short term tests at high temperature are used to predict long term exposure to lower temperatures. Analysis of data for a variety of aluminum-, iron-, nickel-, titanium-, cobalt-, and copper-based alloys [ ]^{b}

[

]^{b}

In a comparison between various extrapolative techniques, [

]^{b,c,e}

Using the relationship illustrated in Figure 8.6.4, the ANSYS constants discussed earlier, normal operating temperature, and differential pressure, a conservative time to rupture analysis for a sleeve with the tube removed can be performed:

d

The analysis summarized in the preceding table is conservative for the following reasons:

c

8.6.3 Creep Fatigue Failure Evaluation

The ASME Section III Appendices [12.2] contains rules for experimental stress analysis to determine whether or not a component can withstand the cyclic loading required for its intended application. A specific requirement is for the test sample to have the same composition and to be subjected to identical mechanical working and heat treatment as the actual component. The purpose of identical processing is to produce mechanical properties equivalent to those of the material in question.

[

]^{d}

The testing summarized in Section 7.4 included the following safety margins:

[ ]^{d}

8.6.4 Creep Summary

[

]^{c,d}

8.7 Design Summary

The results of material properties testing, mechanical tests and the analyses are combined to define the design definition of an installed sleeve. Key aspects of this design definition are summarized below.

The Electrosleeve™ has been qualified for installation in the following steam generator designs:

Westinghouse Series 33, 44, 51, D, E, and F
CE Models 67, 3410 and System 80
CE SG at ANO-2, Ft. Calhoun and Maine Yankee

The Electrosleeve™ is qualified for installation over all tube defect types, including IGA, circumferential cracks, axial cracks, pitting, and other similar defects. The Electrosleeve™ is qualified for installation in tube freespan regions, at tube expansion transitions, and at tube support plate regions. The sleeve is a complete structural repair of the parent tube. Installation of the Electrosleeve™ can be at all tube support plates without limitations.

The minimum and nominal sleeve wall thicknesses for installation are:

Tube Size	Installed Sleeve Minimum Wall Thickness (Inches)	Installed Sleeve Nominal Wall Thickness (Inches)
11/16" OD x 0.040" wall	[ ]^c	[ ]^c
3/4" OD x 0.042/0.043/0.048" wall	[ ]^c	[ ]^c
7/8" OD x 0.050" wall	[ ]^c	[ ]^c

Note that the field process is operated to obtain the nominal sleeve wall thickness on installation.

Testing showed that a [ ]^d bond length between the sleeve and tube will carry all structural loads. For conservatism, the bond length for field acceptance will be set at a [ ]^d. Refer to Figure 8.7.1 for a sketch of the bond length and pressure boundary. The minimum bond length of [ ]^d of the sleeve provides adequate structural attachment to a degraded parent tube. If the Electrosleeve™ does not show bond to the parent tube, between the minimum bond lengths, and the quality of the thickness and material are acceptable, the installation meets all design requirements.

The plugging limit for the sleeve was established at [ ]^d sleeve thickness based on

]^{c,e}

These will be documented when completed.

[

]^d

TABLE 8.1.1
PRIMARY MEMBRANE STRESS INTENSITY RANGE

[ ]^{d}

TABLE 8.2.1

SUMMARY OF FATIGUE TEST LOAD RANGES

d

TABLE 8.2.2
CIRCUMFERENTIAL DEFECT FATIGUE TEST LOADS

[ ]^{d}

TABLE 8.2.2 (Cont'd)
CIRCUMFERENTIAL DEFECT FATIGUE TEST LOADS

[ ]d

TABLE 8.2.2 (Cont'd)
CIRCUMFERENTIAL DEFECT FATIGUE TEST LOADS

[ ]d

TABLE 8.2.3
AXIAL DEFECT FATIGUE TEST LOADS

d

TABLE 8.3.1
SLEEVE FLOW-INDUCED VIBRATION ANALYSES RESULTS
(WORST CASE TUBE IN RSGs ANALYZED)

a

TABLE 8.4.1
THERMAL/HYDRAULIC EFFECTS OF
SLEEVES IN 3/4" TUBING

[ ]^{d}

TABLE 8.4.1 (Cont'd)
THERMAL/HYDRAULIC EFFECTS OF SLEEVES IN 7/8" TUBING

[ ][a]

