ELECTROSLEEVE™ PROCESS FOR IN-SITU NUCLEAR STEAM GENERATOR REPAIR

E. Renaud
Babcock & Wilcox Canada
Cambridge, ON, N1T 1S5

A. M. Brennenstuhl
Kinectrics
800 Kipling Ave.
Toronto, ON, M8Z 5S4

D.R. Stewart
Framatome Technologies Inc.
Lynchburg, VA, USA, 24502

F. Gonzalez
Integran Technologies Inc.
1 Meridian Rd.
Toronto, ON, M9W 4Z6

ABSTRACT

Degradation of steam generator tubing by localized corrosion is a widespread problem in the nuclear industry that can lead to costly forced outages, unit de-rating, steam generator replacement or even the permanent shutdown of a reactor. In response to the onset of steam generator degradation at Ontario Power Generation'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 steam generator tubing repair and the unique properties of the advanced sleeve material. The successful installation of fourteen Electrosleeves that have been in service for more than six years in Alloy 400 tubing at the Pickering-5 CANDU unit, and the more recent (Nov. 99) extension of the technology to Alloy 600 by the installation of 57 sleeves in a U.S. pressurized water reactor (PWR) at Callaway, is presented. The Electrosleeve process has been granted a conditional license by the U.S. Nuclear Regulatory Commission (NRC). In Canada, the process of licensing Electrosleeve with the CNSC / TSSA has begun.

Background

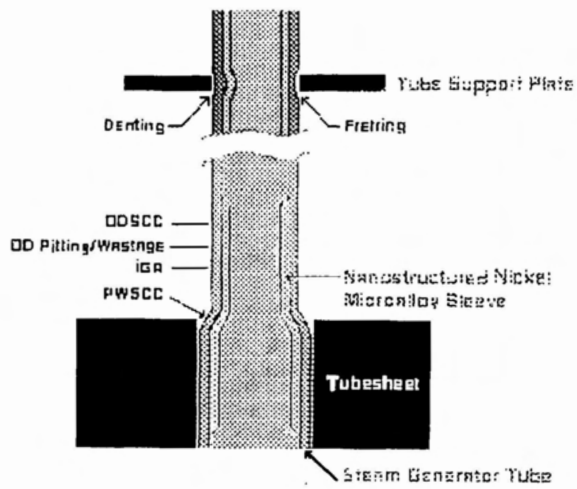
The development of the Electrosleeve™ Process was initiated in response to an increased level of steam generator tube leaks at Ontario Hydro's Pickering 'B' Unit 5 Nuclear Generating Station (PNGS-B-5). A substantial number of Monel 400 SG tubes had already been plugged as a result of prior degradation via pitting corrosion. Ontario Hydro management required an appropriate repair technology to negate possible reactor down rating if tube failures continued at the present level. At the time, the conventional approach to tube rehabilitation was to repair the damaged area of tubes via the insertion of tubular sleeves which were either welded or mechanically bonded at their extremities to the host tubing. Due to the disadvantages associated with the conventional sleeving methods (i.e, parent tube deformation, requirement for PWHT, corrosion concerns associated with weldments, etc.,), Ontario Hydro recognized the need for a new, different and improved repair method.

Through an extensive research program Ontario Hydro Technologies developed a prototypical process for the in-situ electrodeposition of a >99% nickel sleeve on the inner diameter of Monel 400 SG tubes. Characteristics of the electrodeposition process allow the material to form an ultrafine or nanocrystalline grain structure. Nanostructured materials are made up of grains whose mean diameter is smaller than 1 um. As a result of the fine grain size, nanocrystalline materials possess unique properties, including enhanced corrosion resistance and wear properties along with improved hardness, strength and with good ductility. The corrosion properties of high purity nickel (99%+) are well documented and have been confirmed by extensive OHT testing for the Candu operating conditions, and by Framatome Technologies for the US PWR operating conditions. Unless oxygen or highly oxidizing species are present, nickel (and its alloys) are effectively resistant to corrosion in acid, neutral and alkaline environments. Nanocrystalline nickel is not susceptible to SCC in either primary or secondary side environments. Furthermore, the nanocrystalline nickel sleeve provides a barrier to propagating cracks in host SG tubing.

