Guidelines for PWR Steam Generator Tubing Specifications and Repair

Volume 3: Steam Generator Tube Sleeving: Design Specification, and Procurement Checklist

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Technical Report

REPORT SUMMARY

SUBJECTS	Steam generator reliability / Nuclear component reliability / Nuclear plant corrosion control
TOPICS	Nuclear steam generators; Boiler tubes; Specifications; Inconel alloys
AUDIENCE	Generation engineers / R&D scientists

Guidelines for PWR Steam Generator Tubing Specifications and Repair

Volumes 1–4

The variety of PWR steam generator tubing now in service complicates procurement and repair. The guidelines in this report will assist utilities in choosing steam generator tubing and sleeve materials, in maintenance practice, and in the removal and examination of tubes to determine causes of corrosion damage.

BACKGROUND Numerous vendors manufacture thermally treated (TT) PWR steam generator tubing. As a result, tubing with various microstructures, mechanical properties, residual stress states, and corrosion resistance are currently in service. These differences in tubing characteristics result from different philosophies at the tube mills and among nuclear steam supply system (NSSS) vendors. Perhaps because of this lack of agreement in the technical community, tubes in some steam generators are corroding at a rate in excess of what the utilities originally planned when they ordered their nuclear power plants. This corrosion and mechanical damage experience has led to development of techniques for tube repair and for the removal of tubes from service for examination.

OBJECTIVE To formulate authoritative guidelines for the best industrial practice, for utility use in tube procurement, for the sleeving of existing tubing, and for the examination of tubes removed from operating steam generators.

APPROACH In order to formulate guidelines on tube procurement, maintenance, and testing, the authors surveyed existing industrial practice, visited appropriate manufacturers, assisted EPRI in sponsoring workshops on current manufacturing practices, and visited domestic and foreign utilities to obtain operating experience. They reviewed the resulting guidelines with utility and vendor experts to validate their findings.

RESULTS The researchers produced four separate sets of guidelines:

- Volume 1, the alloy 600 TT guideline, already used to manufacture tubing for laboratory purposes around the world, defines the best practice for producing tubing, including sleeving, from this alloy. It has served as a valuable resource for the preparation of the alloy 690 guideline, for which there was essentially no production experience.

- Volume 2, the alloy 690 TT guideline, also already in use, defines the best practice for producing tubing, including sleeving, from this alloy.

- Volume 3, the sleeving guideline, provides the only complete source of information in the industry relating to sleeve designs and procurement. It also contains a checklist for the utility on installation procedures, designs suitable for steam generators, and the positive and negative attributes of sleeve installation and maintenance.

- Volume 4, the tube removal and examination guideline, describes standardized methods of tube removal and subsequent laboratory examination.

EPRI PERSPECTIVE Implementation of these four guidelines will improve the quality of the service and materials purchased by utilities. Implementation, however, must include an evaluation of utility needs as well as supplier services and materials. Additional background data can be found in the following EPRI reports: NP-5072, *Specially Prepared Alloy 600 Tubing;* NP-4665-SR, *Proceedings: Workshop on Thermally Treated Alloy 690 Tubes for Nuclear Steam Generators;* NP-6750-M and NP-6750-SD, *Proceedings: 1989 Alloy 690 Workshop*; and NP-6719-M, *Proceedings: Primary Water Stress Corrosion Cracking—1989 EPRI Remedial Workshop.*

PROJECTS RPS303-12, RPS407-7, RPS408-1, RPS408-5
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Guidelines for PWR Steam Generator Tubing Specifications and Repair

Volume 3: Steam Generator Tube Sleeving: Design, Specification, and Procurement Checklist

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ABSTRACT

As a result of recent laboratory research and lessons learned from the field over the past several years, it has become desirable to collect industry knowledge relative to PWR Steam Generator Tubing Materials. These four volumes, NP-6743-L, volumes 1 through 4, contain the results of research work combined with field experience distilled into four guidelines that relate to Steam Generator tubing materials: their procurement, field repair and destructive examination after removal of tube segments from operating steam generators.

The two tubing procurement guidelines (volume 1 for alloy 600 and volume 2 for alloy 690) combine the best practice of the metals industry with extensive research effort from the Steam Generator Owners Group, Electric Power Research Institute, PWR vendors and other laboratories. These Guidelines have been subjected to extensive review by interested parties. They have been implemented successfully in earlier preliminary format for replacement steam generators.

The tube sleeving guidelines (volume 3) derives from an earlier EPRI publication, NP-4296-LD, combined with a detailed survey of vendor practice and plant installation and operating experiences. After evaluating and combining data from the different sources the document was reviewed by vendors and utility experts.

The guidelines for tube removal and examination (volume 4) is a new document which aims to collect nondestructive and destructive examination practice from various laboratories around the world into one cohesive practice that utilities can use as a reference for removal and examination of tube segments removed from their steam generators. It has also been reviewed by experts in the field.

This report volume describes the major factors which should be considered in planning for sleeving of tubes in pressurized water reactor steam generators, current licensing concerns regarding sleeving and sleeve designs currently being offered by service vendors. The report also gives a summary of sleeving experience through the summer of 1989.

A draft specification is provided which can be used to assist utilities in procuring sleeving services.

A design review checklist is provided which can be used to assess vendor proposals. This checklist includes factors such as: suitability for sleeving repairs, sleeve design, licensing status, prior experience, materials, qualification testing, material control, installation, inspection, etc.

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SUMMARY

INTRODUCTION

Tubes used in PWR steam generators are subject to several types of degradation including primary water stress corrosion cracking (PWSCC), secondary side IGA, secondary side IGSCC, and secondary side wastage. Primary side degradation typically occurs at locations of high residual stresses such as expansion transitions, dented tube support plate intersections and inner row U-bends. Secondary side degradation typically occurs at locations where impurities can concentrate such as in the crevice between tubes and tube sheet for part depth rolled tubes, in the sludge pile region and at tube support plate crevices. Remedial action is required if the degradation exceeds allowable limits. Possible remedial actions include: (1) plugging, which takes the tube out of service, (2) sleeving, which allows the tube to remain in service, (3) electroplating the inside of the original tube with nickel, which is a form of sleeving which seals leaks and prevents further corrosion but does not restore structural integrity, and (4) steam generator replacement.

SUITABILITY FOR SLEEVING

Many factors must be considered in making a decision to install sleeves. Several of the more important factors are:

Tube Plugging Margin

Tube plugging is typically less expensive than sleeving and may be preferable if: (1) the plant has a large plugging margin and a slow degradation rate, (2) future degradation is anticipated above the planned sleeving elevation, or (3) fully qualified sleeves are not available. It is oftentimes possible to increase the plugging margin by performing more refined analyses.

Sleeving Qualification Status

Sleeves should not be installed until the qualification testing work has been completed. The only exceptions should be when a few sleeves are installed for evaluation purposes or when the tube plugging margin has been reached and the only available course of action is to install the best available sleeves. If evaluation sleeves are installed, they should have successfully completed all qualification tests except possibly longer term PWSCC tests in high temperature water.

PWSCC Susceptibility of Original Tube Material

If the original tube is susceptible to PWSCC, caution must be exercised to ensure that the sleeve joints do not result in residual stresses which will cause PWSCC in the original tube material at the joint within the intended life of the sleeving repair.

SLEEVE DESIGN CONSIDERATIONS

Design Objectives

Sleeves, and their joints, must have: (1) adequate strength to compensate for structural degradation of the original tube, (2) adequate corrosion resistance to survive for the desired remaining life, (3) adequate leak tightness to meet technical specification, and (4) ALARA requirements.

Dimensions

Sleeves must be long enough to bridge the degraded portion of the original tube such that joints can be made in sound material. Sleeve lengths are typically 26-45 inches for tube sheet area sleeves in plants with part depth expansion, 12-45 inches for tube sheet area sleeves in plants with full depth expansion and 10-11 inches for tube support plate sleeves. The maximum length of rigid sleeves at the tube sheet periphery is limited to 11-12 inches due to interference with the lower channel head. Some vendors offer curved sleeves for these peripheral locations which are straightened as the sleeve is installed. The sleeve outside diameter is made as large as practical consistent with being able to insert the sleeve into the tube. The sleeve wall thickness is established primarily upon strength considerations.

Materials

Three materials must be considered. First, the original tube material is important, especially if it is susceptible to PWSCC since there is the potential to produce tensile residual stresses at sleeve joints. Second, the sleeve material should be resistant to the primary and secondary environments. Thermally treated alloy 690 has been tested and has demonstrated acceptable performance under these conditions. It is the most commonly applied material for this purpose. Third, it must be confirmed that any materials added in making joints such as welding filler metal or brazing materials will withstand the operating environment and are compatible with the original tube and sleeve materials.

Joints

Joints are required at the top and bottom of sleeves. Freespan joints are typically made by expanding the sleeve into contact with the tube and then making a seal by TIG welding, laser welding, brazing or hard rolling in the center of the expanded region. An alternative approach is to make a kinetic weld which expands and seals the joint simultaneously. Tube sheet area joints are made by expanding the sleeve into contact with the original tube and then possibly making a weld or hard roll seal. A desirable approach for tube sheet area joints is to expand the sleeve into the tube using a hydraulic or explosive expansion process which results in low residual stresses at the expansion transition, and then make a hard roll or seal weld in the middle of the expanded length if necessary.

Problems encountered with joints in the past have included: (1) PWSCC at mini-sleeve joints, (2) distortion and residual stresses at joints resulting from axial restraint of original tube at tube support plates, (3) problems with brazing process controls, and (4) leakage at hydraulically expanded joints.

Stress Relief

In some cases, especially involving PWSCC susceptible material, it may be necessary to stress relieve freespan joints to reduce residual stresses to the level where they will not lead to PWSCC of the parent tube or sleeve. The stress relief procedure must be qualified by testing. Problems have occurred in the past with high temperature operations such as brazing and stress relief when the qualification test program did not accurately reproduce conditions in the steam generator. For example, temperatures measured at one location may not accurately reflect temperatures at other locations due to differences in thermal boundary conditions along the tube. Also, locking of the tube at tube support plates may lead to buckling and/or unacceptably high tensile residual stresses as a result of heating and cooling of the joint.

In most cases, it is not necessary to stress relieve tube sheet area joints since the original tube will be in a state of residual compression and the expanded portion of the sleeve will also be in a state of residual compression. Tensile residual stresses in the sleeve at the expansion transition can be kept low by proper selection of expansion method. If a stress relief is performed in the tube sheet region, several factors must be considered including: (1) reduction in pullout force due to shrinkage of the sleeve during cooling, (2) development of a small tube to tube sheet crevice, and (3) the effect of the stress relief temperatures on tube sheet material properties.

Qualification Tests

Past experience has demonstrated the need to carry out sleeving qualification tests which realistically simulate conditions to be encountered in the steam generators. Problems have occurred when the tests did not reasonably simulate key parameters such as tubes locked at tube support plates, sludge pile thermal conductivity, OD deposits, tube OD emissivity, full range of expansion parameters, tube sheet crevice thermal conditions and the presence of secondary side moisture.

Qualification tests of freespan and tube sheet joints should include: (1) tests of stainless steel specimens in boiling magnesium chloride or sensitized alloy 600 tubing in sodium tetrathionate to quickly confirm that residual stresses in the joints are low, (2) tests of alloy 600 tubes and sleeves in 10% sodium hydroxide at operating temperature, or in elevated temperature steam, to confirm preliminary results under more representative, but still accelerated conditions, (3) for plants with significant PWSCC susceptibility, tests in elevated temperature primary water to determine long term PWSCC performance under the most representative accelerated conditions, and (4) field installation of a small number of sleeves a year or so prior to installing large numbers of sleeves to verify installation methods and provide advance warning of rapidly occurring problems.

Installation

Sleeve installation involves a number of major steps including: (1) tube cleaning, (2) initial inspections, (3) sleeve insertion, (4) joint expansion, (5) joint sealing, (6) possible stress relief, and (7) final joint inspection. These operations are generally performed using remote manipulators to maximize efficiency and minimize radiation exposure. The reliability of installation equipment should be confirmed by testing prior to actual sleeving and the installation procedure should include contingencies to cover likely field problems. Particular attention must be directed towards qualification of the inspection procedure to ensure that it is capable of identifying flaws in the sleeve, joint and original tube behind the sleeve.

SLEEVE DESIGNS OFFERED

Steam generator sleeves are currently offered by a number of vendors. All currently offered sleeves are fabricated from thermally treated alloy 690 material. The sleeves are inserted into the original tube and joined to the original tube by joints above and below the degraded location. Freespan joints are made by first expanding the sleeve into contact with the original tube and then welding the sleeve to the original tube by TIG, laser, or kinetic welding. In the case of kinetic welding, the expansion and weld are performed simultaneously.

SLEEVING EXPERIENCE

Over 25,000 sleeves have been installed in PWR steam generators through the summer of 1989. There have been some problems, but the overall experience has generally been good. However, relatively few sleeves have been installed using some of the newer approaches and in plants with original tubing which is highly susceptible to PWSCC. Accordingly, attention should be directed towards ensuring that the proposed sleeve design has been properly qualified and an attempt should be made to install small numbers of trial sleeves prior to installing large numbers of sleeves.

DRAFT SLEEVING SPECIFICATION AND DESIGN REVIEW CHECKLIST

A draft sleeving specification and design review checklist are provided to assist in evaluating and procuring sleeving services.

Section 1

INTRODUCTION

Steam generator tubes in pressurized water reactors (PWR's) are subject to several types of degradation which have the potential to reduce steam generator operating life. Some types of degradation can be repaired by installing a sleeve inside the original tube to effectively bridge the degraded location (1,2,3,4). The purpose of this report is to discuss sleeve design requirements, describe NRC sleeving concerns, describe sleeve designs currently being offered by vendors, and summarize field experience with sleeving through the summer of 1989. Appendices contain a draft specification to aid in procuring sleeving services and a checklist which can be used in evaluating sleeving proposals.

Degradation which can occur in PWR steam generator tubes includes: denting, wastage, intergranular attack (IGA), intergranular stress corrosion cracking (IGSCC), erosion-corrosion, fatigue, fretting, wear, and pitting. Degradation can initiate from either inside or outside the tube. Corrective action must be taken if the degradation reaches the acceptance criterion established in a plant technical specification. This is typically a depth of 40% of the tube wall thickness. Corrective action can consist of plugging the tube or installing a sleeve inside the tube. Sleeving is an attractive solution since it permits degraded areas to be bridged structurally without having to take the tube out of service. This is particularly important for plants with a low tube plugging margin. Figure 1-1 shows typical locations and types of degradation within a PWR steam generator which have been repaired by sleeving.

In some cases where PWSCC has occurred, but the strength provided by a sleeve is not required, the inside surface of the tube can be electroplated with nickel to prevent primary water from entering the crack and leading to further PWSCC. This may prove a useful remedial measure for two cases: (1) for tubes which have a high susceptibility for PWSCC and shallow depth cracks which do not exceed the plugging depth criteria, and (2) for tubes with cracks which exceed the plugging depth criteria and for which a licensing position is developed which will permit operating with axial defects which exceed normal plugging depth limits. In the latter case the electroplating serves to prevent further cracking and stop leakage. The nickel plating approach is being developed and applied in Belgium (27,35,36). Nickel plating is not discussed further in this report.