TABLE 8.5.1
SLEEVE PLUGGING LIMITS
LEVEL A CONDITIONS

TABLE 8.5.1 (Cont'd)
SLEEVE PLUGGING LIMITS
LEVEL D CONDITIONS

a

TABLE 8.6.1
TOTAL CREEP STRAIN FOR ELECTROSLEEVE™ INSTALLED IN THE TUBE FREE SPAN

[ ]^{d}

TABLE 8.6.1 (Cont'd)
TOTAL CREEP STRAIN FOR ELECTROSLEEVE™
INSTALLED IN THE TUBE FREE SPAN

[ ]d

TABLE 8.6.2
CREEP STRAIN FOR ELECTROSLEEVE™ INSTALLED AT TOP OF TUBESHEET

d

FIGURE 8.6.1
CREEP STRAIN v/s TIME

c

FIGURE 8.6.2

TUBE DEFECTS MODELLED IN CREEP ANALYSIS

[ ]^{d}

FIGURE 8.6.3

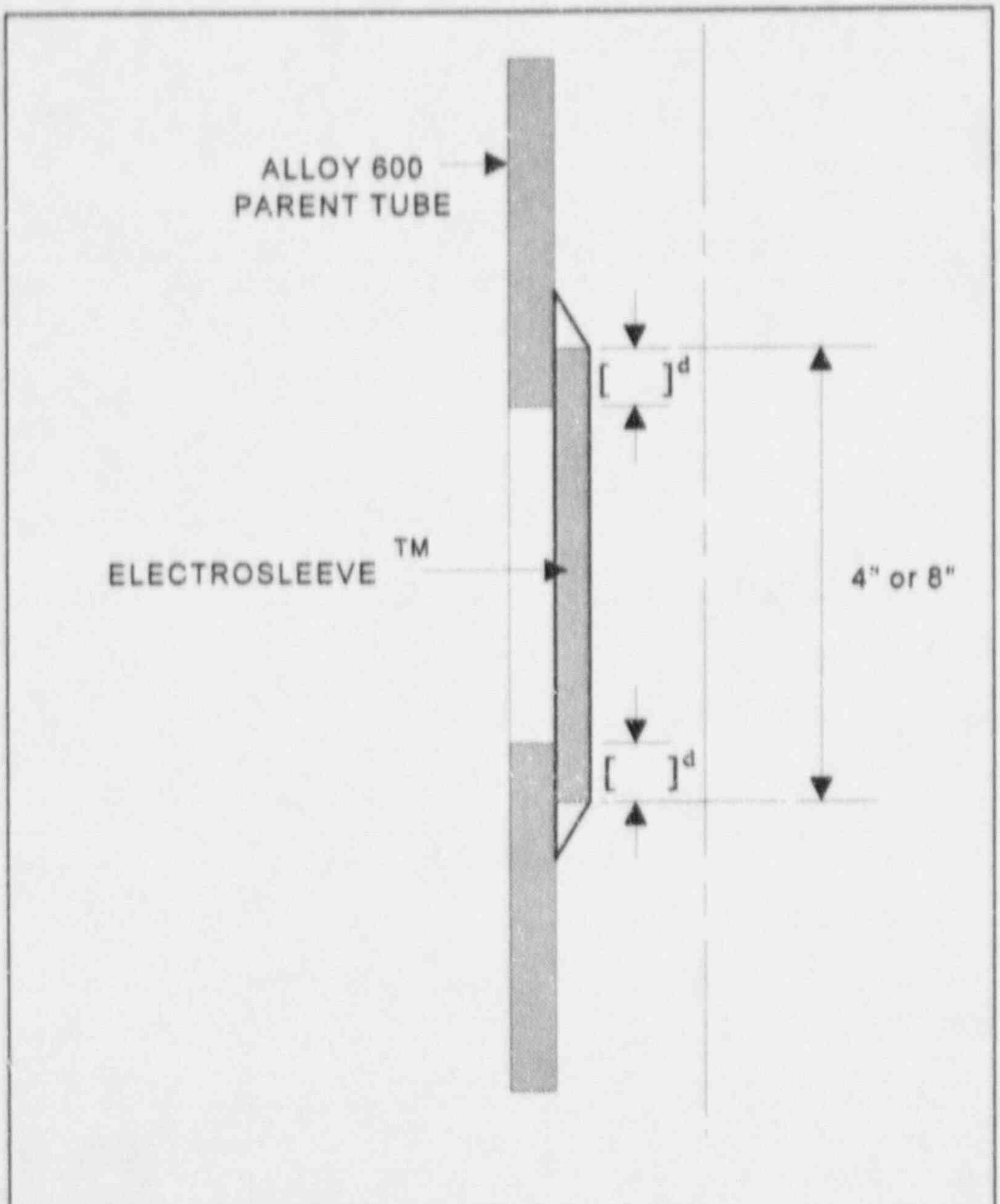
ANSYS v/s CREEP TEST DATA

[ ]^{d}

FIGURE 8.6.4 (Cont'd)
CREEP RUPTURE TIME PREDICTIONS
(MONKMAN-GRANT MODEL)

[ ]d

FIGURE 8.7.1
PRESSURE BOUNDARY



NOTE: Pressure Boundary region is denoted by the shaded area.

9.0 DESIGN VERIFICATION - CORROSION

The objectives of the corrosion evaluation are to determine the susceptibility of the Electrosleeve™ material to known Alloy 600 degradation mechanisms, such as stress corrosion cracking (SCC), and to evaluate the corrosion potential of the Electrosleeve™ material in environments that might exist in an operating steam generator.

The corrosion evaluation was performed by addressing general corrosion characteristics first, followed by evaluation of primary side environments and secondary side environments.

9.1 General Corrosion Properties

The electroformed sleeve consists of high purity (>99.5%), ultra-fine grained (nanocrystalline) nickel material. The corrosion resistance properties of high purity nickel have been thoroughly investigated and documented. Also, excellent material performance has been demonstrated in both testing and in actual steam generator and reactor system in-service applications.

9.1.1 Literature Survey of Nickel Corrosion

A general literature review was performed comparing the corrosion behavior of Alloy 600 and pure nickel [12.40]. The results are summarized in Table 9.1.1.

