ELECTROSLEEVE™ PROCESS FOR IN-SITU NUCLEAR STEAM GENERATOR REPAIR

R.A. Barton
Ontario Hydro Technologies
800 Kipling Avenue, Toronto, ON M8Z 5S4

T.E. Moran
Framatome Technologies, Inc.
Lynchburg, VA, USA 24502

E. Renaud
Babcock & Wilcox Industries Ltd.
Cambridge, ON N1R 5V3

ABSTRACT

Degradation of steam generator (SG) tubing by localized corrosion is a widespread problem in the nuclear industry that can lead to costly forced outages, unit de-rating, SG replacement or even the permanent shutdown of a reactor. In response to the onset of SG tubing degradation at Ontario Hydro's Pickering Nuclear Generating Station (PNGS) Unit 5, and the determined unsuitability of conventional repair methods (mechanically expanded or welded sleeves) for Alloy 400, an alternative repair technology was developed. Electrosleeve™ is a non-intrusive, low-temperature process that involves the electrodeposition of a nanocrystalline nickel microalloy forming a continuously bonded, structural layer over the internal diameter of the degraded region. This technology is designed to provide a long-term pressure boundary repair, fully restoring the structural integrity of the damaged region to its original state. This paper describes the Electrosleeve™ process for SG tubing repair and the unique properties of the advanced sleeve material. The successful installation of Electrosleeves that have been in service for more than three years in Alloy 400 SG tubing at the Pickering-5 CANDU unit, the more recent extension of the technology to Alloy 600 and its demonstration in a U.S. pressurized water reactor (PWR), is presented. A number of PWR operators have requested plant operating technical specification changes to permit Electrosleeve™ SG tube repair. Licensing of the Electrosleeve™ by the U.S. Nuclear Regulatory Commission (NRC) is expected imminently.

1.0 INTRODUCTION

The degradation of steam generator (SG) tubing, particularly by localized corrosion, is a widespread problem in the nuclear industry that can lead to costly forced outages, and in severe cases, may require unit de-rating, SG replacement or even the permanent shutdown of a reactor. The mandated inspection of SG tubing during maintenance outages is used to monitor degradation, which, if serious enough to compromise structural integrity, requires removing the affected tube from service (i.e., plugging) or repairing it. The standard method of tube rehabilitation involves the installation of a "sleeve," which is either mechanically expanded or welded at its axial extremities to the inside surface of the host tubing. The applied sleeve spans the defect and restores the mechanical integrity of the region. Although widely applied in the nuclear industry, tube repairs cause concerns about reliability because of the intrusive nature of existing installation methods that inherently tend to produce high levels of residual stresses, heat-affected zones, tube deformation or microstructural alterations. The high-temperature, post-installation heat treatment usually performed to relieve the high installation-induced stresses for improved service life, has also been implicated as the cause of further compromising the integrity of the host tube where support-plate deposits restrict thermal growth (i.e., locked-tube scenario).

An alternative, non-intrusive SG repair technology, Electrosleeve™, has recently been developed by Ontario Hydro Technologies (OHT) which circumvents the above-noted concerns while providing long-term, pressure-boundary restoration. The process involves the in-situ electrochemical fabrication/installation of a continuously bonded, structural sleeve made possible by a new generation of advanced materials and their synthesis techniques. The resulting Electrosleeve is illustrated in Figure 1. The proprietary Electrosleeve technology [1], described in this paper, has been field implemented in both Canadian CANDU and U.S. PWR plants and is now offered commercially under a licensing agreement with Framatome Technologies, Inc. (FTI) and Babcock & Wilcox Industries Ltd (BWI).

Electrosleeve™ is a trademark of Ontario Hydro

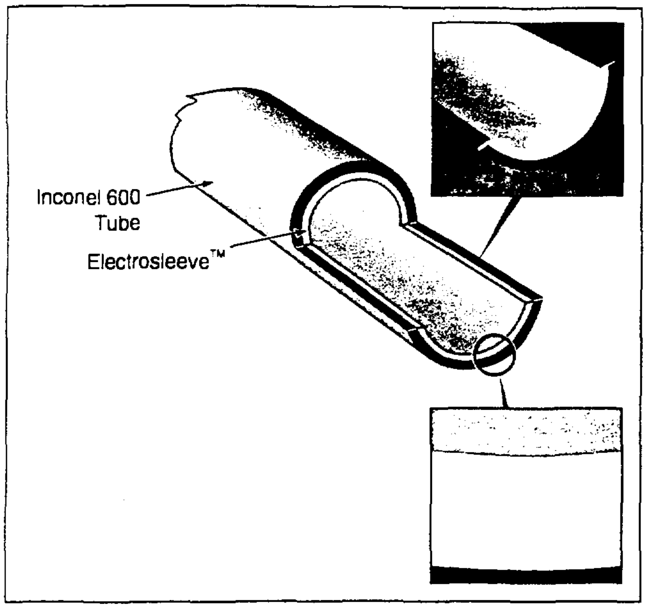

Figure 1: Cut-away view of the Electrosleeve installed in SG tubing.