Sleeving services are currently offered by a number of vendors. While each vendor has proprietary sleeve designs, all sleeves tend to have similar features. Figure 1-2 shows a typical sleeve installed in the tube sheet region of a recirculating type PWR steam generator. The sleeve consists of a smaller diameter tube which is inserted into the larger diameter original tube and then joined to the original tube by top and bottom joints. The sleeve prevents leakage past, and ensures structural integrity at, the degraded location.

In addition to repairing degraded tubes, sleeves have also been used to improve structural support and to provide vibration damping. While these applications are outside the scope of this report, the sleeving fundamentals covered in the report still apply. The emphasis in the report is on recirculating type steam generators rather than once-through generators since some recirculating type generators have exhibited the greatest degradation. However, most of the fundamentals covered in this report apply to once-through steam generators as well.

While sleeving is often an attractive solution for repair of degraded tubes, the sleeves must be resistant to degradation and the joints which attach the sleeves to the original tube must not create conditions which result in rapid degradation of the original tube at the joint. Therefore, sleeves must be carefully designed and installed if they are to achieve the objective of extending steam generator life.

Finally, this report emphasizes current sleeving technology. More complete coverage of sleeving concepts used prior to 1985 is included in a previous EPRI report (5).

The following acronyms are used in this report:

ABB - ASEA Brown Boveri
B - Braze
B&W - Babcock & Wilcox
BKWU - Bechtel/KWU
DR - Double roll
ECT - Eddy current testing
EE - Explosive expansion
EW - Explosive weld
HAZ - Heat affected zone (of weld)
HE - Hydraulic expansion
IGA - Intergranular attack

IGSCC	-	Intergranular stress corrosion cracking
LW	-	Laser weld
NRC	-	Nuclear Regulatory Commission
NYPA	-	New York Power Authority
OTSG	-	Once through steam generator
PF	-	Press fit
PWSCC	-	Primary water stress corrosion cracking
R	-	Roll
RG&E	-	Rochester Gas and Electric
SCC	-	Stress corrosion cracking
TIG	-	Tungsten inert gas welding
TS	-	Tube sheet
TSP	-	Tube support plate
TT	-	Thermally treated
UT	-	Ultrasonic testing
VT	-	Visual testing
W	-	Westinghouse

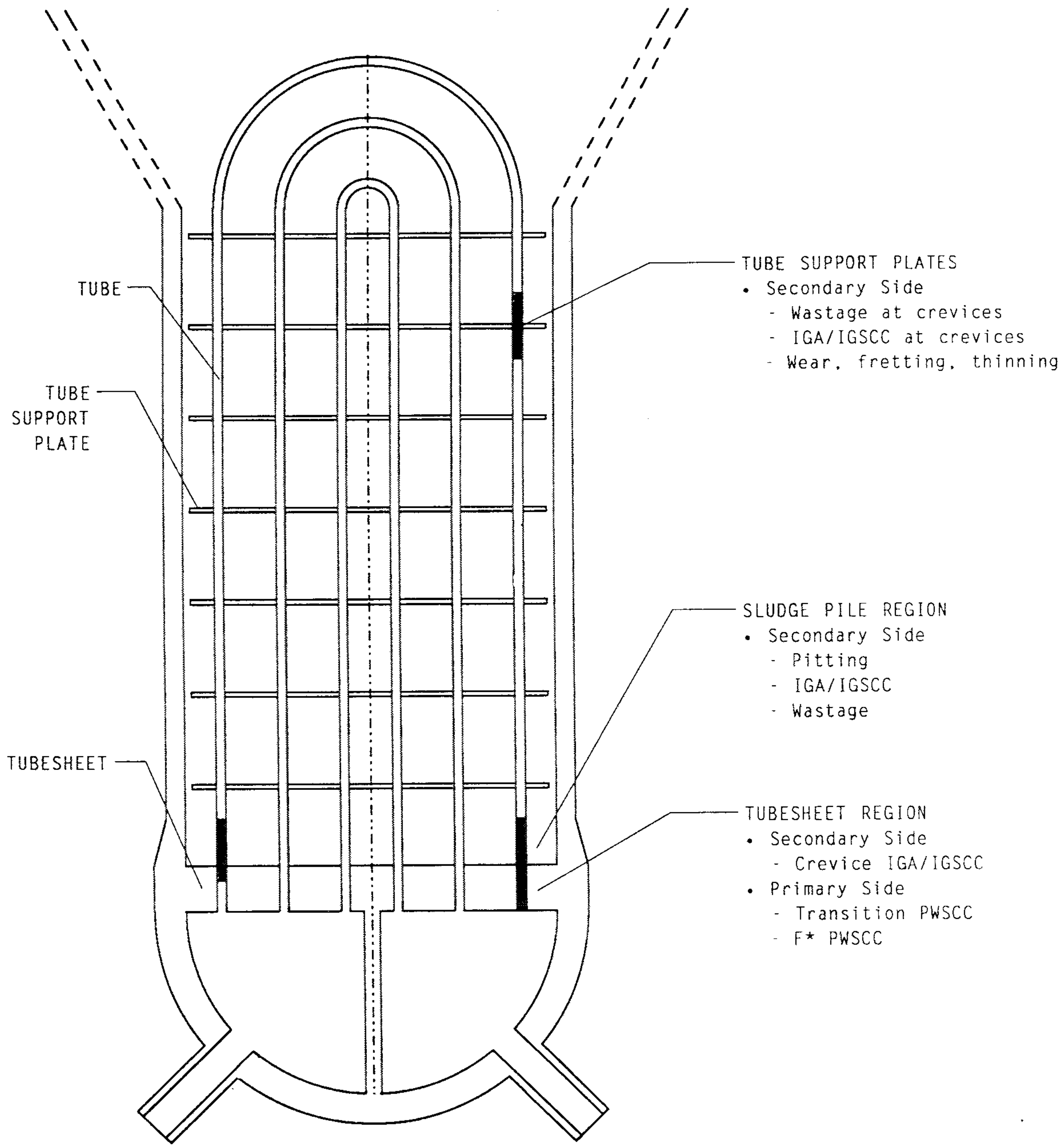


Figure 1-1. Typical Sleeve Locations in Recirculating Type PWR Steam Generators

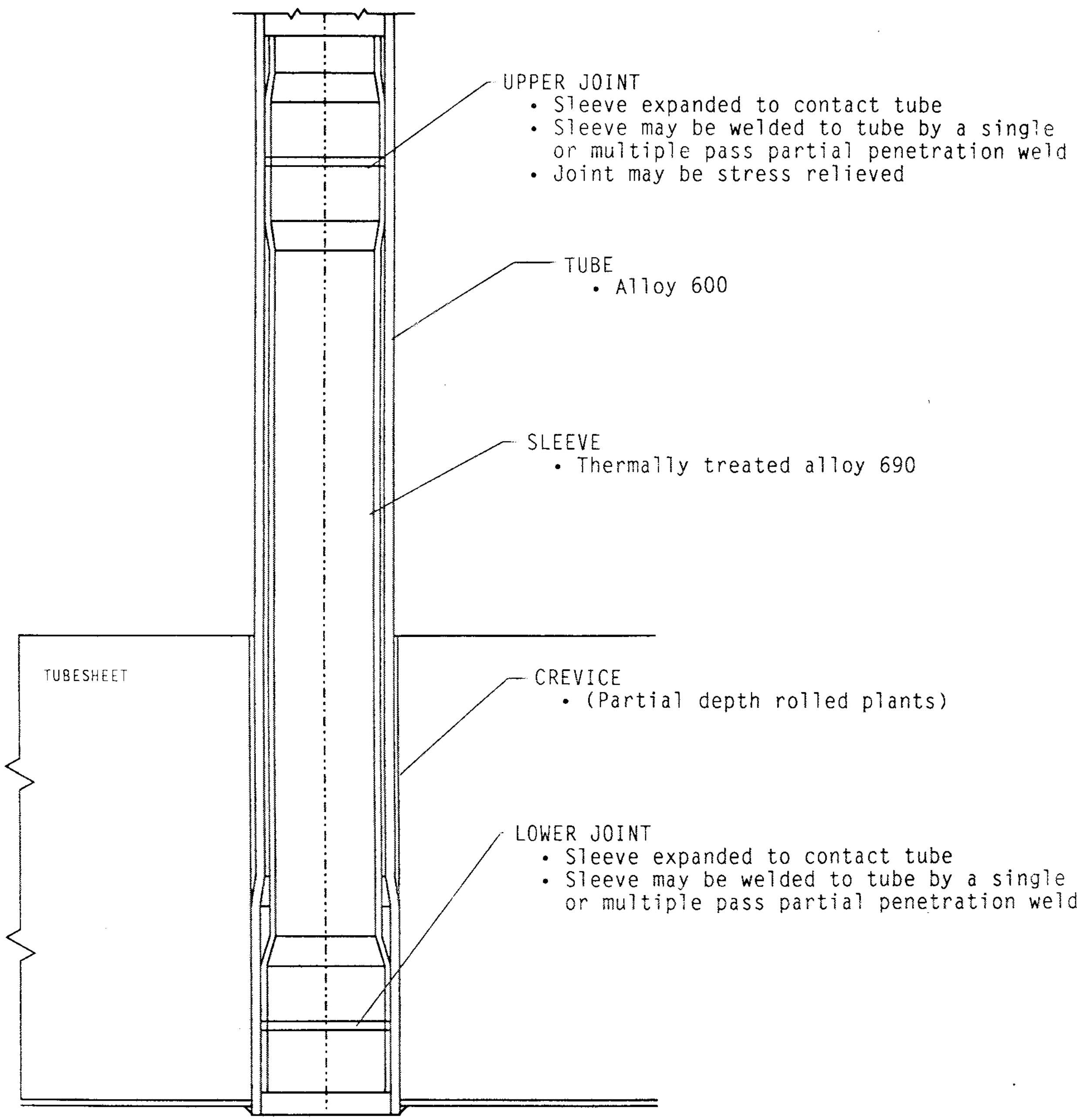


Figure 1-2. Typical Sleeve Configuration

Section 2

SUITABILITY FOR SLEEVING

As discussed in the following sections of this report, sleeves can be installed in most straight sections of steam generator tubing and sleeving services are currently being offered by a number of vendors. However, sleeving is not the only remedial measure which can be applied once damage has occurred. The other main remedial measures are to install plugs and to replace the steam generators. The generally accepted approach regarding these remedial measures is to: (1) install plugs if there is adequate plugging margin, (2) install sleeves when the plugging margin is approached but the rate and extent of degradation do not warrant replacement, and (3) replace the steam generators when the predicted life cycle cost, including current and projected sleeving costs, exceeds that for replacement.

It is not an intent of this report to present a model to predict when steam generators should be plugged, sleeved or replaced. However, the following factors should be considered in making such decisions.

Tube Plugging Margin

Tube plugging is typically much less expensive than sleeving. Therefore, for cases where there is a large tube plugging margin and a slow degradation rate, it is generally preferable to install removable plugs which can be replaced with sleeves at a later date if required. This is especially true if fully qualified sleeves are not available, or degradation might occur above the planned sleeving elevation.

If the number of plugged tubes approaches the plugging margin, then consideration should be given to increasing the plugging margin. In many cases the plugging margin can be increased by performing more detailed analyses. In addition, it is sometimes possible to increase the plugging margin by reducing conservatisms and allowances in other areas of the overall plant thermal-hydraulic design basis, e.g., in the core design.

Sleeving Qualification Status

Once sleeves have been installed in a steam generator it will be difficult to replace them with another sleeve design. Therefore, if a proposed sleeve has not been fully tested and otherwise qualified, it would be preferable to install removable plugs, and to replace the plugs with sleeves when it is certain that the sleeves will have the required life. The only exceptions should be when a few sleeves are installed for evaluation purposes, or when the plugging margin has been reached and the only available course of action is to install the best currently available sleeves.

Susceptibility of Original Tube to PWSCC

If the original tubing is at the high end of the PWSCC susceptibility range, it will be more difficult to install sleeves without creating conditions which might lead to PWSCC at the joints than in tubing which is at the low end of the PWSCC susceptibility range. For example, many sleeves were successfully installed in early steam generators which experienced secondary side IGA, pitting and wastage. However, the tubing in these plants is generally considered to have a low susceptibility to PWSCC. The main reasons for low susceptibility in these plants are thought to be a higher tube mill annealing temperature and a lower operating temperature. This does not imply that sleeves cannot be installed successfully in plants with PWSCC susceptible tubing, but that close attention must be paid to ensure that the sleeve and installation procedure will not lead to PWSCC at the sleeve joints.

Degradation Location

Most sleeves to date have been installed in the tube sheet region. Many vendors offer sleeves which extend from the bottom of the tube sheet to a point above the top of the sludge pile. Some vendors offer sleeves which can be installed at all tube sheet locations. Other vendors offer sleeves which can only be installed in the central portion of the tube sheet where there is a large enough clearance between the tube sheet and channel head for a rigid sleeve and installation tooling. However, this is not always a significant limitation since secondary side degradation is often most severe in the sludge pile region near the center of the tube bundle where tube sheet to channel head clearances are largest.

Fewer sleeves have been installed at tube support plate locations than at tube sheet locations, though they are being used on a large scale at three plants in Japan. It is generally more difficult to install sleeves at tube support plate locations since the work must be performed using longer tooling and the sleeve must pass through a longer length of tube prior to reaching the installation location. Geometric irregularities in the tube, including dented tube sheet or tube support plate intersections, complicate the insertion of sleeves higher up in the generator. Also, it would not be possible to install a sleeve at a higher elevation tube support plate if a sleeve has previously been installed at the tube sheet, or a lower elevation tube support plate. This leads to the practice being followed in Japan, where, if sleeves are installed at a lower tube support plate elevation, sleeves are also installed two to four support plates above the affected elevation.

Degradation Extent and Rate

As indicated in Table 6-1, the maximum number of sleeves at any single plant as of the summer of 1989 is about 7,000 at San Onofre 1. These were installed in 1980/81 to repair tube to tube sheet crevice IGA and installation required about 30 weeks. The largest number of sleeves installed at a single plant during recent outages is about 3,600 at Kewaunee in 1988/89. This installation required about 5 weeks total. Therefore, while installation methods have improved substantially since sleeving at San Onofre in 1980/81, large scale sleeving operations remain both time consuming and expensive, and require planning and commitment on both the part of the customer and the sleeving vendor.

At the limit, a plant with four steam generators, 4,600 tubes per steam generator and six tube support plates, could require over 250,000 sleeves to cover all potential hot and cold leg locations. Therefore, the decision to sleeve must include an assessment of the extent of degradation and predicted degradation rate.

Integrity of Original Tube at Joint Locations

Joints between the sleeve and original tube must be made at locations where the original tube is sound. This implies that sleeving will be practical for most cases where the degradation is concentrated in the tube sheet region or locally at tube support plate intersections. Sleeving would not be a suitable remedial measure for freespan joints where the degradation extends through the area where joints must be made. In the case of tube sheet area joints below the original expansion transition, it may be possible to make the lower joint on top of degraded tubing.

Section 3

DESIGN CONSIDERATIONS

Steam generator sleeving requires the successful integration of many factors including: sleeve configuration, sleeve material, joint design, qualification testing, installation procedures and production controls. Key considerations in these and other relevant areas are as follows.

DESIGN OBJECTIVES

Three primary design objectives for most sleeving applications are:

Strength

Sleeves are generally installed because damage to the inside or outside of the tube has resulted in the effective wall thickness being less than the minimum required thickness. In these cases, a prime design objective is for the sleeve to provide a structural bridge around the degraded tube section. This requires that the sleeve and top and bottom joints be capable of carrying the tube structural loads assuming that the original tube contributes no strength. This in turn requires that the top joints be made in sections of the original tube which are free of degradation. Exceptions to the requirement for sleeve strength are sleeves installed to prevent leakage at pits or to retard growth of small cracks, where it is known that the pits or cracks are sufficiently small and isolated to not affect structural integrity.