In general, both nickel and its alloys are very noble and are effectively resistant to corrosion in acid, neutral, and alkaline conditions. The presence of highly oxidizing species have been found to decrease this resistance in some chemical environments. For example, corrosion of both nickel and nickel alloys has been observed in an acidic and highly oxidizing environment containing sulfur species.

Galvanic attack between pure nickel and Alloy 600 or Monel 400 material will not occur in SG environments due to the very low potential difference generated by the formation of a couple of these two materials.

9.1.2 Comparison of Nickel Plating and Electrosleeve™

Nickel plating has been used successfully to repair SG tubes since 1985 [12.39]. This experience is summarized in Section 3.0 (Table 3.1). The nickel plating utilized has been typically thin walled (5-8 mils) compared to the thicker walled (> 25 mils) Electrosleeve™ repair method. The nickel plating is intended to be a corrosion resistant "patch" rather than a structural repair.

Both circumferential and axial SCC have been repaired with nickel plating. The nickel plating has also been installed over alloy 600 tube cracks that are 100% throughwall. Thus, the nickel plating has been exposed to primary side environments as well as secondary side environments (via the tube cracks) [12.56]. This is exactly the same manner that the Electrosleeve™ will be exposed to the two environments. In-plant performance of the nickel plating has been excellent in 10 years of service.

Both Electrosleeves™ and nickel plating are >99.5% pure nickel.

]^{c,e} Nickel plating has a conventional polycrystalline grain structure, whereas the Electrosleeving process produces a nanocrystalline microstructure. [

]^{c,d}

The corrosion properties of nanostructures was evaluated in a literature survey. Most of the corrosion evaluations conducted to date have been laboratory studies involving potentiodynamic polarization techniques.

]^{c}

[

]c,d

The general conclusion from this comparison is that the Electrosleeve™ material will perform the same as SG nickel plating in regards to corrosion behavior. Specific tests to evaluate the Electrosleeve™ material's corrosion characteristics were performed as discussed below.

9.1.3 General Corrosion Tests of Electrosleeve™

Corrosion tests were performed on Electrosleeves™ to confirm general corrosion properties for the material. The environments used are extremely severe and do not exist directly in the steam generators. However, the corrosion mechanisms which were tested for are known problems encountered with Alloy 600. Thus these tests are meant to show the characteristics of Electrosleeve™ material, not specifically to predict the life in a SG.

The corrosion mechanisms tested were IGA, SCC, pitting and crevice corrosion. Standard ASTM test procedures were followed.

9.1.3.1 Boiling Sulfuric Acid IGA Test

The boiling sulfuric acid-ferric sulfate test [12.24] is a standard ASTM method to detect the susceptibility to IGA of wrought, nickel-rich, chromium bearing alloys. This method uses ferric chloride in 50% boiling sulfuric acid. The test is very aggressive to nickel base materials with little or no chromium due to the oxidizing nature of the ferric ion.

[

]d

[

]^{c,d,e}

9.1.3.2 Polythionic Acid SCC Test

The polythionic acid test [12.25] is a standard ASTM method used to evaluate the relative resistance of stainless steels and related materials to SCC. The test is applied to wrought products, castings, and weld metals by immersing it in a solution containing polythionic acid at room temperature. Cracking of austenitic stainless steels (Type 302 and 304) would be expected in 1 hour or less in this solution. [

]^{c,d}

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]^{d}

After exposure to the corrosion environment, transverse cross sections were examined metallographically.

]^{d}

9.1.3.3 Magnesium Chloride SCC Test

The boiling magnesium chloride test [12.26] is a standard ASTM method employed to evaluate the relative resistance of wrought, cast, and welded stainless steels and related alloys to SCC. The test can detect the effects of composition, heat treatment, surface finish, microstructure, and stress on the susceptibility of these materials to chloride SCC. The test is carried out in a solution of magnesium chloride (about 45%) which boils at 311°F (155°C) for a duration [ ]^{d} hours.

[

]^{d}

After exposure to the corrosion environment, transverse cross sections were examined metallographically.

]^{d}

9.1.3.4 Sodium Chloride SCC Test

The sodium chloride SCC test [12.27] is a standard ASTM method used to characterize the SCC resistance of aluminum, ferrous, and other alloys exposed to alternate immersion or wetting and drying conditions. This test is an accelerated test to evaluate the resistance to SCC and is not intended to predict performance in specialized chemical environments.

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]^{d}

9.1.3.5 Ferric Chloride Pitting and Crevice Corrosion Test

The ferric chloride test [12.28] is a standard ASTM method used to evaluate the resistance of stainless steels, nickel base, chromium bearing and related alloys to pitting and crevice corrosion. This test is an accelerated test designed to cause the breakdown of type 304 stainless steel at room temperature. The test is carried out in two different steps, the first to evaluate pitting corrosion and the second to evaluate crevice corrosion.