The Electrosleeve™ Process is designed to repair SG tubes which have experienced deterioration via common degradation mechanisms which include intergranular attack, stress corrosion cracking, denting, fretting and pitting (see Figure 1). The technology can currently be applied to straight leg areas of RSG and OTSG tubing. This includes the tube-to-tubesheet expansion area and the tube support plate regions.

Figure 1:

Electrosleeve™ Repair of Degraded Steam Generator Tubes



Process Description

The process is applicable to all tube sizes encountered in nuclear steam generators, from 1/2" to 7/8" O.D. Current process capability allows for the sleeving of 18 tubes at a time (8 tubes in 2 different steam generators, and up to 2 in witness samples). The general process described hereafter has been developed for Alloy 600 SG tubing although it can be extended to other steam generator and heat exchanger tubing materials with minor modifications. There is also a process for Alloy 400 SG tubing that was deployed at Pickering.

The steps for installing an electrosleeve are:
- Locate the target tube with a remote manipulator
- Mark the tube end with a site approved marking ink, and verify location
- Gage the tube (optional) if the tube is dented and did not meet minimum ID requirements (as found by ECT),
- Mechanically clean the tube region to be repaired,
- Insert an electrosleeving probe into the tube, at the elevation needing repair,
- Inflate bladders to seal the electroplating cavity chamber,
- 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 strike solution to electrodeposit a transitional bonding layer,
- Rinse thoroughly with DI water,
- Introduce nickel electrolyte to electroform the sleeve,
- Rinse thoroughly with DI water,
- Remove the electroforming probe from the tube,
- Perform a UT inspection to confirm thickness, positioning, bond to the tube, and relative position of repaired defects.

Detailed Step descriptions

Tube cleaning. The tube is mechanically cleaned with standard techniques, such as a rotating hone or scraper, to remove loose oxides from the surface. Only the tube region to repair is cleaned, plus 5 to 10 cm above and below the region. This step minimizes radioactive contamination returning to the electrosleeving solutions.

The electrodeposition of nickel is accomplished by inserting an electrolyte delivery tool, called a probe, into the steam generator tube. The electroforming probe is shown schematically in Figure 2.

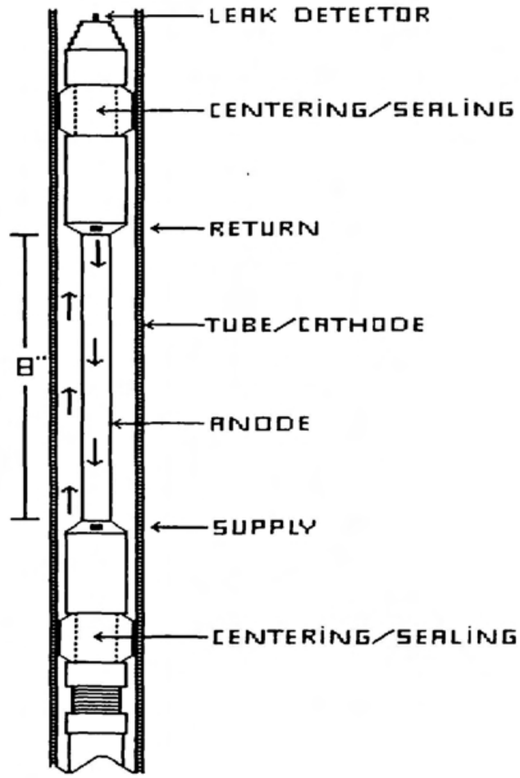


Figure 2: Electroforming probe

The probe, which contains a non-consumable anode, is then pushed up to the target tube repair zone, centering the anode nominally over the defect. Bladders are then inflated to seal the electroplating cavity, effectively creating an electroplating cell at the defect location on the inside of the SG tube. The main components of this cell are an end-effector which comprises a rigid central anode, and sealing modules (i.e. bladders) at both ends of the anode. The chamber is made of the annulus between the probe anode and the tube inner wall (i.e. cathode). The length of the chamber 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 tube sheet. A polymeric conduit connected to the end-effector houses the power cable for the anode and is also connected to the delivery system which supplies process chemicals at a controlled flow rate and temperature.