2.0 BACKGROUND

In 1993, indications of an alarming rate of SG tube degradation and a determined unsuitability of then-available repair methods for application to Alloy 400 (Monel) tubing, resulted in Ontario Hydro being faced with a possible de-rating of Pickering Unit 5 well before the end of its design life. In response, OHT, drawing on its collaborative research achievements in advanced materials, conceived, developed, and through a focused and accelerated effort, successfully delivered a new generation of SG tubing repair technology in time for the Unit 5 maintenance outage in April-May, 1994. The Electrosleeve process is based on in-situ electroforming, which is conducted at low temperature, and is essentially non-intrusive to the host tubing, unlike welding or mechanical expansion.

Although the electroplating of SG tubes has been used extensively in Europe by Framatome (France), only a thin coating of elemental nickel was applied primarily as a preventative measure against primary water stress corrosion cracking (PWSCC) in the roll transition area or to inhibit the propagation of existing stress corrosion cracks [2]. The relatively low mechanical strength of conventional, pure nickel precludes its use as a structural repair where the mechanical integrity of the tube has been compromised, as was the case at Pickering where extensive OD pitting above the tubesheet in the sludge pile region required local pressure boundary replacement (i.e., a structural repair).
The Hall-Petch behaviour of polycrystalline materials indicates that a two to three order of magnitude reduction in grain size, from tens of micrometres (for conventional polycrystals) to tens or hundreds of nanometres (nanocrystalline materials), can improve mechanical properties (e.g., hardness, tensile strength) several-fold [3] (see also Table 1). Based on the pioneering work by Erb and coworkers in the electrodeposition of metals and alloys [4], nickel in the nanocrystalline form, has the mechanical strength for pressure boundary repair applications. Electrodeposition, one of the few methods available for synthesizing fully dense nanocrystalline materials, was the technique adopted for the installation/fabrication of the Electrosleeve[5]. Grain size is controlled by the appropriate selection of current density, ionic concentration, temperature and current waveform [6].

Just as important as ultra-fine grain size, is the effect of minor solute additions of selected elements, preferably phosphorous. The presence of micro-alloyed phosphorous (typically < 3000 ppm) in the Electrosleeve is critical since it has been shown to retard grain growth and ensure the stability of the nanocrystalline structure at elevated temperatures [7,8]. Without the stabilizing influence of the phosphorous, the mechanical strength of the Electrosleeve would quickly revert to that of conventional (microcrystalline) nickel at SG operating temperatures (up to 343 °C for a PWR).

In combination, these concepts enabled the development of a unique, high strength nanostructured nickel microalloy that is fabricated in-situ to provide a non-intrusive, continuously bonded, mechanically superior sleeve repair. Low-temperature installation also ensures that there are no stress relief requirements.

3.0 MATERIAL PROPERTIES

3.1 Composition

The Electrosleeve consists of > 99.5% Ni and also contains typically < 3000 ppm of microalloyed P. In nuclear applications, the cobalt content of the sleeve is limited to < 150 ppm by the use of chemical reagents of suitable purity.

3.2 Microstructural Characteristics

The Electrosleeve material is fully dense (non-porous), generally free of macroscopic defects and possesses a microstructure not resolvable by optical microscopy. Based on transmission electron microscopy and atomic force microscopy, the average grain size of typical Electrosleeve material is approximately 100 nm [9,10].

3.3 Thermal Stability

Pure nanocrystalline Ni can possess a driving force for grain growth that is significantly greater than that for conventional polycrystalline materials [7]. The thermal stability of the nanostructured Electrosleeve is therefore a concern since nuclear SG components can be subjected to long-term (up to 40 years) thermal exposure at design operating temperatures as high as 343 °C. Figure 2 is a plot of Vickers hardness (an indirect measure of grain size) versus annealing time at 343 °C for Electrosleeve material containing 1500 ppm P [(9)]. From an initial, as-plated hardness of 400 VHN, the nanostructured nickel microalloy shows no evidence of grain growth (hardness decay) during a total test period of more than 10 months. In contrast, there is a rapid decrease in hardness to less than 150 VHN within the first few hours of annealing for unstabilized (i.e., pure) nanocrystalline Ni, as shown by the graph, indicating a rapid increase in grain size consistent with that of conventional polycrystals (10-30 μm). The influence of minor solute additions, such as P, on retarding grain growth in nanocrystalline Ni is attributed to (1) solute drag effects on the grain boundaries, (2) the reduction in grain boundary energy from solute segregation, and (3), Zener drag