<u>Pitting Corrosion</u>

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]^{d}

<u>Crevice Corrosion</u>

The same solution used in the pitting step is used in the crevice corrosion test. [

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]^{d}

9.1.3.6 Summary of Characterization Tests

Standard ASTM tests were used to characterize the material's performance relative to corrosion mechanisms. [

]^{d}

[

]^{d}

9.2 Primary Side Corrosion Evaluation

In general, corrosion in the primary system of a PWR is minimized by careful control of the environmental characteristics. The Reactor Coolant System (RCS) is a closed system that does not communicate with outside contaminant sources. The environment is further controlled by limiting the presence of contaminants to very low levels as required by Plant Technical Specifications. The RCS chemistry control parameters and expected limiting values for the various modes of operation are given in Table 9.2.1. [

]^{c}

[

]^{c}

The evaluation of the corrosion performance of the Electrosleeve™ in the primary side environment was done by addressing the following areas:

[

]^{c}

[ ]c

[ ]d

9.2.1 Full Power Operating Conditions

Corrosion testing was performed on nickel plating in environments that included pure water, and primary water chemistry conditions [12.39]. Highly stressed (hard rolled transition zones) or very highly stressed reverse U-bends ("RUBs") specimens were used in the testing. Also, samples were submitted to temperature and pressure cycling in pure water to induce deformations in the nickel layer.

9.2.1.1 Pure Water Testing

The objective of this test was to determine the cracking resistance of highly stressed nickel plating in pure water and to compare it to Alloy 600.

RUB specimens were tested to evaluate the SCC susceptibility of nickel plated S/G tubing in pure water. The test were carried out in an autoclave at the following conditions:

[ ]d

[ ]^{d}

9.2.1.2 Primary Water Testing

The objective of this test was to determine the cracking resistance of highly stressed nickel plating in primary water and to compare it to Alloy 600.

[ ]^{d}

[ ]d

9.2.2 Shutdown Conditions

The main corrosion concern during primary side shutdown conditions is the presence of boric acid. The effect of boric acid, at various temperatures and concentrations were evaluated on nickel plating. In addition, oxidizing shutdown crud burst conditions were tested with Electrosleeves™.

9.2.2.1 Boric Acid - Cold Shutdown

[ ]d

[

]d

9.2.2.2 Boric Acid - Elevated Temperatures

A group of tests were performed on nickel plated Alloy 600 tubes in a boric acid environment at elevated temperatures. [

]d

[ ]^{d}

9.2.2.3 Shutdown Crud Burst/Cleanup

During a typical plant shutdown for a maintenance refueling outage, a RCS crud burst is induced through an adjustment to the coolant pH and oxidant level. For this, the plant is borated to the refueling concentration, the lithium and dissolved hydrogen removed, and hydrogen peroxide (up to 10 ppm) added when the temperature has decreased to less than 200°F. This condition is typically maintained for a period of 12 hours to reduce the crud inventory in the RCS prior to continuing the refueling activities. This condition was evaluated by testing Electrosleeve™ specimens at the following conditions:

[ ]^{d}

[ ]d

9.2.3 Parent Tube SCC

Two tests have been performed to evaluate SCC in the parent tube. The first test was performed with nickel plating to verify that the nickel layer would prevent SCC in the parent tube at highly stressed regions, i.e., provide a protective layer.

A test was also performed with Electrosleeves™ in order to verify that high residual tensile stresses are not induced into the parent tube at the ends of the sleeve. This has been a typical problem with standard, e.g., welded, sleeve designs.

9.2.3.1 Stress Corrosion Cracking Protection

Testing in 10% NaOH (caustic) solution has been shown to rapidly induce stress corrosion cracking in PWSCC-susceptible Alloy 600 specimens containing stresses greater than about 30 to 35 ksi. Steam generator roll transition mockups were used to evaluate the effect of nickel plating on SCC [12.39]. The Alloy 600 tubes were rolled in-place areas using a 5 step rolling process, providing two roll transition regions in each mockup. The specimens were tested at the following conditions:

[ ]d

[ ]^{d}

9.2.3 Parent Tube SCC

Two tests have been performed to evaluate SCC in the parent tube. The first test was performed with nickel plating to verify that the nickel layer would prevent SCC in the parent tube at highly stressed regions, i.e., provide a protective layer.

A test was also performed with Electrosleeves™ in order to verify that high residual tensile stresses are not induced into the parent tube at the ends of the sleeve. This has been a typical problem with standard, e.g., welded, sleeve designs.

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[ ]^{d}

9.2.3.2 Stress Corrosion Cracking (Effect of Stress)

A primary concern with standard SG sleeving has been the introduction of residual tensile stresses into the alloy 600 parent tube due to the sleeving process. Such tensile stresses can lead to PWSCC in the parent tube, while the sleeve typically does not experience SCC. Electrosleeving has the advantage of not introducing these high residual tensile stresses in the tube.

The objective of this corrosion test is to demonstrate the absence of significant residual stresses imparted on the Alloy 600 tube after Electrosleeving. A second objective is to demonstrate the Electrosleeve's™ resistance to SCC.

The corrosion test environment was as follows:

[ ]^{d}

[ ]^{d}

9.2.4 Summary of Primary Side Tests

[ ]^{d}

[ ]^{d}

[ ]^{d}

[ ]^{d}

[

]^d

9.3 Secondary Side Corrosion Evaluation

Evaluating the corrosion performance of a material for secondary side environments is much more difficult than evaluating the primary side performance due to the wide range of chemistry conditions which may be encountered. Steam generator upset chemistry conditions may result of from condenser in-leakage, ion exchange resin regenerant chemicals (caustic and acid) from condensate polishing and makeup demineralizer systems, acidic sulfur species from resin ingress, chlorides and corrosion product iron and copper.

The effect of these contaminants is further compounded by the concentrating mechanisms associated with heat transfer and boiling in the steam generators. The generally accepted steam generator and secondary system chemistry program is All Volatile Treatment (AVT). In this program, no solids are intentionally added to the steam generators for chemistry control. Only volatile chemicals such as ammonia and hydrazine are used for corrosion control.