Corrosion Resistance

Sleeve material and joints must be resistant to the type of degradation which is being repaired. Further, the joints must not create a potential for new degradation mechanisms in the original tube. For example, residual stresses induced during sleeving could possibly lead to PWSCC of the original tube at the sleeve joint, even though PWSCC was not the reason for installing sleeves in the beginning.

Leak Tightness

Sleeve joints must have acceptable leak tightness. A leak tight seal can be obtained by means of brazing or welding freespan joints or hard rolling tube sheet area joints. An acceptably low leakage rate can be obtained from sleeves that have freespan joints which are hydraulically expanded and then hard rolled within the center of the expanded region. Without the support provided by the tube sheet, these joints result in low but controlled leakage of less than 0.001 gallons/hour (0.05 cc/min). Although this leakage may meet technical specification limits it has the potential for spreading contamination from the primary to secondary side and should be considered in the overall evaluation.

DIMENSIONS

Key sleeve dimensions are the length, outside diameter and wall thickness.

Sleeve Length

Figure 3-1 shows typical sleeve locations and illustrates the factors which affect sleeve length. As shown in this figure there are three general categories of sleeves which have differing length requirements: (1) tube sheet sleeves near the center of the steam generator tube bundle, (2) tube sheet sleeves near the tube sheet periphery, and (3) sleeves at tube support plate intersections.

General Sleeve Length Considerations. Three basic considerations apply to the length of all sleeves. First, there is limited clearance between the bottom of the tube sheet and the channel head which limits the length of rigid straight sleeves to 36-45 inches (0.9-1.1 meters) at the center of the steam generator tube bundle, depending upon tooling requirements, and 11-12 inches (0.28-0.30 meters) at the tube sheet outer periphery. However, as indicated later, curved sleeves are being offered which permit greater sleeve lengths at peripheral locations. Second, sleeve joints must be made in sections of original tubing which are free from degradation. Third, it is desirable to make sleeves which extend above the top joint far enough that, should a circumferential crack occur in the tube at the joint, there is a low probability of the tube disengaging the sleeve and impacting adjacent tubes.

Required Length for Tube Sheet Sleeves. The required length for sleeves in the tube sheet region is generally set by the location of the expansion transition and by the height of the sludge pile.

- Position of Expansion Transition - Two expansion transition locations are encountered in recirculating type PWR steam generators: a part depth expansion in which the expansion transition is located 2-4 inches (50-100 mm) above the bottom face of the tube sheet and a full depth expansion in which the expansion transition is located close to the top of the tube sheet. In order to simplify the lower joint, it is generally located below the expansion transition. For ease of installation, some vendors elect to make the lower joint at the bottom of the tube sheet regardless of the expansion transition elevation.

There has been some concern that deflections imposed on lower sleeve joints by tube sheet strains could affect sleeve reliability. These deflections will vary depending on elevation and location in the tube sheet. The joint should be analyzed for the worst case loadings which will be produced by deformations of the tube sheet.

- Depth of Sludge Pile - The top sleeve joint is generally located above the top of the sludge pile to provide protection against secondary side attack and to avoid problems with welding caused by the sludge thermal conductivity. Sludge pile depths are generally less than 6 inches (150 mm), but in extreme cases can exceed 18 inches (460 mm)(6). The sludge pile is typically deepest near the center of tube bundle and decreases near the tube lane and tube bundle periphery.

For example, with a typical tube sheet height of 22 inches (0.56 meters), and the top of the sleeve located 5 inches (127 mm) above the top of the sludge pile to allow for a joint, the minimum required sleeve lengths would be:

Sludge Pile Depth (in) (m)	Minimum Sleeve Length (in)(m)	
	Part Depth	Full Depth
0 (0.00)	27 (0.69)	10 (0.25)
6 (0.15)	33 (0.84)	16 (0.41)
12 (0.30)	39 (0.99)	22 (0.56)
18 (0.46)	45 (1.14)	28 (0.71)

Required Length for Tube Support Plate Sleeves. The minimum length of sleeves at tube support plates is 6-7 inches (150-180 mm). This provides for a 0.75 inch (19 mm) thick plate, one tube diameter on either side of the plate to stay away from crevice area degradation, and a 2 inch (50 mm) long joint at each end of the sleeve. However, it is desirable to increase these minimum lengths by about 4 inches (100 mm) to capture the tube within the sleeve and provide for backup joints in the event that the initial joint is defective. This leads to a desirable length of 10-11 inches (0.25-0.28 m).

Maximum Sleeve Lengths. As shown in Figure 3-1, the curvature of the lower channel head establishes the maximum permissible length of rigid sleeves. The maximum rigid straight sleeve length near the tube sheet centerline is 36-45 inches (0.91-1.14 m) depending upon tooling requirements, while the maximum rigid sleeve length near the tube sheet periphery is 11-12 inches (0.28-0.30 m). These clearances cover the minimum required sleeve lengths for all tube support plate locations and tube sheet sleeves located near the steam generator centerline, provided that the required equipment can be installed. However, the clearance is not adequate for long rigid sleeves at the tube sheet periphery. Accordingly, methods have been developed or proposed to install longer sleeves at the tube sheet periphery. Several such approaches are:

- Flexible Sleeves - The most frequently proposed approach is to start out with a curved sleeve with short straight sections at each end. The leading straight end of the sleeve is inserted in the tube, the sleeve is mechanically straightened as the curved portion is inserted into the tube, and then the trailing straight end of the sleeve is pushed into place. In this manner sleeves 60-80 inches (1.52-2.03 m) length can be installed in peripheral rows, yet the critical joints are made in straight runs of tubing. Qualification testing should demonstrate that tensile residual stresses produced during straightening are acceptable from the standpoint of resistance to PWSCC and to OD attack in the tube to sleeve crevice.

  Figure 3-2 shows the typical increase in coverage provided by use of flexible peripheral sleeves in a Westinghouse Model 51 steam generator with part depth roll expansion.

- Segmented Sleeves - Conceptually, a longer sleeve could be made by butt welding together several shorter lengths of rigid tubing as they are inserted into the tube. However, no vendor was offering this process at the time this report was written.

Sleeve Outside Diameter and Radial Clearance

The sleeve outside diameter is established by the original tube inside diameter and the radial clearance between the original tube and sleeve. The required radial clearance is a compromise between two conflicting objectives:

- It is desirable to make the radial clearance large to ensure that the sleeve can be inserted to the desired elevation without jamming or requiring supplemental installation steps such as reaming.

- It is desirable to make the radial clearance small to minimize the amount of expansion necessary in making the joints and thereby reduce the risk of SCC in the cold worked sleeve material.

Based on the above considerations, the radial clearance is held to the smallest amount which will allow the sleeves to be inserted into the tubes without interference. Some vendors report that the outside diameter and radial clearance are proprietary dimensions, but others have indicated that the nominal radial clearance ranges from 0.012-0.018 inches (0.30-0.46 mm)(9,10)

Sleeve Wall Thickness

In most cases, the sleeve is intended to restore the structural integrity of the degraded tube. Therefore, assuming that the damage penetrates the full thickness of the original tube, or can be anticipated to do so in the future, the sleeve must have a wall thickness similar to that of the tube which is being repaired. It is undesirable to increase the sleeve wall thickness beyond the minimum required since this increases the difficulty in making joints and reduces the flow area. Most vendors consider their sleeve wall thickness proprietary.

The required minimum sleeve wall thickness is often slightly less than the original tube wall thickness for several reasons: (1) since the sleeve fits inside the original tube it is smaller in diameter and therefore requires a smaller wall thickness to withstand the internal pressure, (2) the sleeve material may be stronger than the original tube material, (3) the minimum wall thickness at the sleeve location may be less than at other locations, and (4) the required wall thickness may be based on tube sheet rotations rather than applied loads such that the smaller sleeve diameter results in lower bending stresses.

MATERIALS

Three materials must be considered in a sleeving operation: (1) the sleeve material, (2) the original tube material, and (3) any other material introduced into the joints or produced by the joint fabrication process (e.g., braze materials, weld heat affected zone).

Original Tubing Material

The greatest concern regarding the original tubing material involves some recirculating type steam generators fabricated using mill annealed alloy 600 tubing. The chronology of fabrication and annealing conditions is described in reference 14 and can be summarized as follows:

Plant Vintage	Heat Treating Condition	Approximate Tube Mill Anneal Temperature
Pre 1970's	Mill Annealed	1,875°F (1,024°C)
Early 1970's	Mill Annealed	1,750°F (954°C)
Late 1970's	Thermally Treated*	1,825°F (996°C)

* followed by holding at 1,300°F (704°C) for about 15 hours

In general, tubing mill annealed at low temperature [about 1,750°F (954°C)] has been found more susceptible to primary side SCC than tubing mill annealed at higher temperature. To date, there have been no problems reported for domestic plants with thermally treated tubing. However, there have been recent cases in

France of PWSCC of hard rolled thermally treated tubing, and recent cases in the USA and elsewhere of PWSCC of thermally treated plugs. This points out the need to confirm that sleeve joints in such tubing do not result in residual tensile stresses high enough to cause PWSCC at the joints.

Sleeve Material

Most sleeves installed through the summer of 1983 were fabricated from mill annealed or thermally treated alloy 600 tubing. In some cases these sleeves were coated on the outside diameter with nickel or alloy 625 to improve corrosion resistance. Currently all vendors are proposing use of thermally treated alloy 690 which is generally considered to be resistant to PWSCC and to have improved resistance to IGA relative to mill annealed or thermally treated alloy 600 tubing. Background regarding this material and its processing parameters is discussed in the EPRI draft specification for alloy 690 steam generator tubing (15) and in EPRI alloy 690 workshops (33,34).

Additional Joint Materials

As discussed in the following section, sleeve joints involve expansion followed in most cases by hard rolling or welding. For the case of expanded or hard rolled joints, and joints welded without the addition of filler metal, no new materials are introduced into the joint. However, TIG and laser welding result in different material structure and heat treatment conditions in the HAZ than the sleeve or tube base materials. If brazed joints, or welded joints with the addition of filler metal, are proposed in the future, then it must be confirmed that the new conditions and additional materials will withstand the operating environment and are compatible with the base materials of the original tube and sleeve. Past problems with brazing materials are discussed in the next section.

JOINTS

Joints are required at the top and bottom ends of sleeves to provide structural integrity and leak tightness. Joints typically involve expansion of the smaller diameter sleeve into physical contact with the original tube and then possibly the application of a positive seal and/or structural joint between the sleeve and original tube. The following is a discussion of joint expansion methods, joint sealing methods, and several joint related problems which have been reported during testing, installation and operation. The following discussion covers joint expansion and sealing methods independent of the locations. It should be recognized that there is a significant difference between free span joints above the top of the tube sheet and joints made in expanded tubes within the tube sheet depth.

Expansion Methods

Sleeves must have a clearance fit within the original tube to permit insertion. Therefore, the first step in making the top and bottom joints is to expand the sleeve into contact with the tube wall. This is typically accomplished by mechanical rolling, hydraulic expansion, or explosive (kinetic) expansion. Current practice is generally to follow expansion by a sealing operation. The following expansion methods are typically used:

Roll Expansion. Mechanical rolling has been used to expand the sleeve into contact with the tube wall for bottom joints within the tube sheet depth. Since PWSCC has occurred at the tube sheet roll transitions of many plants, it must be confirmed that the roll expansion process, including any planned stress relief, used for the sleeve joints will not result in PWSCC in the sleeve or original tube. The use of thermally treated alloy 690 sleeves in lieu of the previously used mill annealed or thermally treated alloy 600 increases the sleeves resistance to PWSCC, even without stress relief. However, the original tubing is also subjected to some permanent strain during rolling, and it must be confirmed that the level of residual stress, including the effect of any planned stress relief, will not result in PWSCC of the original tubing at locations which could lead to failure.

Hydraulic Expansion. Hydraulic expansion provides a more gradual expansion transition and therefore should represent an improvement over roll expansion from the standpoint of PWSCC of the sleeve and original tube. Hydraulic expansion has been used frequently for tube sheet area and freespan joints. However, hydraulic expansion does not produce a leak tight seal between the original tube and sleeve and some supplemental sealing method such as a hard roll or welding is generally required.

Explosive Expansion. Explosive expansion is similar to hydraulic expansion in that it produces a more gradual expansion transition than rolling. In this process, an explosive charge is inserted into the tube at the elevation of the joint and detonated to expand the sleeve into contact with the original tube wall. Explosive expansion has been used frequently for tube sheet area and freespan joints. While the explosive expansion transitions are believed to be more gradual than roll expansion transitions, there have been occurrences of PWSCC in explosive expansions.

Sealing Methods

Once the sleeve has been expanded out to the tube wall, the joint is often sealed by hard rolling or welding. Several processes currently, or recently, used are:

Hard Rolling. Hard rolling has been used to produce a better seal between the sleeve and original tube for hydraulically expanded joints. The concerns with hard roll sealing are the same as previously discussed for roll expansion except that a smaller volume of material is subjected to high residual stresses. Because hard rolling results in high residual stresses, it has not been applied as a joint sealing method for freespan joints in PWSCC susceptible tubing material.

However, hard rolling can be used for sealing joints within the tube sheet depth. It is preferable to expand the lower joint first by an explosive or hydraulic process to achieve low stresses in the original tube and sleeve at the expansion transition region and then perform a hard roll to make a seal at some lower elevation. This approach should minimize residual stresses in the expansion transition region.

Brazing. Brazed joints are made by pre-placing brazing compound (typically a gold nickel alloy) on the outside of the sleeve, expanding the joint using hydraulic or explosive methods and then heating the sleeve by induction or electric resistance heating coils to a temperature of about 1,950°F (1,066°C). The high temperature causes the braze material to flow, which seals the joint. Brazing was used in the early 1980's for tube free span joints.

TIG Welding. Welded joints typically consist of a circumferential weld at the centerline of the expanded zone. However, there are cases where the weld is made at the end of the sleeve. The weld is typically made by the gas tungsten arc welding (GTAW) [frequently called the tungsten inert gas (TIG) process.] In this process, heat is generated between the workpiece and a non-consumable tungsten electrode. The electrode tip and workpiece are covered locally by an inert cover gas which prevents oxidation of the molten metal. In the case of TIG welding, the joint is produced by melting the sleeve and tube wall and does not require the addition of filler metal. It is claimed by one vendor that the use of computer controlled pulsed TIG is superior to the conventional TIG process in that the total weld heat input is reduced. This is claimed to reduce weld distortion and subsequently the level of residual stresses.

Laser Welding. Westinghouse recently installed 55 sleeves in the Doel 3 steam generators using a CO_2 laser welding process. Laser welding was selected for trial application at Doel 3 on the basis that it has three advantages over the TIG welding process: (1) less sensitivity to ambient conditions, (2) lower heat input which reduces concern on the secondary side, and (3) a higher production rate (27). Laser welding has also been demonstrated in Japan.

Kinetic Welding. Babcock & Wilcox has developed a freespan kinetic welding process based on their tube sheet kinetic welding process. A small explosive charge is loaded into a cartridge under controlled conditions and the cartridge is preassembled into the sleeve. The sleeve, containing the cartridge is then inserted into the tube and the charge detonated. The claimed advantages of this type of welding are: (1) the expansion step can be eliminated, (2) there is no heat affected zone, and (3) the field tooling is minimal and easy to install. As is the case with any process which deforms the original tube, kinetically expanded freespan joints in PWSCC susceptible material may require stress relief treatment.