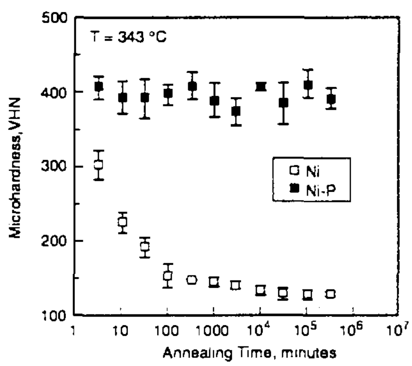

Figure 2: Vickers hardness vs. annealing time at 343°C for nanocrystalline (1) Ni and (2) Ni-1500 ppm P.

effects associated with the possible formation of "grain-boundary-pinning" precipitates [7,8,11]. Based on differential scanning calorimetry measurements[12], exothermic peaks were observed at 560 to 580 °C attributable to the onset of rapid grain growth and an indication of the margin of safety for the thermal stability of the Electrosleeve in nuclear SG applications.

3.4 Mechanical Properties

The mechanical properties of the nanostructured Ni Electrosleeve are summarized in Table 1; the material exhibiting superior strength while maintaining acceptable ductility (elongations to failure in tension consistently exceed 15% at room temperature). The values of yield strength and tensile strength are several times greater than that of conventional, pure nickel (e.g., Ni201) and also significantly greater than those for Alloy 400 and Alloy 600. Due to its superior mechanical properties, the applied Electrosleeve can be somewhat thinner than the original wall thickness of SG tubing (even though no mechanical credit is given for the presence of the host tubing). For example, for 0.50-inch OD Alloy 400 tubing with a nominal wall thickness of 0.049", the target thickness for an installed Electrosleeve is 0.020".

The fatigue properties of the Ni Electrosleeve have been evaluated at both room temperature and at elevated temperature (300 °C with fully reversed bending and frequencies in the range 0.5-25 Hz). Fatigue performance was generally comparable with that of conventional, commercially pure Ni (which is also similar to that of the Alloy 600 parent tubing) and was not compromised at elevated temperature.

3.5 Ductility/Adhesion

The ductility of the bi-material system, comprising the host tubing and the continuously bonded Electrosleeve, was tested per ASTM procedures

TABLE 1
Mechancial Properties of the Electrosleeve Compared to Related Materials

Property	Conventional Ni [13]	Alloy 400 [13]	Alloy 600 [13]	Electrosleeve™
Yield Strength, MPa (25° C)	103	240	310	690
Yield Strength, MPa (350° C)	-	-	-	620
Ultimate Tensile Strength, MPa (25° C)	403	540	655	1100
Ultimate Tensile Strength, MPa (350° C)	-	-	-	760
Elongation, % (25° C)	50	40	40	> 15
Modulus of Elasticity, GPa (25° C)	207	180	207	214

E-290-92 and B-489-85[14]. Longitudinally split Electrosleeved tube samples were bent with the nickel-based sleeve inside diameter in tension (reverse U-bend) over a 6.4 mm (1/4") mandrel as shown in Figure 3. After bending, Figure 4, the sleeves were visually inspected for cracks or evidence of disbonding. Of the hundreds of samples that have undergone this severe test of adhesion and ductility, no defects were observed in any specimen installed per normal process procedures. The ductility of the Electrosleeve material is further demonstrated by the ductile failures the material exhibited during tensile tests. Ultrasonic testing (UT), the preferred post-installation inspection technique for correct positioning and thickness, is also used to provide in-situ verification of bond quality (if the Electrosleeve is not continuously bonded to the entire tube ID, the wave reflects off the nickel outer surface) throughout the entire sleeved area.

3.6 Creep Performance

The high-temperature application of the Electrosleeve in a SG required that the creep performance of the unique nanostructured material be determined. The results of a series of constant load creep tests (covering a range of stresses from

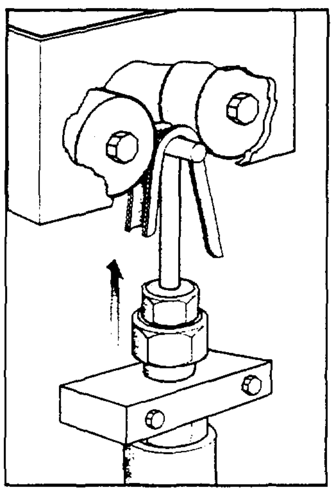

Figure 3: Reverse U-bend test of longitudinally split Electrosleeve sample.