Corrosion of the Electrosleeve™ in the secondary side environment of a PWR is minimized by the following environmental characteristics:

[ ]^d

[

]^d

However, considering that the main reason to utilize Electrosleeves™ is to arrest Alloy 600 cracking, the Electrosleeve™ has to be able to withstand the environment that locally forms at the tip of such cracks. Additionally, it is important to understand the behavior of the Electrosleeve™ in transient (excursion) environments that may be present in localized regions in the SG.

The approach taken to the corrosion evaluation was to demonstrate first the capability of the Electrosleeve™ to arrest cracking at the Alloy 600/Electrosleeve™ interface. This was addressed by exposing [

]^{d}

The performance of the Electrosleeve™ in possible secondary side localized environments was evaluated by exposing the sleeve to [

]^{d}

Evaluation of worst case conditions that may form in Alloy 600 cracks under sludge piles was also tested. [

]^{d}

[

]^{d}

9.3.1 SCC Propagation Tests

To evaluate the crack arrest capability of electrodeposited nickel, two tests were conducted. The first test demonstrated the ability of nickel-plated steam generator tubes containing throughwall cracks to maintain their integrity in a secondary side environment (chemistry and pressure conditions). The second test demonstrated the ability of highly strained Electrosleeves™ to arrest ODSCC in Alloy 600 tubing.

9.3.1.1 Precracked Steam Generator Tubing Test

Steam generator tubing, containing O.D. initiated cracks (including throughwall cracks), was nickel plated and tested in a mockup. Refer to Figure 9.3.1. The purpose of the test is to determine whether throughwall cracks in nickel-plated steam generator tubes will continue to propagate through the nickel plating when exposed to secondary side conditions [12.39].

The test conditions were as follows:

[ ]^{d}

9.3.1.2 Crack Arresting C-Ring Test

Alloy 600 steam generator tubing with and without Electrosleeves™ in the form of highly stressed C-rings were used to evaluate the ability of the Electrosleeve™ to arrest a crack propagating from the tube O.D.

Testing was performed in a 10% NaOH (caustic) environment which is known to cause SCC in susceptible Alloy 600 material.

The test conditions were as follows:

[ ]d

[ ]^{d}

9.3.2 Capsule Tests

The objective of this test was to characterize the corrosion performance of the Electrosleeve™ material in confined conditions of extreme bulk water chemistry.

Test conditions were as follows:

[ ]^{d}

[ ]d

The conclusion from this test is that the Electrosleeve™ material [

]d

9.3.3 Heat Transfer Sludge Corrosion Tests

The objective of these corrosion tests was to assess the corrosion performance of an Electrosleeve™ when a large area of it is exposed to extreme chemistry conditions under a sludge pile.

These tests address the formation of dynamic crevice environments of the type that form in operating SGs and yield information on the performance of the Electrosleeve™ material under these environments. Note, however, that in the SG the sleeve is not exposed to these environments over large areas. Typically the only portion of the sleeve exposed will be the tips of the cracks in the Alloy 600 tube.

Heat transfer corrosion tests allow the direct comparison of bulk water environments between the operating unit and the laboratory test. The test design used herein involved heat transfer of the same magnitude as in the hot leg of a SG and the simulation of a pile of corrosion products deposits (sludge piles) around the tube.

Accelerated conditions were chosen to assess the chemistry limits of the material performance. The three bulk water environments selected addressed three different operating scenarios of feedwater contamination: condenser cooling water, sodium hydroxide and sulfuric acid. The latter species are used as ion exchange resin regenerants and could be accidentally produced in the event of operational malfunctions in the water treatment or condensate polishing systems. Normally, these events are short lasting (in the order of a few hours). The present water chemistry specifications call for remedial action in such events which may even necessitate immediate unit shutdown.

Condenser cooling water in-leakage has afflicted many units in the past; however, the present practices are quite strict and call for prompt remedial action. Many units are equipped with full flow condensate polishers so that in the event of such leaks, the impurities do not reach the SG.

Experimental

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[ ]d

Electrochemical Environments

[ ]d

[

]d

9.3.3.1 Fresh Water Ingress Test

This test addresses the condition whereby a chronic and massive condenser cooling water intrusion occurs during operation. The test parameters were as follows:

[ ]d

[

]^d

9.3.3.2 Acid Ingress

This test addresses the condition of a massive continuous acid ingress in a SG during operation. Test parameters were as follows:

[ ] [d]

[

]^{d}

9.3.3.3 Caustic Ingress

This test addresses the condition of a massive continuous caustic ingress in a SG during operation. The test parameters were as follows:

[

]^{d}

[

]^d

9.4 Nickel Electroplating Operating Experience

9.4.1 Framatome Experience

Since 1985, PWRs in Belgium and Sweden have utilized nickel plating as a repair method for steam generator tubes exhibiting cracking and degradation. Section 3.0 (Table 3.1) summarizes the history of nickel plating of these Belgian plants. The repair method has been successfully used to prevent cracking, as well as to repair existing 100% throughwall cracks within the parent tube. These electroplated nickel sleeves have had excellent in-service performance over the last 10 years. Figure 9.4.1 provides a summary of examinations on pulled tubes exhibiting these results.