Joint Problems

Sleeve expansion and sealing are special processes which depend upon qualification testing and strict process controls to ensure a long life. Potential problems in sleeved joints include:

PWSCC and Secondary Side SCC of Expansion Transitions and Joints. Joint expansion and sealing operations have the potential to induce tensile residual stresses in both the sleeve and original tubing. Therefore, it is important that tensile residual stresses in joint assemblies be kept below the threshold which will cause in PWSCC during service. Low stresses are also desirable to minimize the risk of SCC from the secondary side.

For example, short 1.75 inch (44 mm) long mini-sleeves were explosively expanded over cracked expansion transitions in the Doel 2 plant. It was hoped that the thermally treated alloy 600 sleeves would effectively bridge the cracked transitions in the original tubing and provide resistance to PWSCC. However, accelerated testing performed after installation of the first group of mini-sleeves, showed that high enough tensile residual stresses were induced to cause cracking of the original tube at the ends of the sleeves. An attempt was then made to perform an in-situ induction heating stress relief of the mini-sleeved joints. Again, accelerated testing performed after the field stress relief, showed that the stress relief was not fully effective in reducing residual tensile stresses below the threshold for PWSCC. The problem was traced to varying thermal conditions in the crevice between the original tube wall and tube sheet which resulted in an inadequate stress relief temperature being developed (16). Subsequent examinations showed the field joints to be cracked (36).

In summary, if either the original tube or sleeve material are susceptible to PWSCC, and the sleeving process induces sufficiently high tensile residual stresses, then the joint can crack during qualification testing, and may crack during service. Similarly, high tensile stresses may increase the risk of SCC from the secondary side. Accordingly, several precautions should be taken to prevent PWSCC and secondary side SCC: (1) the sleeve material must be resistant to PWSCC and other forms of SCC, (2) the installation procedure must consider all factors which could possibly lead to high tensile residual stresses, (3) the installation process must minimize tensile residual stresses, (4) accelerated testing must show that the sleeve design and installation process will result in joints which are resistant to PWSCC and secondary side SCC, and (5) process controls must ensure that actual installation conditions represented by conditions simulated during the qualification testing. Stress relief of freespan sleeve joints will probably be required if the sleeve is installed in PWSCC susceptible tubing.

Distortion Due to Axial Restraint at Tube Support Plate. Problems have been encountered with sleeve joints which involve heating of tubes which are effectively locked by denting at tube support plates, or possibly at the top of the tube sheet. The problem is that the tube tries to expand axially when heated by welding, brazing or stress relief. If the tube is prevented from expanding axially, axial compressive stresses developed in the tube during heating can lead to local yielding or buckling at the heated location, which has a lower yield strength than the rest of the tube. Two primary solutions have been developed for this situation: (1) tubes can be pre-tensioned such that axial compressive stresses are not produced during heating, and (2) heating processes can be designed and controlled to minimize both the temperature reached and length of the original tube heated, and thereby minimize the axial thermal expansion.

Brazing Problems. Several problems occurred during early brazing work at San Onofre and Ginna. These problems, their likely causes and their solution were as follows:

- Inadequate Heating. Difficulties were experienced in developing adequate bond in brazed joints at San Onofre. This problem was attributed to sludge which was present on the outside of the tubes at the brazed joint elevation. Apparently, the sludge increased heat transfer from the outside of the tube such that the temperatures reached during brazing were less than required. The solution was to improve the brazing process control. Where tubes had already been brazed, and the tube was of acceptable quality, a "hybrid expansion joint" was made below the poor quality brazed joints. Where tube quality was not acceptable, the tubes were plugged.

- Dissolution. Some brazed joints at San Onofre experienced dissolution of the sleeve and/or tube material due to attack by the brazing alloy (18). This apparently resulted from overheating produced by excessive brazing current. This problem necessitated reinspection of tubes, and plugging of some affected tubes. This type of problem can be prevented by improved process controls.

- Poor Bond due to Axial Restraint. Some brazed joints at Ginna were not adequately bonded. The problem was attributed to restraint of axial thermal expansion by the tubes being locked at the first tube support plate (19). The solution developed for this problem was to pre-tension locked up tubes by a proprietary process, such that axial compressive stresses were avoided during brazing operations. A proprietary pre-tensioning process was also used by Westinghouse for installing sleeves in 17 tubes at Ringhals 2 which were locked at the first tube support plate.

Leakage of Hydraulically Expanded Joints. Hydraulically expanded sleeve joints at Palisades had a small clearance between the tube and sleeve after expansion. This resulted in small primary to secondary leaks in tubes with through wall defects. If numerous tubes are sleeved, and if many of the tubes have through wall defects, then the total primary to secondary leakage from this type of joint may be excessive. One solution to this problem is to include a mechanically rolled zone centered within the hydraulically expanded area. This approach appears to reduce the leakage rate per sleeve from about 0.08 gph (5 cc/min) (20) to less than 0.001 gph (0.05 cc/min) (18).

Laser Weld Problems. Problems were encountered during initial installation of laser welded sleeves, with undulations in the surface of some welds. These undulations made it difficult to inspect the joints by ultrasonic methods (27). It has been reported that this problem was resolved by equipment adjustments although the delay in resolving the problem resulted in only 55 of the planned 200 tubes being sleeved (27).

Summary. The above problems point out that actual conditions encountered in a steam generator can differ significantly from conditions assumed for sleeve design and qualification testing. The best way to avoid problems of this type is to: (1) develop a good understanding of the conditions which exist in the steam generator, (2) carry out a sleeving qualification test program which simulates all conditions which will be encountered, and (3) try to carry out a demonstration sleeving program with a small number of sleeves prior to installing large numbers of sleeves.

STRESS RELIEF

One approach to reducing tensile residual stresses is to perform a stress relief heat treatment after expanding the tube and making the seal. Optimal stress relief conditions are about 1,300°F (704°C) for 3-5 minutes (14). Lo, Mayo and Weissmann have reported that 50% of the residual stress in alloy 600 material deformed to 0.3% of plastic stress is relieved after 3 minutes at 1,300°F (704°C) (32). Stress relief within a free section of tube can be accomplished using resistance or induction type heaters. Stress relief of single tubes within the tube sheet region has generally been considered as being too difficult to perform to be practical, and not essential with appropriate lower sleeve joint designs. In essence the lower joint is designed such that only the sleeve has tensile stresses. Therefore, if the sleeve is of a suitable material, and if the stresses in the sleeve are kept low, the risk of SCC is low. If the lower joint were to be stress relieved the stress relief would probably be performed by induction heating or global stress relief. In either case, the effect of the stress relief on tube and tube sheet material properties must be considered.

A number of factors should be considered in performing a stress relief, including:

Temperature Control. If a process is only effective over a narrow temperature range, and heat transfer conditions can vary, then it may not be sufficient to apply a constant heat input. If active temperature sensors are used to control the process, it must be confirmed that they produce accurate results. For example, fiber optics sensors have been demonstrated to be a practical method for measuring temperatures achieved by induction heating. However, experience at Doel 2 indicated that temperatures measured at one location may not accurately reflect temperatures developed at other locations due to variations in heat transfer properties in the gap between the tube and tube sheet (16). Accordingly, practical means must be developed and tested to provide accurate temperature control taking into account variations in geometry and thermal conductivity.

Surface Contamination. The potential for cracking or grain boundary attack due to surface contamination present during stress relief has not been fully resolved. Westinghouse has performed some tests with simulated secondary side sludge and these tests did not indicate a problem. However, some additional testing may still be required.

Buckling and/or Tensile Residual Stress due to Axial Restraint. If the tube is locked at the top of the tube sheet, or at the first TSP, by denting, there is a potential to develop local buckling and/or tensile residual stresses during brazing, welding or stress relief operations. For example, the tube expands during heating, buckles or yields due to the restraint at the top, and then is put into residual tension during subsequent cooldown. The potential for this to occur, and the effect on primary and secondary side IGSCC, must be resolved by test. Consideration must also be given to the subject of propagation of preexisting circumferential cracks, if any exist.

Effects of Stress Relief in Tube Sheet Area. In the event that stress relief is found to be necessary of joints in tube sheet areas, the following should be considered:

- Reduction in Pullout Force. When an expanded area is subjected to induction heating the resultant yielding and shrinkage upon cooling will result in some loss of the interference force holding the tube in the tube sheet. The effect of the loss of interference force must be evaluated on a case basis. Some guidance in this regard is included in Appendix A of Reference (22).

- Development of Tube to Tube Sheet Crevice. In addition to reducing pullout force, induction heating could cause a gap of a few mils to open up between the tube and tube sheet. This gap could be as long as 1/4 inch (6mm) or more, depending on the details of the induction coils. The acceptability of this gap from a secondary side corrosion standpoint needs to be verified.

- Effect of Stress Relief on Tube Sheet Metallurgy. If stress relief is performed of joints within the tube sheet depth, the effect of the stress relief temperature on the tube sheet material properties, such as fracture toughness, must be addressed.

QUALIFICATION TESTING

Qualification testing is generally required for all new sleeving designs and all significant modifications to previously tested designs in order to: (1) confirm that the installation method produces the required joint strength and leak tightness, (2) confirm that the joints have acceptable resistance to PWSCC, (3) assess the range of anticipated process variables, and (4) confirm that the proposed equipment and procedures will permit production schedules and radiation exposure objectives to be met. In the event that additional materials are introduced when installing the sleeves, such as at brazed joints, or welded joints using filler metal, qualification testing is required to confirm that the additional materials are compatible under all conditions.

Corrosion Tests

Accelerated corrosion testing is required to assess the effectiveness of candidate sleeving technologies. Corrosion testing is of particular importance for sleeves which are to be installed in PWSCC susceptible LTMA alloy 600 tubing. The main intent of such testing is to demonstrate that stresses in the sleeve assembly are low enough that the potential for PWSCC and secondary side SCC occurring are low.

There are two major concerns with accelerated corrosion testing. First, the accelerated tests may not accurately simulate real life degradation mechanisms. Second, the accelerated tests may not have the same stress threshold for cracking as the actual operating environment. Field experience implies that a practical stress threshold for PWSCC of susceptible LTMA alloy 600 tubing under actual operating conditions is about 40 ksi. This apparent stress threshold is close to the elastic limit for LTMA alloy 600 tubing and about 80% of the engineering yield strength (0.2% offset). This apparent stress threshold is consistent with test work reported by Yonezowa (41) which shows that the time to PWSCC for LTMA alloy 600 tubing increases greatly when the applied stresses are limited to 80% or less of the engineering yield strength. The stress thresholds for SCC in secondary side crevice/sludge pile environments are not well known but may be less then 1/2 yield stress.

Based on the apparent stress threshold of 40 ksi, accelerated corrosion tests used to evaluate sleeve designs for installation in LTMA alloy 600 tubing should also have a stress threshold of 40 ksi or less. Some of the accelerated test methods produce SCC with tensile stresses as low as 20% of yield strength.

Specimens which pass accelerated testing with very low stress thresholds should perform well in service, but cracking of specimens under accelerated testing with a very low stress threshold does not necessarily mean that tubes and/or sleeves will crack in service. In all cases, control specimens, such as stressed C-rings, should be included to permit residual stress levels to be determined. For the case of sleeving tubes with significant PWSCC susceptibility, roll expansion specimens should be included in the test matrix for correlation with field experience.

Consideration must also be given to the fact that stress relief processes have the potential to affect the sensitization of test specimens. Specifically, it may be determined that a thermal treatment reduced residual stresses to an acceptable level, when in fact, the thermal treatment changed the degree of sensitization such that cracking would not occur in the test environment.

Accelerated test methods currently used include:

Stainless Steel Tubes in Boiling Magnesium Chloride. A commonly used method to rapidly determine that a sleeving method results in low residual tensile stresses is to test stainless steel specimens in boiling magnesium chloride for about 24 hours. The threshold stress for SCC for this test can vary depending on factors such as the type of stainless steel or composition of the test environment. However, under typical conditions, specimens which have tensile stresses in excess of about 90 MPa (13 ksi) will fail by stress corrosion cracking in as little as 24 hours (23). If the tensile stresses are less than about 90 MPa (13 ksi), the specimens generally will not crack during the 24 hour period. Therefore, this is an effective test to quickly determine if residual tensile stresses in a particular sleeve design are low. One cautionary note is that occasionally, SCC does not occur as expected. In order to monitor for this possibility, samples with known stress should be included in the test matrix to verify that the stress vs time to failure behavior is as expected.

Polythionic Acid and Sodium Tetrathionate. Another commonly used, and rapid, method to assess residual tensile stresses is to test sensitized alloy 600 tubing in a reduced sulfur oxyanion containing environment such as polythionic acid or sodium tetrathionate at low temperature. If the specimens have tensile stresses in excess of about 55-70 MPa (8-10 ksi), they will fail by stress corrosion cracking in as little as 24 hours (23). If the tensile stresses are less than about 55-70 MPa (8-10 ksi), the specimens should not fail during the

24 hour period. This stress threshold is about 20% of the yield strength of mill annealed alloy 600 tubing.

Sodium tetrathionate testing may not be applicable for remedial measures involving high temperature processes such as welding or stress relief since the thermal processes could possibly desensitize the material. In this case it might be concluded that the remedial measure reduced the residual stress when in fact it may have desensitized the material such that it would not crack in the sodium tetrathionate solution.

10% Sodium Hydroxide. Sodium hydroxide concentrations of 10% or more can occur in steam generator secondary side crevices which are exposed to alternate wetting and drying conditions. Tests have shown this to be an aggressive environment which causes IGSCC similar to that observed for mill annealed alloy 600 in primary water at higher stress levels and over longer periods of time. An anodic electric potential may be applied in the laboratory to accelerate the rate of attack. The multiplier on life between test specimens in 10% sodium hydroxide at 288°C (550°F) with an applied potential of +190 mv, and primary water at a typical hot leg temperature of 324°C (615°F) is reported to be about 250 (24). Accordingly, a year of operation is simulated in about one and a half days under these conditions. The stress threshold below which cracking does not occur for this type of test is less than 20% of the room temperature yield strength of mill annealed alloy 600 tubing for test durations greater than about 700 hours (24).

10% Sodium Hydroxide at 660°F (349°C). This test environment has been used by several vendors to qualify sleeves and other remedial measures. It appears to provide results quite similar to the lower temperature applied potential procedure described above.

Elevated Temperature Steam Tests. Considerable testing over the past several years has demonstrated that PWSCC can be accelerated by performing tests at elevated temperatures. One approach is to test alloy 600 tubing in high temperature pure water with a hydrogen overpressure. Since water cannot be raised above 705°F (374°C), tests at higher temperatures can only be performed using steam. Accelerated steam testing is currently conducted at a temperature of 750°F (400°C) and the external pressure is adjusted to simulate the operating pressure differential across the tube wall. Based on an activation energy model, PWSCC under these conditions should be accelerated by a large factor relative to that at a typical 615°F (324°C) hot leg operating temperature.