180 to 450 MPa at 343 °C, as well as additional tests at 315 °C and 288 °C to determine the effect of temperature) demonstrate that no failures due to gross distortion, creep rupture from long-term loading, or creep fatigue will occur under SG design operating conditions[15]. In addition, no evidence of intergranular creep cracking (the predominant mode of premature creep failure for engineering materials)

Figure 4: Typical reverse U-bend test specimen exhibiting excellent ductility and adhesion.

has been noted in any of the specimens tested, with completely ductile fracture features exclusively observed. Despite the higher steady state creep rates expected with decreasing grain size, a recent study has shown that nanostructured materials are highly resistant, and possibly immune to intergranular creep failure[16]. This feature, together with the observed time-independent elongation to failure (to greater than 14000 hours), is likely to manifest itself in extended creep life for nanostructured materials. The substantially lower creep rates for the material at 315 °C and below also provide an added margin of safety in CANDU SG applications (304 °C design temperature).

4.0 CORROSION PERFORMANCE

Due to a lack of information on the corrosion resistance, particularly localized attack, of nanocrystalline nickel, especially for material microalloyed with phosphorous, a comprehensive corrosion test program was undertaken for the Electrosleeve. The technical literature does indicate, however, that at phosphorous concentrations of less than 0.9% the general corrosion behaviour of the polycrystalline alloy is similar to that of high-purity nickel[17] including the nickel-plated coating that has been used successfully by Framatome (with greater than 10 years of in-plant service) to inhibit SCC in SGs in Belgium. Due to their greater inherent grain boundary component, nanostructured mateiials are more resistant to intergranular corrosion phenomena (e.g., SCC and intergranular attack, IGA)[18,19]. Therefore, the corrosion performance of the Electrosleeve is expected to be as good as, or better, than conventional commercially pure nickel.

4.1 General Corrosion Tests

Standard tests, designed to evaluate the performance of SG alloys exposed to known corrosion mechanisms in well characterized environments (ASTM G28 for susceptibility to IGA, ASTM G48 for susceptibility to pitting and crevice corrosion, ASTM G35/G36/G44 for susceptibility to SCC) were conducted on Electrosleeve specimens. Test results in these extremely severe environments (they do not exist directly in SGs) confirmed that the material possesses the general corrosion properties of conventional nickel but is intrinsically resistant to intergranular processes such as IGA and IGSCC[10,20]. The Electrosleeve material was also resistant to pitting attack and showed signs of only slight crevice corrosion.

4.2 Corrosion in Specific SG Environments

In general, the corrosion of nickel and nickel-base alloys is minimal during power operation due to careful control of environmental characteristics, such as the addition of reducing agents to limit dissolved oxygen and the maintenance of a slightly alkaline pH. A series of accelerated tests were conducted to simulate upset conditions known to be detrimental to steam generator materials. These tests included freshwater, acid and caustic ingress under a combination of oxidizing and reducing environments at 300/256 °C primary/secondary water temperatures.

The results of the freshwater ingress test revealed no attack of the Electrosleeve after a 4500 hour exposure. Excellent resistance was also demonstrated in alkaline environments, as well as in reducing acidic environments. When exposed to a combination of an oxidizing and an unbufferred acidic environment, corrosion resistance was limited, as expected. However, based on the severity of the test conditions (accelerated tests had 1000X higher acid concentration than the anticipated event) and that an acid ingress requires immediate operator intervention, the test results indicate that the Electrosleeve offers good corrosion resistance, by a large margin, in any realistic acidic excursion scenarios in nuclear plant operation.

4.3 Crack Arrest Capability

One of the most prevalent degradation modes afflicting nuclear steam generators is IGSCC. Commercially pure nickel is a known SCC-resistant material, and as previously discussed, has been successfully used to inhibit or arrest such degradation in an SG environment. Unlike conventional sleeves, which are bonded at their axial extremities, creating an artificial crevice between the host tube and the sleeve, the Electrosleeve provides a continuous high-strength metallurgical bond to the SG tube. In most respects, a continuous metallurgical bond is superior to a weld or mechanical expansion joint at the sleeve extremities. However, there were concerns that a continuous metallurgical bond might allow cracks to propagate from the host tube through the bi-material interface and into the Electrosleeve. However, Sugimura et al. have shown that for bi-material systems of similar elastic modulus, but different plastic properties, cracks propagating toward the bi-material interface from the material of lower yield strength (the SG tube) will always tend to blunt upon encountering the interface[21]. Moreover, a recently developed geometric model has shown that the decreasing grain size of nanostructured materials should yield enhanced resistance to intergranular crack propagation[22,23]. These characteristics of nanostructured materials ensure that the long-term integrity of the Electrosleeve is in no way compromised when used in IGSCC repair applications.