9.4.2 FTI Experience

In 1993, FTI performed nickel plating of the Baltimore Gas & Electric Company's Calvert Cliffs Unit 1 pressurizer heater nozzles. Nickel plating was successfully performed on 118 pressurizer heater sleeves to mitigate the potential occurrence of PWSCC in the Alloy 600 heater sleeves.

In 1995, FTI successfully installed 9 Electrosleeves™ in Oconee-1. All sleeves were installed at the 1st TSP. The objective was to demonstrate the tooling and procedures for Electrosleeving. Since the sleeves were not licensed, the tubes were removed from service.

9.4.3 Ontario Hydro Experience

Ontario Hydro has utilized Electrosleeving to repair corrosion damaged tubes in the Pickering Units. Section 3.0 (Table 3.1) provides a summary of the OHT field experience with Electrosleeving.

9.5 Corrosion Evaluation Summary

Qualification of the corrosion properties of the Electrosleeve™ was performed using a three phased program. The first phase involved a literature review and selection of tests, including ASTM standard tests, to determine the susceptibility of the Electrosleeve™ to known forms of Alloy 600 damage, such as IGA and SCC. The second phase focused on corrosion testing in specific primary side environments that are known to be detrimental to Alloy 600 tubing. The third phase focused on secondary side environments including alkaline, neutral, and acidic, in the presence of oxidizing and reducing species, and in many cases at extreme conditions to accelerate the corrosion processes.

A comparative review of the general corrosion characteristics of nickel and Alloy 600 [

]^d

Testing was performed on Electrosleeves™, including caustic and ASTM standard tests, to determine the susceptibility of the material to IGA and SCC. [

]^d

Corrosion testing was conducted on both nickel plating and Electrosleeves™ to evaluate the Electrosleeve™ material performance in primary and secondary environments. Primary side tests included pure water, primary water and boric acid. Secondary side tests included heat transfer conditions, sludge, and confined geometry (crevices) with the associated concentrating mechanisms evaluated. The following conclusions were reached based on the results of these tests and comparison to expected conditions:

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]^{d}

It is concluded that general corrosion, crevice corrosion, pitting, SCC or IGA of nickel Electrosleeve™ material is not a concern in PWR environments. The excellent in-service experience of electrodeposited nickel materials supports this conclusion.

TABLE 9.1.1
SUMMARY OF LITERATURE SURVEY
NICKEL AND ALLOY 600 GENERAL CORROSION
RATES IN VARIOUS ENVIRONMENTS

TABLE 9.2.1
PRIMARY SIDE MATRIX CHEMISTRY

[d]

TABLE 9.3.1
SECONDARY SIDE MATRIX CHEMISTRY

[d]

TABLE 9.3.2

SECONDARY SIDE CAPSULE TESTS

FIGURE 9.3.1

SECONDARY SIDE CAPSULE TESTS

c,d

FIGURE 9.3.2
CAPSULE FURNACE SETUP

[ ]^{c,d}

FIGURE 9.3.3

CAPSULE TESTING FOR FAULTED SECONDARY SIDE ENVIRONMENTS

c,d

FIGURE 9.3.4
REFRESHED AUTOCLAVE LOOP

c,d

FIGURE 9.3.5
STEAM GENERATOR ELECTROSLEEVED™ TUBE MOCKUP

c,d

FIGURE 9.4.1
ELECTROPLATED TUBES PULLED FROM DOEL-2

10.0 SLEEVE INSTALLATION

10.1 Installation Procedure

The Sleeve Procedure Specification (SPS) defines the generic requirements for field installation of the Electrosleeves™. The SPS has been prepared following the guidelines of the ASME Code Section XI for steam generator tube sleeving. The essential and non-essential variables for the process are identified. The following is a summary of the installation procedure

[ ]^{d,e}

d,e

10.2 Process Verification

The sleeving process can be verified [

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]^{e}

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]^{e}

All essential process variables as listed in the Sleeve Procedure Specification are monitored and recorded as specified in the SPS.

10.3 Installation System/Tooling

The installation of the electroformed sleeve is accomplished remotely by tooling attachments mounted on a manipulator. Typical manipulators that may be used for sleeving include: ROGER™, Cobra™, and FLEXIVERA™ manipulators. The sleeve installation tooling used minimizes the personnel radiation exposures in accordance with ALARA principles.

The sleeving system utilizes a series of skids and trailers, each containing a different portion of the fluids and chemicals required to successfully perform the plating process. [

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10.4 ALARA

The ALARA evaluation has been prepared using the process steps for electrosleeving in conjunction with radiation dose fields representative of Series D steam generators. The exposure estimate is based on sleeving 100 tubes in a single steam generator channel head. This quantity is representative of a typical sleeving campaign and provides a useful standard for comparison. Table 10.4.1 provides detailed information regarding the assumed radiation fields, as well as estimated exposures for the various sleeving activities and the total estimated process exposure.

Remote manipulators will be used for the electroformed sleeving process. The estimate provided does not include exposure associated with manipulator installation or removal, as the manipulator is typically installed at an earlier time in support of inspection or repair. [

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Factors affecting process exposure include batch size, intensity of radiation fields, and sleeve placement locations. FTI ALARA Engineers prepare detailed estimates for each job and carefully consider all aspects of each activity in order to further minimize personnel exposure. The batch size and total quantity of sleeves installed play a significant role in the exposure received per unit. As the number of sleeves installed increases, the exposure per sleeve will decrease substantially since several tasks are performed only once for each sleeving job.