Accurate predictions of the accelerating factor for steam tests cannot be defined due to chemical differences between steam and lithiated borated water with pH and hydrogen fugacity influences. Testing by EdF (25) has indicated that, while the elevated temperature steam tests show the correct ranking of susceptibility of materials to PWSCC, they may not provide accurate estimates of relative times to failure of materials or remedial measures. This was determined by testing reverse U-bends (higher stress) and flat U-bends (lower stress) of the same heats of material in 750°F (400°C) steam and 617°F (325°C) water. Results of the testing were as follows:

Test Conditions	Time to First Failure (hr)		Time to Failure Ratio
	Reverse U Bends	Flat U Bends	
400°C steam @ 1 bar H_2	100	>3,000	>30
325°C water @ 3 bar H_2	3,000 - 4,000	15,000	≈5

Several theories have been proposed to explain these results, but to date there is no generally accepted explanation.

Early attempts to identify a threshold stress in pure steam using C-rings has indicated a threshold stress greater than 57 ksi (38). However, subsequent testing, using steam doped with impurities, has indicated that lower stress thresholds can be achieved (39). Accordingly, it may be possible to use steam tests to verify that total stresses (residual, pressure, thermal and bending, etc.) are equal to or less than 40 ksi. The stress threshold and appropriate multipliers on time to failure in the steam environment should be verified using C-ring or other control standards.

Primary Water Tests at Elevated Temperature. The most representative accelerated test condition for PWSCC is primary water at a temperature moderately higher than the hot leg water temperature. The temperature typically used has been about 680°F (360°C). For non-stress relieved alloy 600 tubing under simulated operating conditions, the multiplier on life between the 615°F (324°C) hot leg condition and the 680°F (360°C) autoclave test conditions has been reported between 6 and 20 times (26,24). More recent work suggests that factors such as dissolved hydrogen activities and the chemistry of high temperature water operate to reduce their acceleration. The stress threshold below which no cracking has been reported for this type of test is about the same as for PWSCC under normal operating conditions.

Primary Water Tests at Operating Conditions. Ideally, it would be desirable to perform tests for effectiveness of a sleeve design, with regard to resistance to PWSCC, under simulated operating conditions using actual tubing which is known to be susceptible to PWSCC in a steam generator environment. These conditions would be primary water at a hot leg temperature of about 615°F (324°C), with a hydrogen overpressure, and with elevated pH. However, this type of test is not practical for screening or procedure development since actual plant operating experience has shown that it can take years for PWSCC to occur under these conditions.

Field Experience. Field experience is also not a practical method for screening potential sleeve designs or for procedure development since it may take years for PWSCC to occur, even with susceptible material. However, field experience provides valuable information regarding installation problems, and whether specific remedial measures have been effective to date. Also, some utilities install small numbers of sleeves to obtain practical experience prior to installing large numbers of sleeves of a single design.

Summary. The ideal sleeving corrosion testing would include the following phases:

- tests of stainless steel specimens in boiling magnesium chloride or sensitized alloy 600 specimens in sodium tetrathionate to confirm that residual stresses are low on both primary and secondary sides (including the crevice),
- tests under more representative accelerated conditions, such as mill annealed alloy 600 tubing in 10% sodium hydroxide or high temperature doped steam, to confirm that total operating stresses will be less than about 40 ksi,
- tests in elevated temperature primary water to determine long term performance, with respect to PWSCC, under most representative accelerated conditions, and
- field installation of a small number of sleeves a year or so prior to having to install large numbers of sleeves to verify installation methods and to provide advance indication of any unanticipated problems.

Control specimens should be included in all tests to confirm that tests results are as anticipated. In the case of accelerated testing of LTMA alloy 600 tubing in 10% sodium hydroxide or doped steam, the control specimens must support the conclusion that the total operating stresses in the joint including residual stresses, pressure stresses, thermal stresses, bending stresses, etc. will be below 40 ksi.

Qualification Test Program Issues

The main issues regarding sleeve qualification testing have been: (1) installing sleeves prior to completing testing, (2) not testing all features of the sleeve design, (3) not accurately simulating actual field conditions, and (4) not testing the full range of process variables. Accordingly, qualification testing should include:

- Simulated locking at top of tube sheet and tube support plates, unless it is determined that tubes are free at these locations
- Simulated range of tube sheet crevice deposit conditions (if applicable)
- Simulated sludge pile thermal conductivity & OD deposit conditions such as emissivity, or demonstrating that the process is unaffected by O.D. sludge
- Maximum and minimum allowed expansion
- Maximum and minimum temperatures

Laborelec Qualification Test Program

Laborelec has been involved for a number of years in the qualification testing and application of a number of different remedial measures for PWSCC as a result of cracking in the Doel and Tihange steam generators. The following is an outline of their upper sleeve joint qualification testing matrix as of August 1989 (37).

1) Visual Inspection - The inner and outer surfaces of sleeve specimens are examined visually. The outside surface is examined using a stereomicroscope and the inner surface is examined using an endoscope before cutting the tube open. These inspections cover the weld starting and stopping points. The inside surface of the tube is examined again with a stereomicroscope after cutting the tube open.

2) Dimensional Measurement - The inside and outside diameters of the specimen are measured as a function of length. The outside diameter is measured using a micrometer and the inside diameter is measured with a 3-point micrometer.

3) Leak Test - Leakage through the joint is checked using low pressure 100 psi (7 bar) freon gas. The gas is injected between the tube and sleeve on one side of the joint and detected between the tube and sleeve on the other side of the joint.

4) Residual Stress Measurement - Axial and circumferential residual stresses are measured using x-ray techniques on the outside surface of the tube as a function of tube length for several types of specimens: (1) specimens welded but not stress relieved, (2) specimens welded and stress relieved using the proposed production stress relief equipment, and (3) specimens stress relieved in a furnace. The purpose of the furnace stress relieved specimens is to compare the efficiency of an in-situ heat treatment to that which is performed using an internal probe. Some measurements are taken after electropolishing to eliminate surface interferences and some measurements are taken around the tube circumference to check homogeneity.

5) Metallographic Examination - Longitudinal cross-sections through the weld are examined with a scanning electron microscope (SEM). Several different etching methods are used: Marble etching, electrolytical etching in oxalic acid, and bromine-methanol etching.

6) Intergranular Sensitization Tests - Specimens subjected to metallographic examination are polished and then subjected to tests for intergranular sensitization. Three test methods are used:

   a. a modified Huey test involving immersion in boiling 65% HNO_3 for 7 to 24 hours,

   b. ASTM G-28, practice A involving immersion in boiling ferric sulfate - 50% H_2SO_4, and

   c. EPR (Electrochemical Potentiometric Reactivation) in a solution of 0.3 M H_2SO_4, 0.001 M KCNS at 30°C. The specimen potential, versus a calomel reference electrode, is screened in the following way:

      - stabilize the rest potential,
      - perform an anodic sweep at 1.4 mV/sec, + 0.4 V vs SCE,
      - maintain the specimen potential in the passivation range for 8 minutes at + 0.4 V vs. SCE,
      - cathodic sweep with 1.4 mV/sec.

7) Hardness Measurements - the hardness (Vickers, 2 kg load) is measured on the tube inside diameter at the expansion transition. The microhardness (Vickers, 100 gr load) is measured on cross-sections covering the weld and heat affected zone.

8) Tensile Tests - Tensile tests may be performed on strip specimens at ambient temperature.

9) Stress Corrosion Cracking Tests of As-Received Specimens - Stress corrosion cracking tests are performed in an autoclave with 10% NaOH at 660°F (350°C) without internal pressure and with 1,450-2,900 psi (100-200 bars) internal pressure. Specimens tested include: (1) upper joints without heat treatment, (2) upper joints with heat treatment, and (3) roll expanded joints of the mill annealed material without remedial measures.

   A purpose of the stress corrosion testing is to obtain a ranking of the mock ups prepared by different vendors, fabricated from the same mill annealed alloy 600 parent tube, and to compare this ranking to that for roll expansions which crack during service. Another purpose is to obtain better knowledge of the role of residual stresses and applied stresses in the cracking process.

ANALYTICAL VERIFICATION

New sleeve designs must be verified analytically as well as by qualification testing. The following main types of analyses are required:

Stress Analysis

A stress analysis must be performed in accordance with Section III Part B of the ASME Boiler and Pressure Vessel Code. The stress analysis includes pressure and thermal stresses and covers the full range of expected normal and abnormal conditions including postulated faulted conditions such as a main steam line break, feedwater line break, and loss of coolant accident. Primary and primary plus secondary stresses are calculated and compared to the code allowables, and the fatigue usage factor is calculated and shown to be less than 1.0. In some cases, designs have been subjected to fatigue tests if not amenable to accurate analysis.

Vibration Analysis

Analyses must be performed to confirm that the addition of sleeves will not cause vibration amplitudes or vibration induced stresses to exceed acceptable values.

Thermal/Hydraulic Analysis

Analyses must be performed to confirm that sleeves result in acceptable primary side flow and pressure drop. This analysis is often expressed as a sleeve-to-plug ratio. This allows rapid comparison of plant conditions to the allowable plugging limits.

Seismic Analysis

Consideration must be given to whether the installation of sleeves has an adverse effect on the seismic adequacy of the tubes. This includes verification that a sleeved tube, with no strength left in the degraded area of the parent tube, has satisfactory strength to resist postulated loadings.

Accident Analysis

Analyses must be performed to confirm that sleeves do not increase the possibility of double ended tube breaks under accident conditions such as feed line breaks, main steam line breaks, and LOCA's. This includes verifying that a sleeved tube, with no strength left in the degraded area of the parent tube, has satisfactory strength to resist accident loads.

INSTALLATION

Sleeve installation involves several major steps including: (1) tube cleaning, (2) initial inspections, (3) sleeve insertion, (4) joint expansion, (5) joint sealing, (6) possible stress relief, and (7) final joint inspection. These operations are most efficiently performed using a remote manipulator which minimizes the work which must be performed in the steam generator head and minimizes radiation exposure to personnel. Details of typical installation operations are covered in Section 5.

Vendors should have contingency plans to cover likely field problems. These contingency plans will be dependent upon the specific sleeving method being used and may include re-expansion at a different elevation, welding at a different elevation, or plugging. Installation of removable plugs should generally be included in the provisions since it will allow the tube to be repaired at a later date after the required corrective action has been qualified. Unqualified corrective actions should not be used in the field.

INSPECTION

Three types of inspections must be performed associated with sleeving: (1) inspections to establish that a tube is ready for sleeving, (2) inspections to verify satisfactory sleeve installation, and (3) periodic inservice inspections to verify that the sleeve/tube assembly remains satisfactory in service.

Required Inspections

Pre Sleeving Inspections. Inspections must be performed prior to sleeving to verify that: (1) the base tube is sound at the joint locations, (2) the inside diameter is as expected, (3) the tube is properly cleaned, (4) the sleeve is clean, (5) the sleeve has the correct length, diameter and wall thickness, and (6) the sleeve is positioned at the correct elevation (this may be controlled by tooling without a special inspection). The inspections, performed inside the steam generator, are normally carried out visually and by eddy current profilometry.

Post Sleeving Inspections. Additional inspections are required after sleeves are installed to: (1) confirm that joint expansion is dimensionally correct, (2) confirm that welds are of acceptable quality, and (3) serve as a baseline for examining the sleeve and tube for future degradation. Joint expansion is normally confirmed using eddy current profilometry. Weld quality is generally confirmed by visual inspection, eddy current and/or ultrasonic testing.

Inservice Inspections. Periodic inservice inspections similar to those required for the original steam generator tubes are required for sleeved tubes. These inspections are normally performed using eddy current methods. However, because the sleeves introduce changes in wall thickness and diameter, they reduce the eddy current sensitivity to some extent. Thus, testing is required to demonstrate that each sleeve design is compatible with eddy current examination requirements. Special calibration standards must be manufactured for each sleeve design used.

Baseline Examination

In-plant baseline eddy current data should be acquired for all sleeved tubes. This will provide a data base for comparison with subsequent inservice inspections. Some units with sleeved tubes have experienced problems with primary-side magnetite accumulating within the gap between sleeve and parent tube above the upper expansion. This has caused distorted signals in sleeved tubes which have been duplicated experimentally in the laboratory and verified destructively. The greater distortion of sleeved tube baseline eddy current is not necessarily cause for immediate concern with regards to tube integrity. However, service related sleeved tube signal distortion should be carefully monitored during subsequent inservice inspection and any changes resolved. Also, the reduced signal to noise ratio will modify the detectability for small volume cracks.

Typical Inspection Methods

As previously noted sleeving inspections include visual inspections, dimensional inspections and eddy current and ultrasonic nondestructive examination. The following are two illustrations of the EC and UT methods reported at the 1989 EPRI workshop on PWSCC remedial measures.

B&W has reported on results of qualification testing for eddy current examination of the sleeve and parent tube wall behind the sleeve (30). Figure 3-3 shows the locations to be inspected and the current rotating bobbin coil sensitivity claimed by B&W for the case of kinetic welds in recirculating steam generator tubing. At all locations B&W is reporting a sensitivity of 20% through wall defects.

Degreve and Dobbeni of Laborelec have reported on the ultrasonic examination of laser welded sleeves to determine the width and tightness of the freespan joint (28). Figure 3-4 shows a typical equipment arrangement for the inspection. A weld is determined to be good if there is no UT signal with an amplitude higher than a given threshold at the tube to sleeve interface.

Probe Type

Inspection areas of particular difficulty include the expansion area and the portion of the tube above the upper expansion which is shielded by the sleeve. The expansion areas represent regions within the sleeve where large extraneous signals are typically encountered by conventional eddy current bobbin coils due to end effects or changes in diameter. These signals can be significantly reduced using alternate test coils, such as cross-wound probes, or transmit/receive probes, which by design tend to suppress axisymmetric tube conditions. In general, these probes require careful quality control in their manufacture in order to achieve proper balancing. In addition, a non-uniform tube wall coverage is characteristic of their design. It is important that the coil circumferential coverage be verified prior to in-plant use to assure adequate inspection of the entire tube wall. Furthermore, their signal to noise ratio improvement may not be sufficient to satisfy the inspection requirements in all areas.

Bimetallic Sleeves

Bimetallic sleeve designs, which utilize nickel as the clad material for enhanced secondary side corrosion resistance, introduce additional inspection issues. Nickel is ferromagnetic and, accordingly decreases eddy current penetration within the parent tube wall. This effect can be countered somewhat by reducing the eddy current coil excitation frequency. Variation in the nickel cladding thickness and permeability introduces extraneous signals which reduce inspection capability as compared with a non-ferromagnetic clad material. This latter problem can be mitigated somewhat by using magnetic saturation techniques in conjunction with the eddy current inspection. The inspectability will be a function of the thickness of the nickel layer since the available probe dimensions may not allow for a high magnetic separation.

Inspection Procedure Confirmation

Subsequent to selecting a sleeve design, it is important to confirm that the proposed inservice inspection methods are capable of detecting defects in the sleeve and in the tube behind the sleeve. It is recommended that postulated failure modes of the sleeved tube be identified and that calibration samples be fabricated containing discontinuities of appropriate geometries, depths and locations with respect to extraneous test variables, e.g., tube end, expansion area, etc. The capability of the proposed inservice inspection method should then be demonstrated using these mockups. A degradation mode of particular concern is circumferential cracking in the tube above the top sleeve to tube weld.

Inspection Summary

There must be acceptable inspection sensitivity in the sleeve itself, in the joints, in the tube behind the sleeve, and at the end of the sleeve. The ability to detect 40% through wall defects in the area of the tube behind the sleeve has been considered to meet licensing requirements, and results reported at the 1989 PWSCC remedial measures workshop appear promising (30). However, the main concern is with circumferential defects in the weld HAZ in the tube above the top joint. Because such degradation may be shielded by the sleeve, may be circumferential, and may occur in transitions, the degradation may be difficult to detect.