The crack-arrest capability of the Electrosleeve was confirmed experimentally by C-ring specimens (produced from Electrosleeved tubing sections having a thinned outer layer of host Alloy 600 tubing and statically stressed to 2% outer surface strain) exposed to 10% sodium hydroxide solution at 350 °C, an environment commonly used to evaluate the SCC performance of nuclear SG tubing alloys.

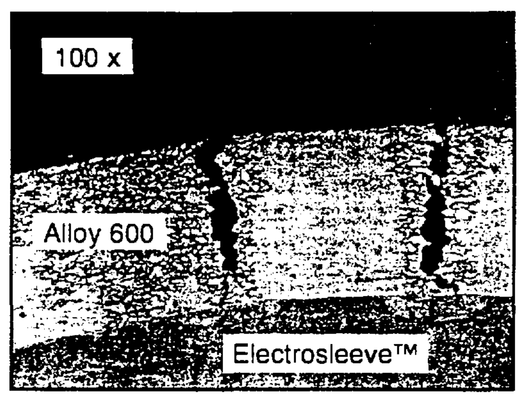

Figure 5: Cross-sectional optical micrograph showing crack arrest/blunting capability of the Electrosleeve in a stressed (2% tensile strain) Electrosleeved Alloy 600 C-ring exposed to 10% NaOH at 350°C for 3000 h.

Figure 5, a cross-sectional optical micrograph of a C-ring following a 3000 hour exposure, shows that the OD initiated, intergranular cracking that is highly prevalent in the Alloy 600 tubing, is completely arrested upon encountering the nanostructured Ni Electrosleeve [9,24]. Stress corrosion cracks were not observed to propagate into the Electrosleeve in any of the 6 specimens tested. Despite the relatively lengthy time the cracks were likely to have remained blunted (estimated at >1500 hours based on full thickness Alloy 600 control samples exhibiting average crack depths of 780 μm), no evidence of sleeve detachment or crack propagation along the bi-metal interface was noted.

5.0 PROCESS DESCRIPTION

In the Electrosleeve process, an integral sleeve of desired length and thickness is synthesized in-situ using a series of relatively simple mechanical and electrochemical operations. A short length of SG tubing encompassing a defect is isolated by insertion of a delivery tool into the primary side of the tubesheet face as shown in Figure 6. The delivery tool (or probe) can be inserted to any vertical distance in the SG tube. This technology also allows tube repairs at restricted ID locations (e.g., dented tubes commonly occurring at the support plates). Moreover, there is the capability of installation above previous Electrosleeve repairs (installation above conventional sleeves is also considered possible). Previously plugged tubes may also be repaired and returned to service.

A pair of inflatable seals at either end of the probe head are used to create a miniature electroplating cavity, as shown in Figure 7, through which Ni-based electrolytes are passed during the electrochemical steps as outlined below. An integral part of the delivery tool is the central, tubular non-consumable electrode (anode) which allows the electrolyte to be circulated back to a remote chemical process station via a polymeric conduit, containing all fluid supply, return and electrical lines, connected to one end of the probe. Continuous recirculation of the process fluids ensures that the specified temperature and chemical composition is maintained in the plating cavity. Upon application of an electric field between the central anode and the SG tube (electrical ground or cathode), electrodeposition of a fully dense, nanostructured Ni micro-alloy occurs on the internal surface of the host tubing. The desired thickness is accurately controlled by electrical-charge integration (current-time). The annulus between the central anode and the SG tube internal wall (cathode) defines the dimensions of the electrochemical cell and thereby the length of the Electrosleeve. No post-installation stress relief or heat treatment is required; the only additional operation is the thorough rinsing of the plating cavity to remove chemical residues to below specified levels.

The sequence of steps for the installation/fabrication of an Electrosleeve are:

- Mechanically clean the tube region to be repaired,
- Insert an electrosleeving probe into the tube, at the elevation needing repair, and inflate bladders to create an electroplating cavity,
- Perform a pressure test, with either water or nitrogen, to ensure sealing integrity,
- Introduce activation solution to clean the parent tube,
- Introduce a nickel-based prefilming solution to electrodeposit a transitional bonding layer,
- Introduce nickel electrolyte to electroform the sleeve,
- Rinse thoroughly with water,
- Remove the electroforming probe from the tube,
- Perform a UT inspection to determine thickness and bond to the tube, and evaluation of defects.