An electrochemical cell is then created whereby the probe acts as the anode and the tube acts as the cathode. The probe remains in place as fluids are flowed through this sealed cavity for the electrochemical steps of the process. Electrosleeving is a three-step process, and uses a different solution (or electrolyte) for each of these steps. The three solutions are:

- activation solution (also known as Woods); used to prepare the tube surface,
- prefilming solution (also known as Strike) ; used to produce a strongly adherent nickel layer,
- electroforming solution (also known as Watts) ; used to build up the thick structural sleeve.

The first step is a surface activation to remove the indigenous oxide from the tube surface. Oxide removal can be quite challenging in the case of Alloy 600 which forms a very stable passive oxide film. An acidic activation solution is circulated through the sealed chamber and an electrical current is applied to dissolve the surface oxide layer. To avoid re-passivation of the tube surface (ie, formation of a new oxide layer), the activation solution is immediately followed by the prefilming or Strike solution, in which a thin layer of nickel is deposited on the cleaned surface. Upon application of an electric field in the cavity, electrodeposition of pure nickel begins to occur on the tube ID. The deposit thickness is controlled by charge integration (current-time), and is kept very thin. This prefilming step leaves a strongly adherent layer which will serve as a stable transition interface to the final structural material yet to be applied.
After the Strike solution is flushed from the system, another high-nickel solution (Watts) is introduced to build the structural sleeve. A special pulsed electric current is initiated and maintained over several hours to yield a thick high strength nickel deposit. The current density, temperature, and flow in the plating cavity chamber, and the chemistry of the electrolyte are chosen to ensure massive nucleation during electrocrystallization leading to a very fine grain structure.

The required sleeve thickness to obtain a structural repair is function of tube size. This varies from 0.5 mm for a 1/2" tube, to almost 1 mm for a 7/8" tube. The Watts process takes approximately 4-4.5 hours to electroform the necessary 0.74 mm thick nickel layer for 5/8" tubing. To achieve economical repair production rates, multiple probes are installed in the same channel head of a steam generator, and two channel heads can be serviced per pumping system.

Following deposition of the sleeve, the tube and probes are rinsed with warm DI water. Tubes are inspected at first opportunity, and may be inspected even as the next batch of sleeves is in process.

Sleeving Rig

Under agreements with FTI, B&W has built most of the components of the FTI-designed production delivery system. This system is made of the following modular components:

- one Watts skid,
- one Woods / one Strike / two Watts mixing stations,
- one Strike skid,
- one Woods skid,
- one distilled water skid,
- one recycled water skid,
- one spent solution skid,
- one diverter box,
- two distribution headers,
- 18 power supplies,

- several thousand feet of chemical hosing and wiring.

The system is designed to service 2 SG channel heads concurrently, with flow splits that allow fully independent fluid control. Each probe has separate control of power and flow. The Watts skid was installed inside its own custom sea-land trailer, and shares the room with the three mixing stations and a chemical fume-hood for environmental control. The Watts trailer is typically outside containment, up to 150 meters way from the RB penetration, and dual hose lines feed each SG. The Woods and Strike skids can be installed either inside the reactor building, or outside in their own trailer with lines running to the RB penetration. If the Woods and Strike skids are installed inside the reactor building, they are located near the deionized water skid, the recycled water skid, the spent solution skid, and the diverter box. Solution lines as long as 50 meters run between these skids and the distribution headers. There is one header system for each channel head.
A divertor box is used to direct flow of water, Strike or Woods to one or the other SG. Simultaneous feeding to 2 channel heads is not required since the use of these skids is short-term and is staggered once during startup to prevent conflict of need between the two SG's.