10.5 Sleeving Experience

As part of the qualification process, a number of tube conditions were Electrosleeved™ to demonstrate the process capabilities. The tube conditions in which sleeves were successfully installed include:

[ ]^{c}

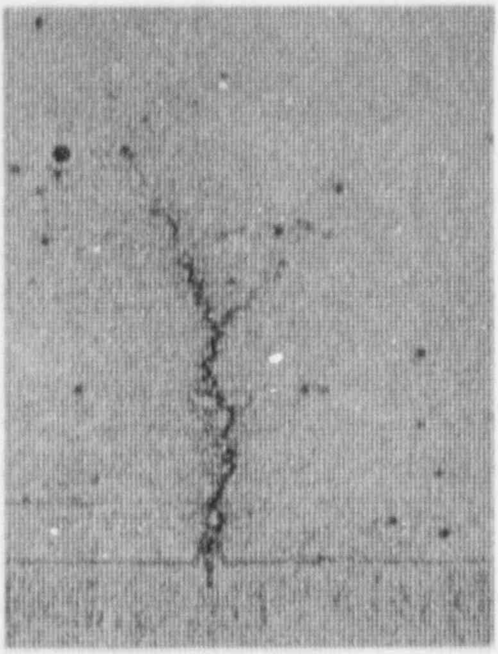
(1) Refer to Figure 10.5.1 for pictures of the installed sleeves.

FIGURE 10.3.1

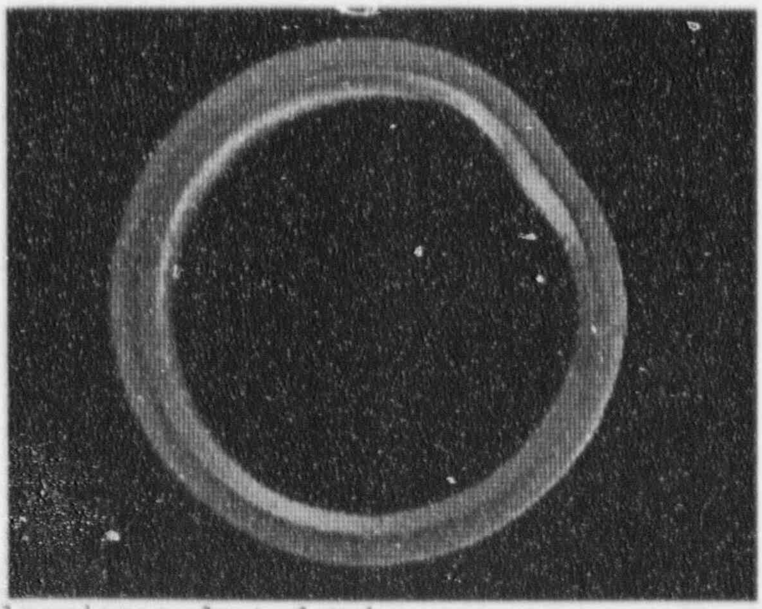
ELECTROSLEEVE™ INSTALLATION SYSTEM SCHEMATIC

[ ]^{d}

FIGURE 10.5.1
ELECTROSLEEVE™ INSTALLATION EXPERIENCE



Sleeving a cracked tube



Sleeving a dented tube

TABLE 10.4.1

SLEEVE ALARA EVALUATION (100 SLEEVES)

AVERAGE AREA DOSE RATES

c,d

ELECTROFORMED SLEEVE EXPOSURE

11.0 NONDESTRUCTIVE EXAMINATION

NDE is performed on the sleeve and parent tube after installation in order to verify correct positioning, proper sleeve to tube bonding, sleeve thickness, and to provide a baseline inspection of the new primary pressure boundary. NDE is also performed during subsequent inspection outages to verify that the pressure boundary has not degraded.

Ultrasonic Testing (UT) is the primary NDE inspection technique for the sleeve and is described below. The UT is required for the installation examination to provide the sleeve thickness measurement and to provide verification of bond quality. [

]^{b}

11.1 Ultrasonic Testing Background

A UT examination is conducted by transmitting ultrasound into the tubing wall and waiting for a returning echo from a reflective surface (i.e., tube outer diameter (OD) wall, Electrosleeve™ wall, crack corner trap, tube end, etc.). The time and amplitude of the returning echo yields information about the reflecting surface and its distance from the transducer. This process is analogous to sonar in that a "ping" of energy is released for the purpose of detecting and measuring the distance of objects that reflect some of the transmitted energy. [

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11.2 UT Defect Qualification Program

Nickel sleeve samples [

]^{d} The qualification samples contained nickel sleeves which were installed into parent tube material as in the design verification sections of this report. A variety of flaws in different sleeve locations were made to test and define the UT capabilities.