A more detailed description of each step is given starting with tube cleaning. The tube is mechanically cleaned with standard techniques, such as a rotating hone or scraper, to remove loose oxides from the surface. This step minimizes radioactive contamination returning to the electrosleeving solutions.

The probe is inserted to the damaged section of a selected tube where bladders are inflated such that the defect is located approximately mid-span.

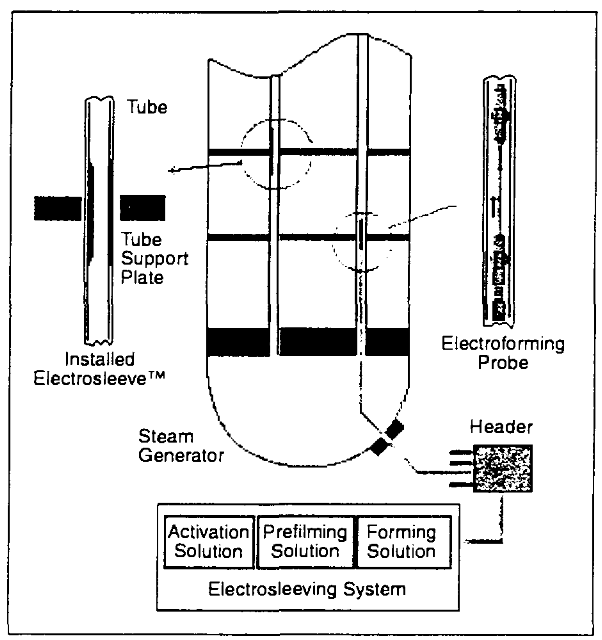

Figure 6: Simplified schematic of Electrosleeve delivery system.

The length of the anode establishes the effective length of the deposit, typically 10 to 20 centimeters. As a general rule, a sleeve of 10 cm long is installed at the tube support plate, while the longer sleeve is used at the tubesheet.

Electrosleeving is a three-step process, and uses a different solution (or electrolyte) for each step. The three solutions are:

- activation solution to prepare the tube surface,
- prefilming solution to produce a strongly adherent nickel layer,
- electroforming solution to build up a thick structural repair nanocrystalline nickel sleeve.

The first of these steps involves surface activation to remove the indigenous oxide from the tube surface. This process is relatively easy with Alloy 400 as the "protective" film formed on this alloy is relatively weak, but is quite challenging for Alloy 600, which forms a very stable passive oxide film. In the later case, the activation solution is circulated through the sealed chamber and an electrical current (reverse polarity) is applied to clean the parent tube by dissolving the surface oxide layer. This step leaves the tube surface in an active state and ready for the initial bonding layer of nickel. To avoid repassivation (formation of a new oxide layer) of the tube surface, the activation solution is immediately followed by the prefilming solution from which a thin layer of nickel is deposited to the as-cleaned surface. The prefilming step leaves a strongly adherent and fully bonded layer on the tube internal diameter. This prefilming layer serves to immediately protect the surface from oxidizing and provides a smooth transition layer between the tube surface and the Electrosleeve. Chemical species associated with the prefilming solution allow for optimum nickel bonding to the host tubing.

After the prefilming solution is flushed from the system, a sleeve-building (electroforming) solution is circulated in the plating cavity. This third and final step involves introducing a nickel solution to complete the full thickness of the sleeve. An electric current is then initiated and maintained for several hours to yield a thick, high-strength nickel deposit.

The target sleeve thickness is determined by pressure-boundary minimum-thickness calculations in accordance with the ASME Boiler and Pressure Vessel Code and other design analyses based on the material properties test results.

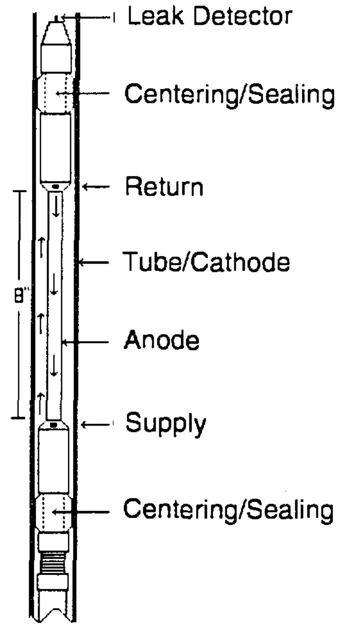

Figure 7: Schematic of plating cavity created in the SG tube by the delivery tool (probe).