The flow from the divertor box loops through the distribution headers, where the flow is locally split into nine individual flows, and then recombined on the return leg. 16-meter lines from the supply and return header feed a local bulkhead box where up to nine individual probes can be attached. The only equipment staged near the SG's are the bulkhead boxes and the probe power supplies. These power supplies are custom built and can be located up to 16 meters away from the bulkhead.

Although capable of 9-probe operation per bulkhead, there is typically one probe used to simultaneously sleeve a witness sample staged on the platform. That specimen can be used for mechanical testing or be archived. Unused probes are bypassed. The FTI system is capable of repairing 16 tubes at a time (8 tubes in 2 different SG channel heads in parallel). Typical cycle time for one batch is about 8 hours.

Process Control:

The sleeving process is highly automated, with numerous air-actuated valves, detectors, level indicators and level switches. Default logic is incorporated to allow proper control of all fluids and to safely depressurize all lines under loss of power, air, or computer communication. Since the fluids are acidic, and may be radioactive, they are controlled by suitable double-boundaries or are bermed to contain any fluid loss. The system has on-line detection of leaks or fluid loss for the Watts solution since this fluid remains in circulation almost continuously.

During the Electrosleeve process, all critical process parameters are continuously monitored (using data loggers) and controlled to within established limits. This is to ensure that sleeve installation is in accordance with parameters as defined in tube or site-specific procedures, much like is done for welding documents. The material is ASME Code qualified; the Code Case defines specific documentation and qualification requirements, again modeled after welding PQ's.

The process parameters can be divided in three groups: chemical, physical, and electrical. The chemical parameters include nickel, boric acid, phosphorous acid and chloride concentrations in the solutions, and the pH of the solutions. The physical parameters include temperature, flow, and surface tension of the solutions. The electrical parameters are those used in pulse plating to define the waveform: frequency, duty cycle, current density and the charge in amperes-minutes that is function of the quantity of nickel to be electrodeposited.

System operators and process engineers monitor the process from remote stations. Specialized software allows parameter output in graphical or data format, and on-line process trending is achieved. On-line chemical injection and adjustment is also performed under computer and operator control to hold process parameters within acceptable ranges.

Waste Management

Framatome Technologies, Inc (FTI) recently completed the development of the process and associated mobile equipment for the processing of spent solutions generated during Electrosleeving operations. The return stream of process fluids is diverted under automatic process control to several different locations. If not being returned to the source tank, the flow is split into one of 3 waste streams. One stream is simply hydrotest water, and typically can be sent directly to plant drains. The waste stream from on-line operation is mixed or rinsed process fluids, and is further divided into two streams depending on level of chemical concentration. Rinse waters represent about 65% of the total on-line waste volume, and contain less than 1% process salts or fluids. The remaining 35% contains about 10% concentration of salts or chemicals. Residual full concentration process-fluids at the end of the sleeving campaign are collected separately. Cold waste can be disposed of as non-hazardous once neutralized.

The processing technique employs a combination of Ultra Filtration/Reverse Osmosis (UF/RO), Concentration Drying, and precipitation technologies. The combined use of these treatment systems provides for about 90% volume reduction. The final products of the spent solution processing system are liquid water effluent which is low in activity and will meet stringent release criteria, and a dry, stable, buriable product.

For a small campaign, the total waste per sleeve is higher. A 200-sleeve campaign would yield two to three drums (50 gallon drum) of solids. Small campaigns may find it more economical to solidify the unprocessed waste volume in cement.