The key factor in any qualification program is to ensure that the calibration specimens contain representative defects and that the inspection equipment and procedure can locate these defects reliably.

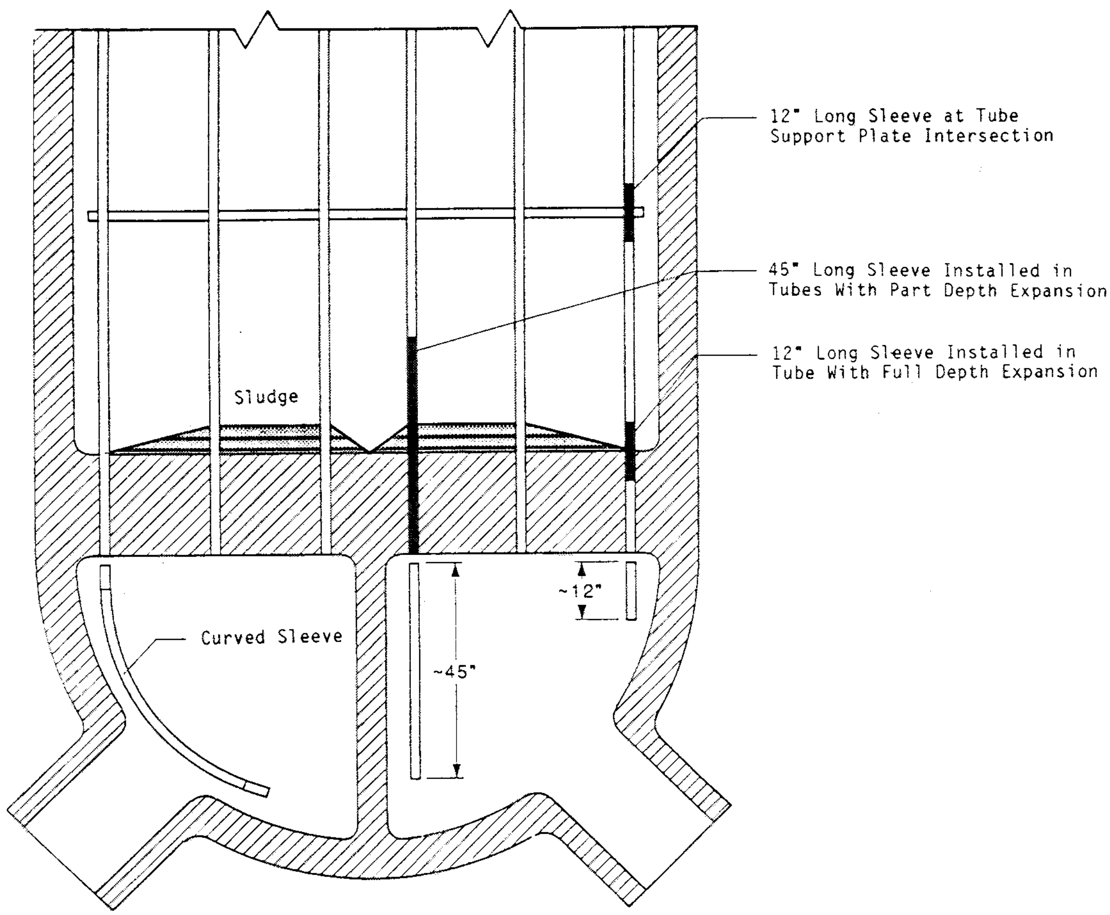


Figure 3-1. Required Sleeve Lengths as a Function of Location

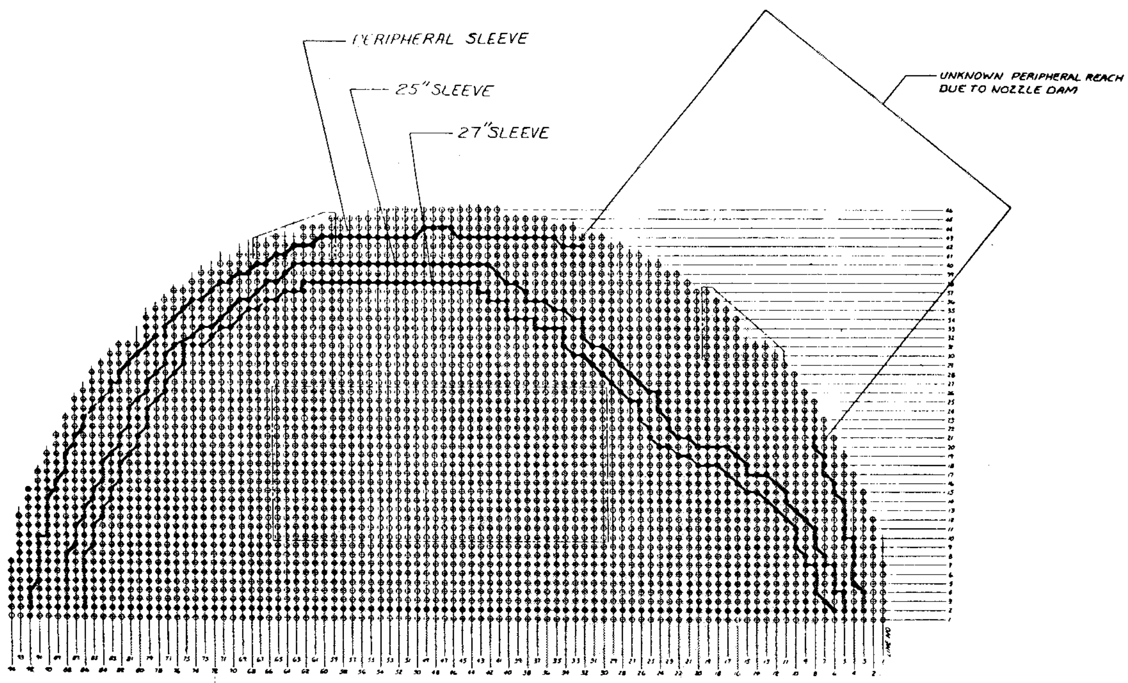
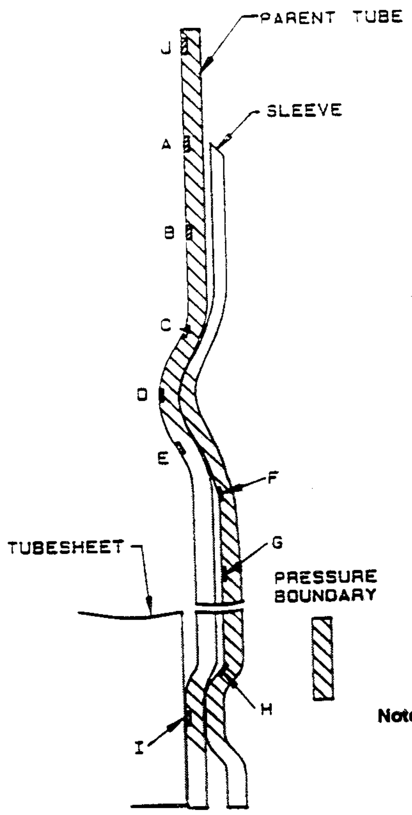


Figure 3-2. Additional Coverage Provided by Curved Periphery Sleeves for Westinghouse Model 51 Steam Generators (10)

B&W RSG KINETIC WELD SLEEVE N.D.E. CAPABILITY



FLAW	ROTATING BOBBIN DEMONSTRATED SENSITIVITY (% TWD)
A	20
B	20
C	20
D	20
E	20
F	20
G	20
H	20
I	20
J	20

Note: All flaws are 0.187-inch diameter flat-bottom holes

Figure 3-3. Inspection Locations and Bobbin Coil Sensitivity Reported by B&W (30)

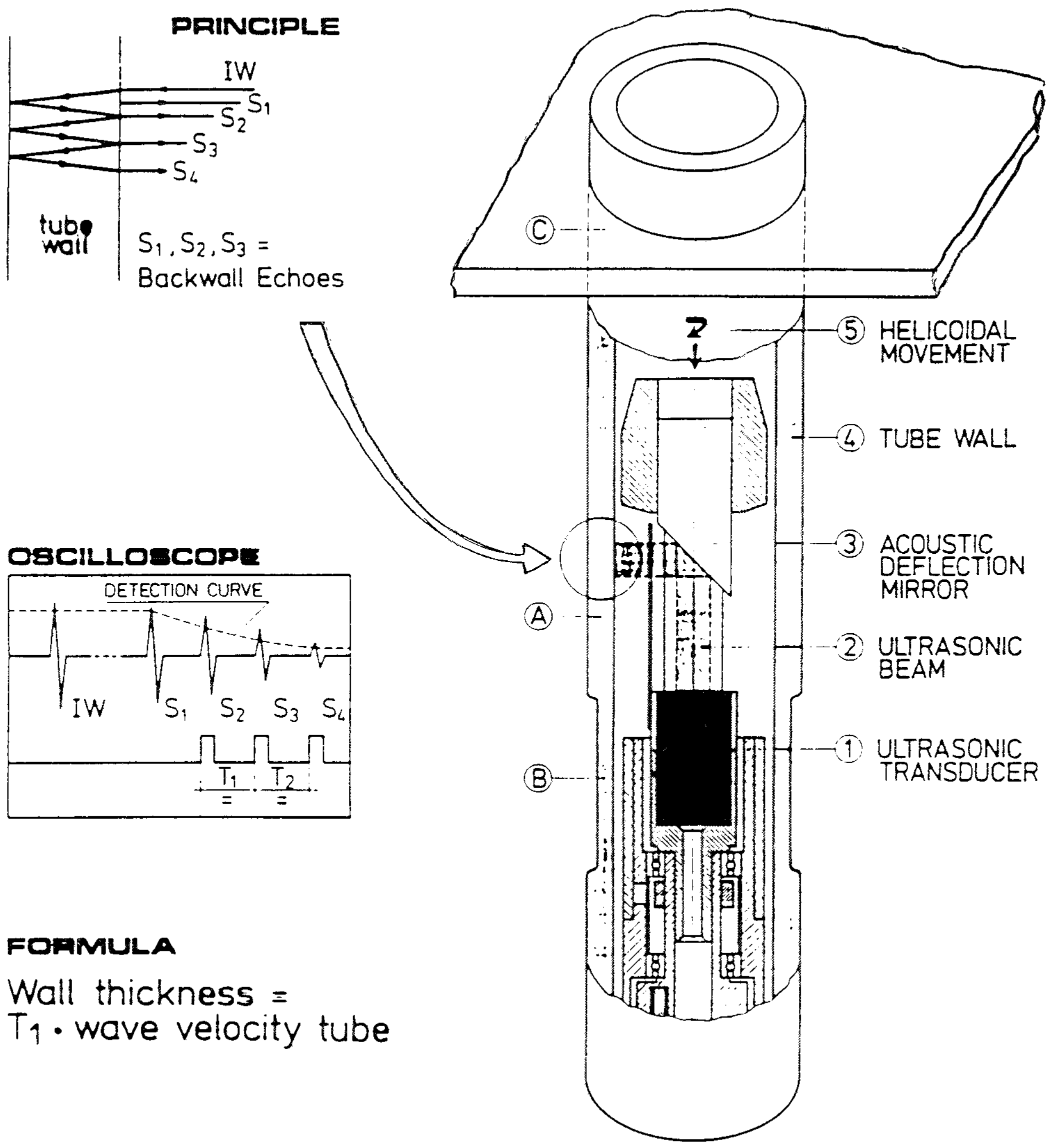


Figure 3-4. Typical Equipment for UT Inspection of Laser Welded Sleeves (28)

Section 4

LICENSING CONSIDERATIONS

Information on file in the NRC Public Documents Room indicates some areas of NRC concern in the form of questions from the NRC to utilities and the utility responses. The following summarizes NRC concerns regarding sleeving which are contained in Public Document Room records for the period 1980 through 1988. Note that this is intended as a list of NRC concerns as expressed in questions to utilities and not as a guide to preparing a sleeving licensing submittal.

NRC Safety Evaluation Report Contents

Some dockets contain NRC Safety Evaluation Reports for proposed sleeving operations. These Safety Evaluation Reports provide an indication of topics the NRC covers in their own evaluations. The topics contained in a typical NRC safety evaluation are listed below, and include most of the topics covered in Section 3 of this report [Dockets 50-266 and 50-301 for Point Beach Units 1 & 2].

- Plug Removal
- Sleeve Process Description
  - Sleeve Configuration
  - Post Sleeve Inspections
- Design Verification Analysis and Test
  - Mechanical Test Program
  - Analytical Verification
  - Thermal Analysis
  - Stress Analysis
  - Evaluation
  - Corrosion
- Braze Joint Integrity
  - Braze Metal Integrity
  - Base Metal Integrity at Braze
- Eddy Current Test Capabilities
- Preservice Hydrostatic Test
- Previous Sleeving Experience

ALARA Considerations

Flow Considerations

Accident Evaluation

Bending Strength of Degraded Sleeve vs Degraded Tube

Utilities have been requested to provide a comparison of the bending strength of a degraded sleeve vs a degraded tube [Docket 50-336 July 25, 1983 Millstone].

Effect of Sleeving on Tube Plugging Criteria

One effect of installing a sleeve in a tube is to increase the pressure drop and thereby decrease the flow rate through the steam generator. This can have an adverse effect on ECCS performance and must be considered [Docket 50-286 Dec 13, 1983 Indian Point 3].

Creation of Unreviewed Safety Questions per 10CFR50.59

The NRC has indicated that sleeving must not create unreviewed safety questions such as increased probability of accidents, accidents different from those already assessed, or reduced margin of safety [Docket 50-213, undated, Connecticut Yankee].

Eddy Current Testing Through Sleeve

The NRC has expressed concern regarding the capability of eddy current testing to insure detection of tube wall flaws through the sleeve. They have also requested that a utility confirm the sensitivity and accuracy of the eddy current testing system stated in their original licensing basis. [Docket 50-244 July 29, 1988 and September 7, 1988 Ginna].

Questions Pertaining to Straightened Peripheral Tubes

The NRC requested additional information from one of the first utilities considering installation of curved sleeves at the tube sheet periphery [Docket 50-244 September 7, 1988 Ginna]. Specific questions and comments included:

- What experimental techniques are used to determine the magnitude of residual stresses?
- What modifications were required to previously reviewed and approved tooling to work at periphery?
- What stress relief and thermal treatment conditions are to be used for alloy 690 sleeve material?
- Have the effects of multiple heat treatments (stress relief, welding, thermal treatment) been considered?

- Should additional corrosion testing be carried out to evaluate the effects of additional deformations and heat treatments?
- Additional corrosion tests should include the effect of faulted chemistry.

Effect of Secondary Side Chemistry on Sleeve Corrosion

The NRC has requested that utilities provide the results of corrosion tests including the case where defects in the parent tube allow secondary side chemistry to come in contact with the sleeve [Docket 50-286 January 11, 1983 Indian Point 3].

Solid, Liquid and Gaseous Waste Produced by Sleeving

The NRC has requested information concerning the solid, liquid and gaseous waste which would be produced by sleeving operations [Docket 50-244 January 31, 1983 Ginna].