6.0 FIELD TRIALS

The repair process was first applied at PNGS-B Unit 5 by an Ontario Hydro Technologies crew, with excellent support from the station, during a pilot demonstration in May of 1994. A total of 46 Alloy 400, 1/2" SG tubes were sleeved at the site, most of these being "witness" specimens installed in a small mockup beside one of the Unit 5 SGs. However, 18 Electrosleeves were actually installed in one of the boilers. Of the eighteen tubes sleeved, 4 tubes were immediately pulled for analysis and 14 sleeves were left in the SG. Approval from the Atomic Energy Control Board (AECB) was obtained to leave these 14 Electrosleeves in service. The sleeved tubes were re-inspected in 1995 by ultrasonic examination; no changes in the bond interface or surface characteristics were observed.

The second field application occurred at Duke Power's Oconee Unit 1 in November 1995. The crew was made up of FTI/OHT/B&W personnel. Oconee 1 has B&W once-through-steam-generators (OTSG's) with 5/8" tubing made from Alloy 600. Nine tubes, which had been scheduled for plugging, were Electrosleeved in one steam generator, as well as 15 "witness" sleeves installed on the SG platform. The nine SG tubes were plugged and not left in service as the process had not been granted a license by the NRC. However, the aim of the exercise was to apply the process to in-service Alloy 600 SG tubing under typical PWR plant conditions. Thus, the demonstration tested B&W/OHT/FTI equipment in a field environment, validated procedures and process specifications, and demonstrated the installation of Electrosleeves under field conditions with a 100% success rate. From this perspective, the trial was a complete success.

7.0 PRODUCTION RIG

To achieve economical production rates, a multiple probe delivery system must be used. Based on a FTI-designed prototype delivery system, BWI and FTI have constructed and commissioned an Electrosleeving production delivery system within the past year. The majority of the equipment is deployed in "Sea/Land" containers to minimize the impact on outage activities, particularly in the reactor building. The modular design of the equipment allows flexibility in deployment (e.g., certain modules may be located up to 200 m from the reactor building penetration).

The pumping and distribution system has a capacity for installing a maximum of 18 Electrosleeves simultaneously. However, due to access and space constraints in the SG bowl, this rate of installation would necessitate the repair of tubes in two or more generators at a time. For typical PWR applications, a maximum of 8 Electrosleeves would be installed per SG with one (spare) channel being used for the production of an optional or "witness" sleeve outside of the generator. Due to more severe space constraints in CANDU applications, a larger number of typically smaller SGs would be expected to be involved at any one time. Based on the installation of 16 Electrosleeves simultaneously in two or more SGs and a 7-hour installation cycle (including the removal and re-insertion of 8 probes), daily production rates of up to 48 sleeves per day for a given system are realistically attainable. This rate is competitive with conventional, zero-leakage SG tube repair technology and approaches the production rate for tube plugging.

During Electrosleeve installation, all critical process parameters are continuously monitored and controlled within specified tolerances from a remote process control computer and data logging system.

8.0 WASTE MANAGEMENT

Framatome Technologies, Inc. (FTI) recently completed the development of a process and the associated mobile equipment for processing spent solutions generated during Electrosleeving operations. The total spent solution volume is segregated into two distinct streams of concentrated solutions (25%) and rinse waters (75%). The processing technique employs a combination of ultra filtration/reverse osmosis (UF/RO), precipitation technologies and concentration drying. The combined use of these treatment systems provides for volume reduction, maximum water recovery and purification, and stabilization of the spent-solution stream to render it non-hazardous. The final products of the spent-solution processing system are liquid water effluent which is low in activity and will meet very stringent release criteria, and a dry, stable, solid with a high nickel content. Expected volumes of both products are given in Table 2 for various size sleeving campaigns.

TABLE 2
Waste Volume Projections

Sleeves Installed	Liquid Waste	Dried Material	45 Gallon Drums for Solids
#	m^3	kg	#
200	6	690	3
500	10.6	915	4
1000	15.5	1140	5

9.0 NON-DESTRUCTIVE EXAMINATION

Following the deposition of the sleeve to the parent tube, the success of the installation is verified through the use of ultrasonic testing (UT). The UT inspection verifies adequate sleeve thickness, sleeve length, bond quality between the sleeve and parent tube, and sleeve position. The sleeve is also inspected to verify there are no unacceptable defects such as pits, or surface roughness that could impede future in-service-inspection (ISI) efforts. The ISI technique used to ensure the structural boundary for the region repaired with the Electrosleeve currently utilizes a UT probe. The probe has multiple transducers to collect data in both zero-degree and shear-wave orientations. This technique has been tested using samples with EDM notches, laboratory-grown indications, and tubes pulled from steam generators with various forms of indications. The results of this testing are currently under review by the NRC. Due to a desire to utilize more standardized ISI equipment, FTI continues to pursue the development of an ISI technique utilizing eddy current testing.