Non Destructive Examination

Following the sleeve electrodeposition, 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 UT 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. FTI recently and successfully presented UT techniques to an EPRI peer group to detect and size axial and circumferential ODSCC. An Appendix-J qualification was granted for the techniques, both for 7/8" and 3/4" tubing, both sleeved and unsleeved. A second Peer review is scheduled later in 2000 for depth sizing techniques.

Eddy current inspection techniques are also under development for EPRI Appendix-H qualification within a few months. EC detection and sizing of flaws has been satisfactorily performed on thin-sleeves. Thin-sleeves have about one-third the deposit thickness of structural sleeves and whose objective is prevention and arrest of PWSCC at tube-support locations.

Field Installations

Pickering Unit 5 Electrosleeves

The first ever production scale Electrosleeving campaign was executed at PNGS Unit 5 during the period April 25 to May 4, 1994. The campaign consisted of a total 46 sleeves including in-boiler and out-boiler witness sleeves. The "Trustie" ultrasonic testing (UT) system was used to determine the Electrosleeve thickness and the bond integrity to the parent tube. The initial inspection performed after the Electrosleeving indicated that 44 sleeves were acceptable as per the quality assurance criteria outlined in the station procedures and material and process approved documents. It is important to note that the steam generator tubing material of PNGS 'B' is Monel 400 and that an unusually thick and tenacious oxide layer was present on the tubes. This oxide is believed to have resulted from the stress relief thermal treatment of the steam generators. The activation step applied during the Unit 5 electrosleeve process involved acid activation *without* anodic polarization.

Fourteen (14) of the eighteen (18) in-boiler sleeves were left in operation and four (4) were immediately pulled for destructive examination. These Electrosleeves and the 28 witness sleeves were tested for chemical composition and mechanical integrity. All sleeves met or exceeded chemical and physical specification requirements. These requirements included yield and tensile strength and ductility determinations. Bend tests were utilized for the measurement of the Electrosleeve/parent tube adhesion. On the basis of these physical test results it was concluded that the remaining 14 in-boiler sleeves possessed the required properties for pressure boundary replacement. The Atomic Energy Control Board granted approval to leave these sleeves in operation.

UT Inspection Spring 1995

In April 1995, as required by the Canadian Nuclear Safety Commission (CNSC), all fourteen in-boiler Electrosleeves were inspected by UT. After approximately one year of operation, the results of the inspection revealed an acceptable performance of the installed sleeves. This was evidenced by the overall continuity of sleeve-to-tube bonding and consistency in sleeve thickness with originally values installed. However, two tubes showed two small areas of disbond. One of these disbonds comprised an area at the limit of UT inspectability ($<1mm^2$); and the second tube had an area slightly larger at approximately 6x8mm. This discontinuity represented 0.7% of the total area of the Electrosleeve.

The root cause of these disbonds was identified as residual patches of oxide which separated from the alloy substrate upon temperature cycling. It is only when the oxide patches are small that the Electrosleeve/oxide bond is stable. It was concluded that the disbond would only occur after one temperature cycle. The qualification results demonstrated that the Electrosleeve/Monel bond was metallurgical and that the bond strength was unaltered after more than five hundred thermal cycles from room temperature to operating temperature.

UT Inspection Spring 1999

In March 1999 UT inspection results showed no measurable changes in any of the fourteen (14) Electrosleeves since the 1995 inspection. The data confirmed that twelve electrosleeves were fully bonded and that the small areas of disbond of the remaining two showed no change from the 1995 inspection. The UT results confirmed the thickness of all the Electrosleeves.