Procedure for Sleeving Tubes "Locked" at Support Plates

The NRC requested that a utility submit information concerning the revised procedure to braze sleeve joints in "locked" tubes. Specific areas covered in the NRC Safety Evaluation included: (1) design verification testing, (2) upper joint strength testing, (3) analyses to demonstrate structural integrity, (4) fatigue, (5) faulted condition evaluation, (6) vibrational suitability, (7) plugging criteria for sleeved tubes, (8) corrosion testing, and (9) inspection [Docket 50-244 June 2, 1983 Ginna].

Additional Inspections if Sample Program Shows Problems

The NRC requested information regarding additional inspections which will be performed in the event that problems are detected in a 10% sampling program of braze quality [Dockets 50-266 and 50-301, undated, Point Beach 1 & 2].

Collective Occupational Dose Rate

Utilities have been asked to provide collective occupational dose rate information for sleeving operations including all site and contractor personnel and including such ancillary operations as steam generator channel head decontamination. The dose rate information is to include estimated dose rates, person-hours and person-rems [Docket 50-336 July 25, 1983 Millstone]. Further, dose rate estimates should include conservative estimates of contingencies [Docket 50-269 Oconee].

Training Program in Accordance With Regulatory Guides

Utilities have been requested to demonstrate that their sleeving training programs are in accordance with Reg Guides 8.13, 8.19 and 8.27 [Docket 50-336 July 25, 1983 Millstone].

Ventilation During Sleeving

Utilities have been requested to describe any special ventilation provisions in the steam generator repair area [Docket 50-336 Jul 25, 1983 Millstone].

Section 5

SLEEVE DESIGNS CURRENTLY OFFERED

Table 5-1 summarizes key parameters of sleeve designs currently being offered. Additional features of these designs are described below. Sleeve designs previously offered by Westinghouse, Babcock & Wilcox and Combustion Engineering are described in reference (5).

ASEA BROWN BOVERI

ASEA Brown Boveri (ABB) has developed two welded sleeve designs shown in Figure 5-1 (7). Both sleeves are made from thermally treated alloy 690 material conforming to the requirements of Section II, SB-163, Code Case N-379-1, of the ASME Boiler and Pressure Vessel Code. The top joints of both sleeves are TIG welded without filler metal. Bottom joints are welded at the middle of the expanded region (Design 1) or at the end of the tube (Design 2). While ABB points out that Design 1 does not disturb the original tube weld, and provides better inspectability of the new weld, they recommend that Design 2 be used, especially for tubes where plugs have been removed. In cases where the tube is flush with the bottom of the tube sheet, or the end of the tube must be milled off due to damage, the sleeve and tube are joined to the cladding by a single new weld. ABB sleeves are offered in lengths of 27.6, 31.5, and 35.4 inches (0.70, 0.80 and 0.90 m).

All sleeve installation operations are performed using remotely operated automatic equipment. ABB provided a significant amount of detail regarding sleeve installation and inspection. The major points made were as follows:

- Cleaning - Tubes are cleaned by honing, brushing with a stainless steel wire brush, brushing with a wool brush, and final swabbing.
- Inspections - The inside of original and sleeved tubes are inspected by a microchip video system which can be rotated 360° to cover the entire tube inside surface. Acceptance of welds is based on comparison with photographs of artificially created defects.

  Tubes are inspected by the eddy current process before and after sleeving. The inspection before sleeving is to determine tube wall degradation, dent size, secondary side deposits, etc. These inspections are performed using a multifrequency technique with standard bobbin coils. Inspection after sleeving is to establish a baseline for subsequent inservice inspections. These inspections are performed using special probes containing two sets of bobbin coils and two sets of crosswound coils with a 90° offset from each other. One set of bobbin coils is standard, and the other is optimized for inspection at low frequencies. The crosswound coils are less sensitive to concentric discontinuities and, therefore, are better able to distinguish defects in the roll expansion transition regions and in the tube behind the top of the sleeve.

Profilometry is performed to determine the tube inside diameter, tube ovality, position of skip rolls, and the size and position of dents before sleeving. Profilometry is also performed of sleeves before installation to determine the diameter at the expanded areas. The profilometer probe contains eight eddy current coils.

All welds which are determined to have anomalies during the visual inspection are inspected by ultrasonics. Also 10% of the sleeves are inspected ultrasonically if requested by the customer.

- Welding - Welding is performed to requirements of the ASME Code, Section XI, and welders are qualified to the ASME Code, Section IX. A preweld test is performed on simulated mockups prior to carrying out production welding. Key welding process variables are recorded during sleeving.

ABB has installed 558 welded sleeves at Kori 1. Based on stress evaluations of mockups, ABB considers that stress relief of their top joints is not required (31).

BABCOCK & WILCOX

Babcock & Wilcox is currently offering four sleeve designs (8). These designs cover: (1) the tube sheet region of recirculating type steam generators, (2) the tube support plate regions of recirculating steam generators, (3) the tube sheet and upper span of once-through steam generators, and (3) the tube support plate region of once-through steam generators. Features of these designs are:

Sleeves for Recirculating Type Steam Generators. Sleeves have been developed for the tube sheet region of steam generators with 3/4 inch (19.05 mm) diameter tubes and for the tube sheet and tube support plate regions for steam generators with 7/8 inch (22.23 mm) diameter tubes. The sleeves are fabricated from thermally treated alloy 690 conforming to the requirements of Section II, SB-163, and Code Case N-20 of the ASME Boiler and Pressure Vessel Code.

Tube sheet sleeves for 3/4 inch (19.05 mm) steam generator tubes have a 0.039 inch (0.99 mm) minimum wall thickness to withstand the design loadings and to provide some margin for defect depth in the sleeve. Sleeves come in two lengths 11 inches (0.28 m) and 17.5 inches (0.44 m). Both lengths are intended to be installed in tubes with full depth expansions. The 11 inch (0.28 m) length may be installed in any tube in the steam generator and spans the roll transition region located near the secondary face of the tube sheet. The 17.5 inch (0.44

m) long sleeve may be installed in 97% of the tubes and can also span the flow distribution baffle, which exists in some steam generators.

Sleeves for 7/8 inch (22.23 mm) steam generator tubes have a 0.050 inch (1.27 mm) minimum wall thickness. Tube sheet sleeves come in two lengths. An 11 inch (0.28 m) long sleeve can sleeve 100% of the tubes which are full depth expanded. A 29 inch (0.74 m) long sleeve extends from the primary face and can sleeve 75% of the tubes which are partial depth expanded. In addition an 11 inch (0.28 m) long sleeve is available to span tube support plate elevations. This support plate sleeve may be installed at all support plate locations except the uppermost support.

Sleeves for recirculating steam generators are welded to the original tube in the freespan using a proprietary kinetic welding process involving a cartridge with a controlled explosive charge. Babcock & Wilcox reports that kinetic welds meet structural requirements and produce a sealed joint. The joints have also been qualified as an expansion without a weld. This precludes the need to inspect to establish a minimum weld length. Freespan joints are stress relieved to reduce residual stresses. A mechanical seal for the lower joint is produced by a torque controlled rolling process. Optionally, a kinetically welded lower joint may also be used.

Prior to sleeving, bobbin coil eddy current inspection results are reviewed to ensure the freespan joint area is defect free and that the tubes do not have any dents which would restrict sleeve insertion. Tubes are cleaned in the region of the weld by a honing process prior to inserting and welding the sleeve. An eddy current inspection is performed following sleeve installation to confirm proper expansion of the freespan joint and to provide a baseline for future in service inspections. Babcock & Wilcox reports that a proprietary inspection process has been developed to detect a 20% ASME flat bottom hole at any position on the tube behind the sleeve (30,31). Joints not meeting post installation checks are individually evaluated for corrective measures.

Sleeves for Once-Through Steam Generators. Sleeves for once-through steam generators are made from thermally treated alloy 600 material conforming to the requirements of Section II, SB-163 of ASME Boiler and Pressure Vessel Code. The sleeves have a 0.045 inch (1.14 mm) minimum wall thickness to withstand the design loadings and to provide some margin for defect depth in the sleeve. The sleeves are of two lengths. An 80 inch (2.03 m) long sleeve spans from the upper tube sheet through the upper (15th) tube support plate. This sleeve is curved to fit in the upper plenum and is straightened as it is inserted. The tube support plate sleeve is about 15 inches (0.38) long and tooling is currently available to install these sleeves down to the 14th tube support plate.

Sleeves for once-through steam generators are expanded into the original tubes and tube sheet by mechanical rolling. The rolling is a controlled process to meet structural and corrosion requirements. Leakage at the freespan joints is controlled within a design limit of 2.5 ml/hr by making a second rolled joint at an elevation different than the first joint.

Preparations for sleeving include flaring the tube end to ease sleeve installation, and performing a bobbin coil eddy current inspection to confirm the tube diameter and to ensure that there are no defects in the intended region for the freespan joint. An eddy current inspection is performed following sleeve installation to confirm proper expansion of the freespan joint and to provide a baseline for future inservice inspections. Repair of sleeved joints is currently limited to rerolling to meet expansion requirements.

Long sleeves have been installed at Rancho Seco, Arkansas Nuclear One, Oconee 1, and Oconee 3. Support plate sleeves have been installed at Oconee 1. Development effort is centered on reducing the length of the support plate sleeve to permit installation in all tubes and developing tooling to install the support plate sleeves at all tube support plate elevations.

BECHTEL/KWU

Figure 5-3 shows the welded sleeve design offered by Bechtel/KWU Alliance (9). The sleeve shown is 39.37 inches (1.00 m) long, but the length can be adjusted to suit the plants corrosion conditions and channel head clearance. The sleeve is fabricated from thermally treated alloy 690 and has a nominal radial clearance between the tube and sleeve of 0.013 inches (0.33 mm). The top joint is expanded using a hydraulic process with the expansion controlled to minimize plastic deformation of the parent tube. After expansion, the upper joint is TIG welded in the center of the expanded area. The vendor reports that tensile residual stresses at the upper joint have been shown by laboratory tests to be less than 0.75 x Sy of the tube material. Nevertheless, the joint is stress relieved, utilizing radiant heaters, to enhance the resistance to PWSCC.

After the upper joint is completed, the bottom of the sleeve is hydraulically expanded into the tube sheet, the bottom of the sleeve and parent tube are milled off flush with the bottom of the tube sheet, and a new weld is made covering the sleeve, tube and tube sheet cladding. This bottom weld is designed to minimize leakage.

Prior to sleeving, the inside diameter of the parent tube is cleaned with a rotary wire brush. The material removed is captured by a vacuum.

The upper weld is inspected by UT and VT. The lower weld is inspected by VT. Finally, a preservice eddy current inspection is performed to establish an inspection baseline.

Bechtel/KWU Alliance reports that corrosion tests have been performed on the latest sleeve design and that tests are continuing of as-welded and stress relieved specimens in a 752°F (400°C) steam/hydrogen environment. A mockup also has been used to confirm the reliability of production equipment and procedures.

Bechtel/KWU Alliance has two other sleeve designs available, a Type II and Type III sleeve, for plants that have full depth expansion. The Type II sleeve is expanded and welded to the tube in the tube sheet area below the degraded region. Shorter versions of this sleeve are available to bridge support plates where tube damage is occurring in the support plate crevice region. These short sleeves can be installed in all locations except the top support plate. The Type III sleeve is similar to the Type II sleeve except it is hard rolled in the tube sheet region instead of being welded.

COMBUSTION ENGINEERING

Combustion Engineering offers a welded sleeve design shown in Figure 5-4 (10). These sleeves are thermally treated alloy 690 material and range from 25-36 inches (0.64-0.91 m) in length. The sleeve is designed to have a nominal 0.012 inch (0.30 mm) radial clearance. The top joint is expanded hydraulically using a bladder to keep the inside surface of the sleeve dry and then seal welded using the TIG process without filler metal. The bottom of the sleeve has a taper which results in an interference fit when the sleeve is pushed into place. Therefore, the bottom of the sleeve is not expanded. A TIG process without filler metal is used to fuse the bottom of the sleeve to the bottom of the original tube.

Combustion Engineering testing has shown that residual stresses in the parent tube, resulting from the upper weld joint, are less than experienced in tube sheet roll transitions. Therefore, Combustion Engineering considers that the as-welded sleeve joint should have better resistance to PWSCC than a roll transition. Nevertheless, welds are stress relieved for plants with tubing susceptible to PWSCC, or when otherwise requested by the utility.

Tubes are cleaned with a rotating wire brush and dry swabs prior to installing sleeves. After installation, the upper weld joint is inspected ultrasonically and the lower weld joint is inspected visually. Finally, an eddy current inspection is performed to establish a baseline for future inservice inspections. The eddy current inspection is performed using a four segment bobbin probe which has proven more sensitive to behind-the-sleeve degradation in the parent tube than the cross wound probe.

As of the summer of 1989, Combustion Engineering had installed a total of 2,119 welded sleeves at Ringhals 2, Ginna, Zion 1, and Prairie Island 1. 109 of these were welded flexible sleeves installed at Ginna. These curved sleeves were straightened during installation to permit sleeving of 90% of all tubes rather than the 60-65% limit with rigid sleeves (<u>Note</u>: Ginna has part depth roll expansion so short ~12 inch (~0.30 m)sleeves cannot reach from the expansion transition to the top of the tube sheet as shown in Figure 3-1.)

Combustion Engineering reports that the combination of thermally treated alloy 690 sleeve material, stress relief of the sleeve after fabrication (curving), proprietary straightening tools which control straightening stresses, and strict process controls keep susceptibility to stress corrosion cracking to a minimum.

FRAMATOME

Framatome has developed three welded sleeve designs shown in Figure 5-5 (<u>11</u>). All three sleeves are thermally treated alloy 690 which is expanded into the original tube at top and bottom joints by rolling. The top joints are all TIG welded without filler metal. Bottom joints on short sleeves, which do not extend to the bottom of the tube sheet, are TIG welded. Bottom joints on long sleeves, which extend to the bottom of the tube sheet, are either left in the expanded condition or TIG welded. The top welded joints are stress relieved after welding to reduce residual stresses. It is reported that the sleeves can be installed in 90% of the tubes in a recirculating type steam generator and that installation is carried out using automated equipment. Sleeve installations are subjected to visual inspection using television and 100% ultrasonic inspection of the weld joint.

Framatome reported that a total of 22 sleeves have been installed at Tricastin 2 for qualification purposes. Ten sleeves were of the short design, and twelve sleeves were of the long design. Two short sleeves were removed for examination and Framatome reports that the welded joints were within the acceptance criteria.

STEIN INDUSTRIE

Stein Industrie is developing a TIG welded sleeve design in cooperation with Electricity de France (12). The alloy 690 sleeves are intended for use in 3/4 inch (19.05 mm) diameter tubes. It is reported that the sleeves can be installed in 90% of the tubes in a recirculating type steam generator and that the top and bottom joints will be made by a TIG process without the addition of filler metal. Sleeves will be installed by automatic equipment. Sleeve installations will be subjected to 100% inspection by profilometry, visual examination, ultrasonic examination and eddy current examination.

Stein Industrie reports that they plan to qualify the procedure on a full scale mockup during the first half of 1989 and install sleeves in a power plant during the second half of 1989.

WESTINGHOUSE

Westinghouse currently offers hybrid expansion sleeves for use on tubes with low PWSCC susceptibility and laser welded sleeves for use on tubes with high PWSCC susceptibility. Figure 5-6 shows a sleeve with hybrid expansion joints consisting of hydraulic expansion at the top and bottom joints followed by hard rolling to achieve low leakage rates. Over 23,000 sleeves of this design have been installed.