10.0 REGULATORY APPROVAL

The pilot demonstration at Ontario Hydro PNGS-B Unit 5 was authorized by the AECB and the Ontario Ministry of Consumer and Commercial Relations (MCCR) to Electrosleeve 18 known good tubes, and leave 14 in service. The implementation of the process on a large scale to repair damaged tubes will require additional regulatory approvals.

To date, the Electrosleeving Process is awaiting licensing approval by the U.S. NRC in order to be used commercially as a steam generator tube repair method in U.S. PWRs. A comprehensive and detailed qualification report outlining process parameters and sleeve material properties (e.g., corrosion, mechanical, fatigue, creep) has been submitted to the NRC. This proprietary "topical report" forms the basis for NRC consideration pertaining to the acceptance of the SG tube repair technology in the U.S. Discussions are ongoing and are favorable. NRC approval is expected before the end of 1997.

In September 1996, an ASME Section XI, Division 1 Code Case was granted for the Electrosleeve Process. The Code Case (No. N-569) entitled "Alternative Rules for Repair by Electrochemical Deposition of Class 1 and 2 Steam Generator Tubing" contains specifics pertaining to process materials, procedural qualifications, operator qualifications and examination requirements. This Code Case was passed within a very short time of submittal (< 6 months).

11.0 APPLICATIONS

The Electrosleeve technology is applicable in a wide variety of SG remediation programs – from preventative maintenance to complete pressure boundary repair for all tube defect types including PWSCC, ODSCC, IGA, circumferential cracks, axial cracks, pitting/wastage, fretting and denting, as shown in Figure 8. Initially developed for application to 1/2" diameter Monel 400 (Pickering B) SG tubing, the technology has recently been applied to PWR 5/8", 11/16", 3/4" and 7/8" diameter Alloy 600 SG tubing, and is considered to be readily adaptable to other iron and nickel-based alloys such as Alloy 690 and Alloy 800.

SUMMARY

A non-intrusive, advanced nuclear SG tube repair process based on in-situ electroforming of a metallurgically superior nanostructured nickel microalloy has been described. The Electrosleeve technology also offers the following advantages and features:

- long-term, structural (complete pressure boundary) repair
- low-temperature installation with no stress relief requirements
- risk-free installation in 'locked tubes'
- installation at any elevation including tubesheet
- capability of installation at restricted ID locations (e.g., dents)
- capability of installation above previous Electrosleeve repairs (installation above conventional sleeves is also considered to be possible)
- superior combination of strength and ductility at operating temperature
- high fatigue and wear resistance
- enhanced SCC resistance (in comparison to host tube) with SCC arresting capability
- multiple sleeve production capability provides competitive installation rate
- full inspectability (currently by UT)

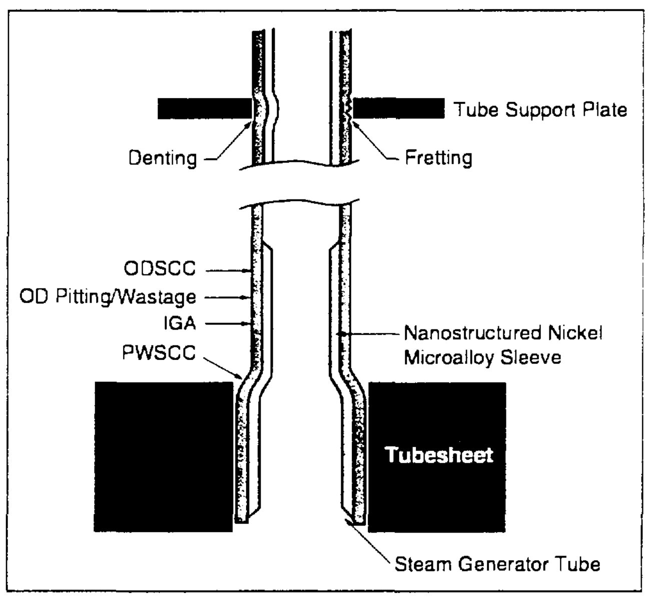

Figure 8: Electrosleeve repair of various SG degradation modes.

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