Pickering Electrosleeve Performance

Electrosleeves have now been in operation at Pickering, Unit 5 steam generators for more than six years. The results of the three UT inspections performed during this period have shown a satisfactory performance of Electrosleeves under the operating environmental conditions of this unit. The comparison of the UT Electrosleeve maps for each tube clearly reveals no corrosion of the material or any other type of degradation. See Figure 3. The experience at Pickering clearly

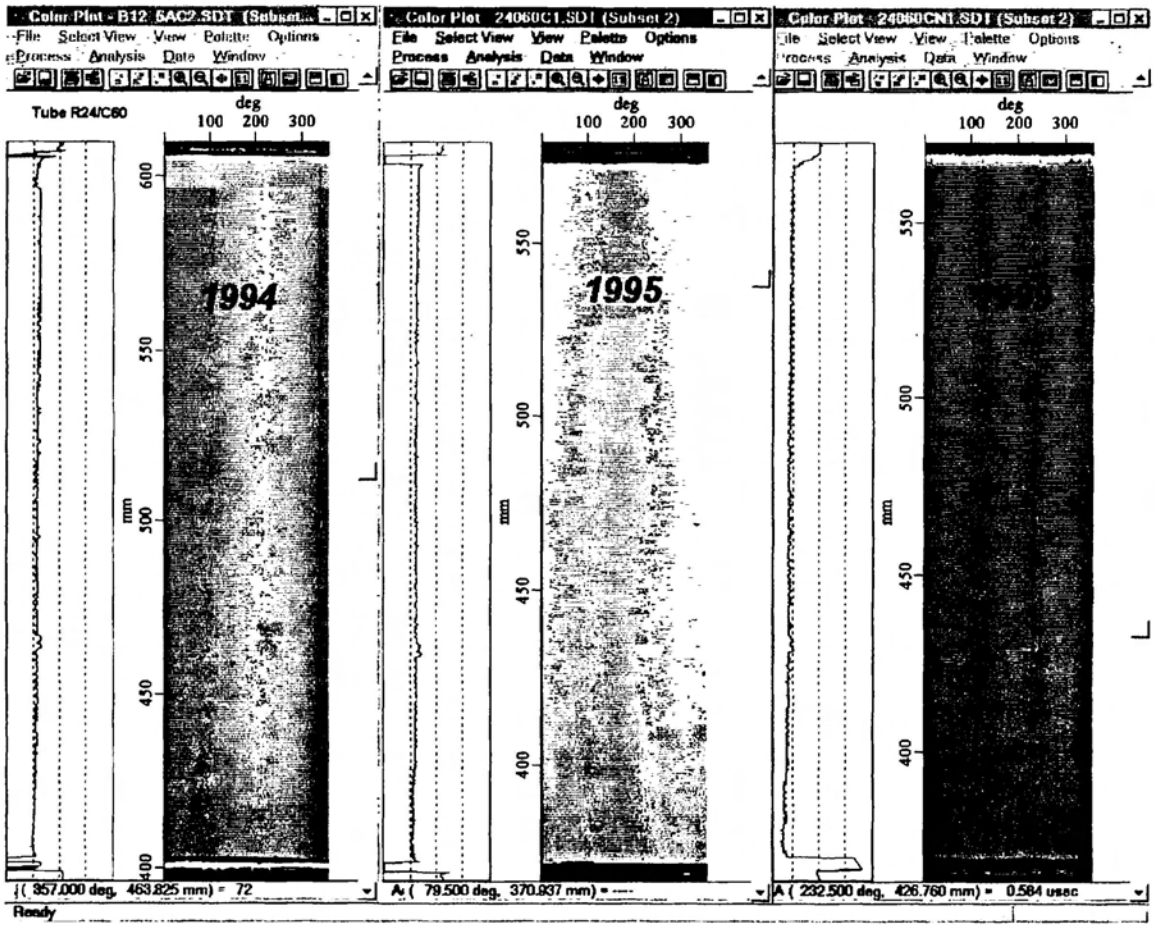


Figure 3: Comparison of UT maps over a 5 year period.

demonstrates that electrosleeving of CANDU steam generator tubes is a viable permanent repair technology.

Second Field Campaign at Oconee Unit 1

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 personal. 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 sleeved in one steam generator. Since the process had not yet been submitted for NRC approval and a tech-spec amendment not been submitted, these tubes were simply inspected to confirm acceptability then plugged. The Electrosleeve™ installation was an exercise only and successfully demonstrated the equipment in a field environment, and validated procedures and process specifications, under PWR field conditions. All nine sleeves were successfully installed.