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11.2.1 UT Detection/Length Sizing Capabilities

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[

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11.2.2 EDM Depth Sizing

[

]^d

TABLE 11.1
SUMMARIZED UT RESULTS OF BOND/UNBOND

[ ]a

FIGURE 11.1
UT WAVE VEE PATH

[ ]d

FIGURE 11.2

REGIONS OF A NICKEL SLEEVE FOR UT QUALIFICATION TESTING

d

11.3 Eddy-Current Testing

Historically, eddy current testing has not been widely used in the examination of nickel plated tube repairs due to the lack of penetration depth in the higher permeability of the nickel. Several eddy current probe designs were evaluated for examination of the Electrosleeve™. [

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]^{d,e}

FIGURE 11.3

DETECTION OF 20% CIRCUMFERENTIAL EDM NOTCH IN MID SLEEVE

d

12.0 REFERENCES

12.1 ASME Boiler and Pressure Vessel Code, Section II, 1989 Edition with 1989 Addenda.

12.2 ASME Boiler and Pressure Vessel Code, Section III and Section III Appendices, 1989 Edition with No Addenda.

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12.4 ASME Boiler and Pressure Vessel Code, Section XI, 1989 Edition with 1989 Addenda.

12.5 ASME Boiler and Pressure Vessel Code, Code Case N-47-33, "Class 1 Components in Elevated Temperature Service".

12.6 Regulatory Guide 1.121, "Bases for Plugging Degraded PWR Steam Generator Tubes."

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12.8 F.P. Vacaro, et al, "Remedial Measures for Stress Corrosion Cracking of Alloy 600 Steam Generator Tubing," presented at Traverse City Third International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, September 1987.

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12.23 ASTM E 92, "Standard Test Method for Vickers Hardness of Metallic Materials".

12.24 ASTM G 28, "Standard Test Methods of Detecting Susceptibility to Intergranular Corrosion in Wrought, Nickel-Rich, Chromium-Bearing Alloys".

12.25 ASTM G 35, "Standard Practice for Determining the Susceptibility of Stainless Steels and Related Nickel-Chromium-Iron Alloys to Stress-Corrosion Cracking in Polythionic Acids".

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12.30 [ ]^c

12.31 [ ]^c

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12.33 [ ]^c

12.34 [ ]^c

12.35 [ ]^c

12.36 [ ]^c

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12.38 [ ]^c

12.39 [

]^{c}

12.40 [

]^{c}

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12.43 [

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12.44 [

]^{c}

12.45 [

]^{c}

12.46 [

]^{c}

12.47 [

]^{c}

12.48 [.]^{c}

12.49 [

]^{c}

12.50 [

]^c

12.51 [

]^c

12.52 [

]^c

12.53 [

]^c

12.54 [

]^c

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12.56 [

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APPENDIX A

PWR DESIGN INFORMATION

TABLE A.1
W-D DESIGN INFORMATION

[ ]^d

TABLE A.1 (Cont'd)
W-D DESIGN INFORMATION

[ ]d

TABLE A.1 (Cont'd)
W-D DESIGN INFORMATION

[d]

TABLE A.1 (Cont'd)
W-D DESIGN INFORMATION

d

TABLE A.2
W-E DESIGN INFORMATION

d

TABLE A.2 (Cont'd)
W-E DESIGN INFORMATION

[d]

TABLE A.2 (Cont'd)
W-E DESIGN INFORMATION

d

TABLE A.2 (Cont'd)
W-E DESIGN INFORMATION

d

TABLE A.3
CE SYS-80 DESIGN INFORMATION

[d]

TABLE A.3 (Cont'd)
CE SYS-80 DESIGN INFORMATION

d

TABLE A.3 (Cont'd)
CE SYS-80 DESIGN INFORMATION

[d]

TABLE A.4
WESTINGHOUSE 7/8" TUBING S/G DESIGN INFORMATION

d

TABLE A.4 (Cont'd)
WESTINGHOUSE 7/8" TUBING S/G DESIGN INFORMATION

d

TABLE A.4 (Cont'd)
WESTINGHOUSE 7/8" TUBING S/G DESIGN INFORMATION

d

TABLE A.4 (Cont'd)
WESTINGHOUSE 7/8" TUBING S/G DESIGN INFORMATION

d

TABLE A.4 (Cont'd)
WESTINGHOUSE 7/8" S/G TUBING DESIGN INFORMATION

d

TABLE A.5
COMBUSTION ENGINEERING 3/4"x .048" TUBING S/G DESIGN INFORMATION

[d]

TABLE A.5 (Cont'd)
COMBUSTION ENGINEERING 3/4"x .048" TUBING S/G DESIGN INFORMATION

d

TABLE A.5 (Cont'd)
COMBUSTION ENGINEERING 3/4"x .048" TUBING S/G DESIGN INFORMATION

d

TABLE A.5 (Cont'd)
COMBUSTION ENGINEERING 3/4"x .048" TUBING S/G DESIGN INFORMATION

d

TABLE A.5 (Cont'd)

COMBUSTION ENGINEERING 3/4"x .048" TUBING S/G DESIGN INFORMATION

d

TABLE A.5 (Cont'd)

COMBUSTION ENGINEERING 3/4"x .048" TUBING S/G DESIGN INFORMATION

d

TABLE A.5 (Cont'd)

COMBUSTION ENGINEERING 3/4"x .048" TUBING S/G DESIGN INFORMATION

d

TABLE A.6
W-F DESIGN INFORMATION

[ ]d

TABLE A.6 (Cont'd)
W-F DESIGN INFORMATION

d

TABLE A.6 (Cont'd)
W-F DESIGN INFORMATION

[d]

TABLE A.6 (Cont'd)

W-F DESIGN INFORMATION

D