Third Field Campaign at Callaway

In October of 1999 Framatome, with assistance from BWI and OPT personnel, installed 60 Electrosleeves at the Calloway-1 plant in 11/16" Inconel-600 tubing. All candidate tubes had defects at or near the top of tubesheet. Three of the four PWR steam generators were sleeved, and 57 of the 60 sleeves were left in service after UT inspection. Those three sleeves rejected had minor anomalies however no effort was made to undertake sleeve repairs. Although the field process was in place for the repairs, schedule did not allow to pursue this task. The Electrosleeving was successful from a process standpoint, and with many lessons learned on production planning, coordination, interface, and improved field durability of sensitive equipment. Callaway has received a temporary 2-cycle tech spec amendment for this installation and awaits final NDE qualifications and approvals.

Regulatory Approval

The trial exercise at PNGS-B Unit 5 was granted a temporary license by the AECB and the MCCR to Electrosleeve 18 good tubes, and leave 14 in service. The implementation of the process on a large scale to repair damaged tubes will require a license in the future.

Discussions have been held with both the CNSC (AECB) and the TSSA regarding the requirements to license the Electrosleeving process for use in Canada. The TSSA has performed a review of the ASME Code Case and the relevant licensing documents for the US (NRC) license application. The TSSA will be witnessing some sample runs in the fall of 2000 after which we will proceed with obtaining their approval for the process. This will improve the state of readiness for the application of the Electrosleeve in Canada. A formal application to the CNSC will be required once a specific application for the process is identified.

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

The Nuclear Regulatory Commission (NRC) issued a license amendment approval for AmerenUE to use an innovative sleeving process in the Steam Generator tubing at its Callaway nuclear plant in May 1999. The NRC safety evaluation report (SER), based on four years of NRC review, limited the use of the Electrosleeve™ to two cycles of operation, pending improved demonstrated accuracy of ultrasonic testing (UT) analysis of tube degradation depth sizing.

While extensive interest in this technology has been expressed, NRC has questioned the risk due to the nickel alloy's reduction in strength in "beyond design basis" accident scenarios. Simulation of a severe accident scenario, using Electrosleeves provided by FTI, were performed at Argonne National Laboratory (ANL) and funded by NRR. Additional testing was performed by FTI. The burst temperatures (maintaining a pressure of 2350 psi while increasing temperature until failure) has been evaluated for EDM (electro-discharge machining) flaws in tubes repaired. The acceptance standard has been based of thermal transients extracted from core damage studies and assumed degraded tube conditions. The review of the risk for the Callaway Plant was found to be acceptable in the NRC's May 1999 SER. Risk assessment concerns continue to be raised within the

NRC which have precluded any additional technical specification change request submittals.

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 6 months of submittal. The attainment of an ASME Code Case for this technology in such short time is considered encouraging for full NRC approval.

Conclusion

The non-intrusive benign nature of the Electrosleeve technology allows its installation as a pressure boundary repair for every tube defects including PWSCC, ODSCC, IGA, axial and circumferential cracks, pitting and wastage, fretting and denting. Moreover, in the case of defects on the ID of the tubing, the Electrosleeve can be applied as a thin sleeve to effectively cover the defects and essentially stopping them from propagating further into the tube. However, the thin sleeve is not a structural pressure boundary repair, and would be used as preventative maintenance.

The Electrosleeve technology offers the following advantages and features:

- low-temperature installation with no stress relief requirements
- installation at any elevation: tubesheet, free span, tube support plate, and even U-bend is considered to be possible
- capability of installation above previous Electrosleeve
- long-term structural repair (thick sleeve)
- preventative maintenance (thin sleeve)
- multiple sleeve production capability provides competitive installation rate
- better corrosion resistance than the parent tube, with SCC arresting capability
- full inspectability by UT

Acknowledgements

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