Figure 5-7 shows a metallographic cross section through a freespan laser welded joint. This process was used to install 55 sleeves at Doel 3 during the 1988 refueling outage. Installation of the 55 sleeves involved a total of 109 laser welds. The laser welding process was selected for use at Doel 3 on the basis that it appeared to offer the following advantages: (1) a reduced sensitivity to ambient conditions, (2) reduced effect on the secondary side, and (3) a higher production rate. According to the utility, qualification tests were conducted to determine that neither humidity nor oxide had any influence on the weld characteristics of: penetration, weld structure (porosity), dimensions of the heat affected zone, or residual stress. A particular point made was that the sensitized zone of material does not penetrate through the original tube parent material. The laser weld installation process is reported to involve the following steps: cleaning of tube, insertion of the sleeve, expansion at top and bottom joints, upper laser weld, lower laser weld, thermal heat treatment of the upper weld, ultrasonic examination of the upper weld and endoscopic examination of the upper and lower welds. As indicated in Section 3 some problems were encountered during installation of the laser welded sleeves at Doel 3 although it is reported that the problems were resolved.

Table 5-1

SUMMARY OF CURRENTLY OFFERED SLEEVE DESIGNS

Vendor / Parameter	ASEA Brown Boveri	Babcock & Wilcox	Bechtel/KWU Alliance	Combustion Engineering	Framatome	Stein Industrie	Westinghouse Hybrid Joint Sleeve	Westinghouse Laser Welded Sleeve
Sleeve Length (in)	27.6-35.4	11-29	7-39.4	25-36	??	??	27-44	27-44
Peripheral Sleeve Process	No	Yes	No	Yes	No	No	No	No
Sleeve Material	TT 690	TT 690	TT 690	TT 690	TT 690	TT 690	TT 690	TT-690
Freespan Joints	Hydraulic expandsion + TIG weld	Kinetic Weld	Roll or hyd. expansion TIG weld	Hydraulic expansion + TIG weld	Roll + TIG weld	TIG welded	Hydraulic expansion + hard roll	Hydraulic expansion + laser weld
Tubesheet Joints	Hydraulic expansion + TIG weld	Roll+ optional kinetic weld	Hydraulic expansion + TIG weld	Press fit + TIG weld	Roll + optional TIG weld	TIG welded	Hydraulic expansion + hard roll	Hydraulic expansion + hard roll (laser weld optional)
Joint Stress Relief	No	Yes at freespan joints	Yes at freespan joints	Yes at free span joints or in suscep-tible mat'l	Yes at freespan joints	??	No	Yes
Process Inspections	Visual, profilometry, eddy current, 10% UT	Eddy current UT available but not required	VT and/or UT top joint, VT lower joint	UT top joint, VT lower joint	Visual + 100% UT of welds	Visual, profilometry, 100% UT	100% eddy current	Visual 100% UT eddy current
Sleeving Experience Thru Summer 89	~800 sleeves installed at 4 plants	~2,400 sleeves installed at 10 plants	18 Sleeves in 2 plants	~2,200sleeves at 5 plants	??	No sleeves installed	>23,000 sleeves installed at 9 plants	>23,000 total sleeves installed at 9 plants
Status of Current Design	558 welded sleeves installed at Kori 1	No welded freespan sleeves. ~1000 with tube sheet weld.	18 Sleeves in 2 plants	2,119 welded sleeves installed at 4 plants	22 welded sleeves installed at Tricastin	Qualification planned first half of 1989	> 16,000 hybrid expansion sleeves installed at 5 plants	55 laser welded sleeves installed at Doel 3

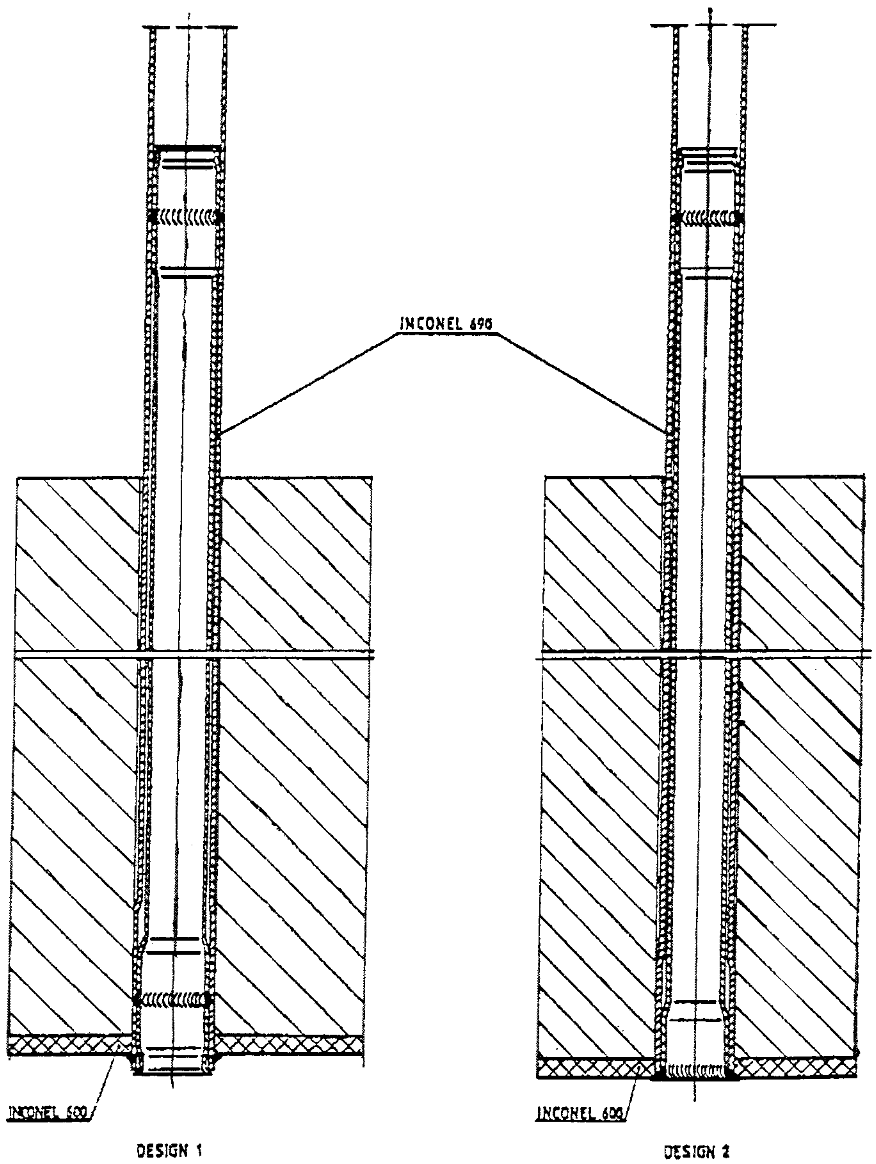


Figure 5-1. ASEA Brown Boveri Welded Sleeves

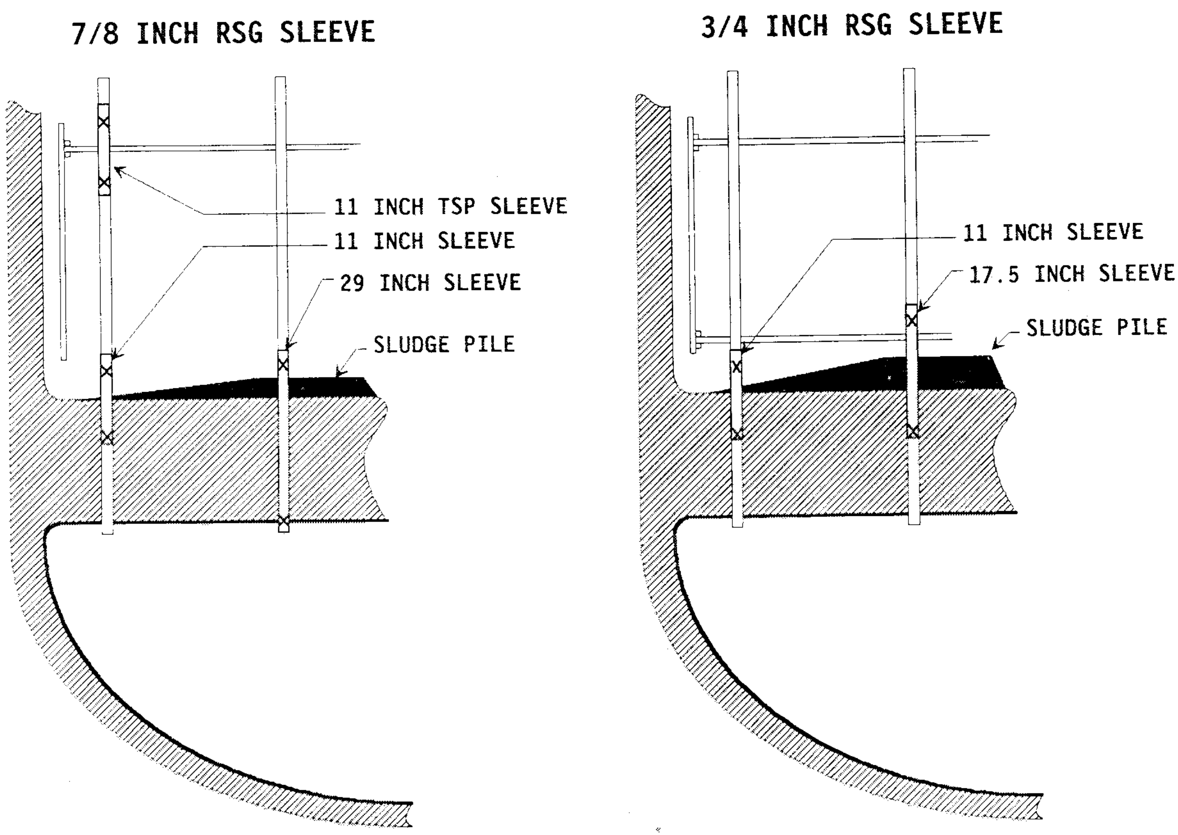
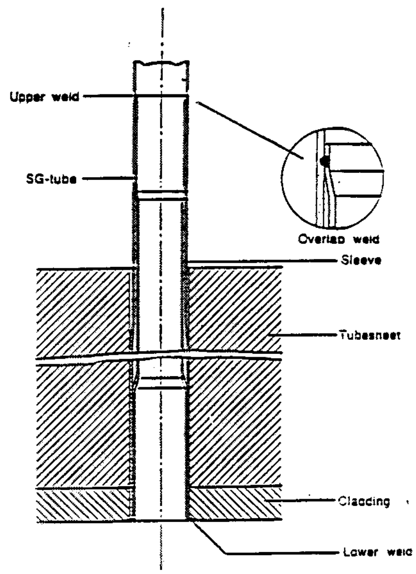
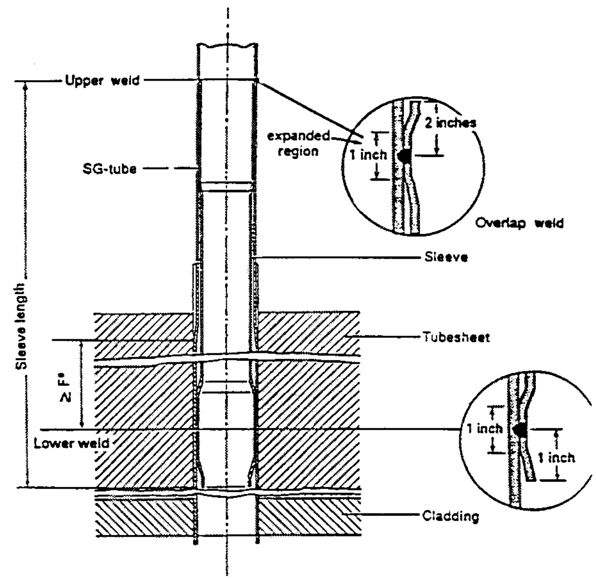


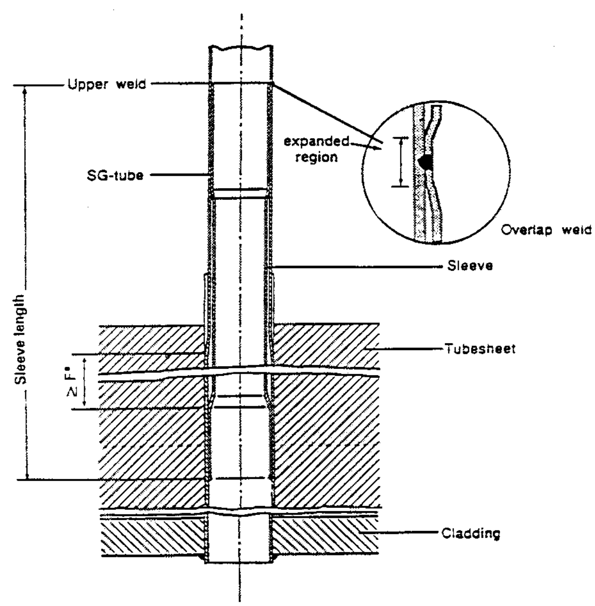
Figure 5-2. Babcock and Wilcox Welded Sleeves for Recirculating Steam Generators



Type I Sleeve

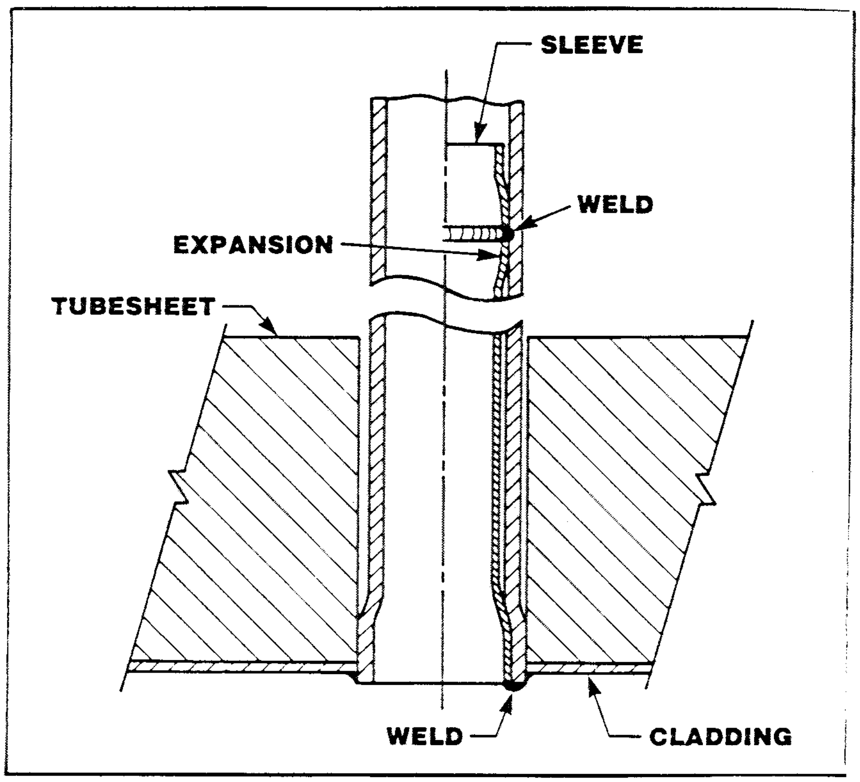


Type II Sleeve



Type III Sleeve

Figure 5-3. Bechtel/KWU Welded Sleeves



Welded steam generator sleeve

Figure 5-4. Combustion Engineering Welded Sleeves

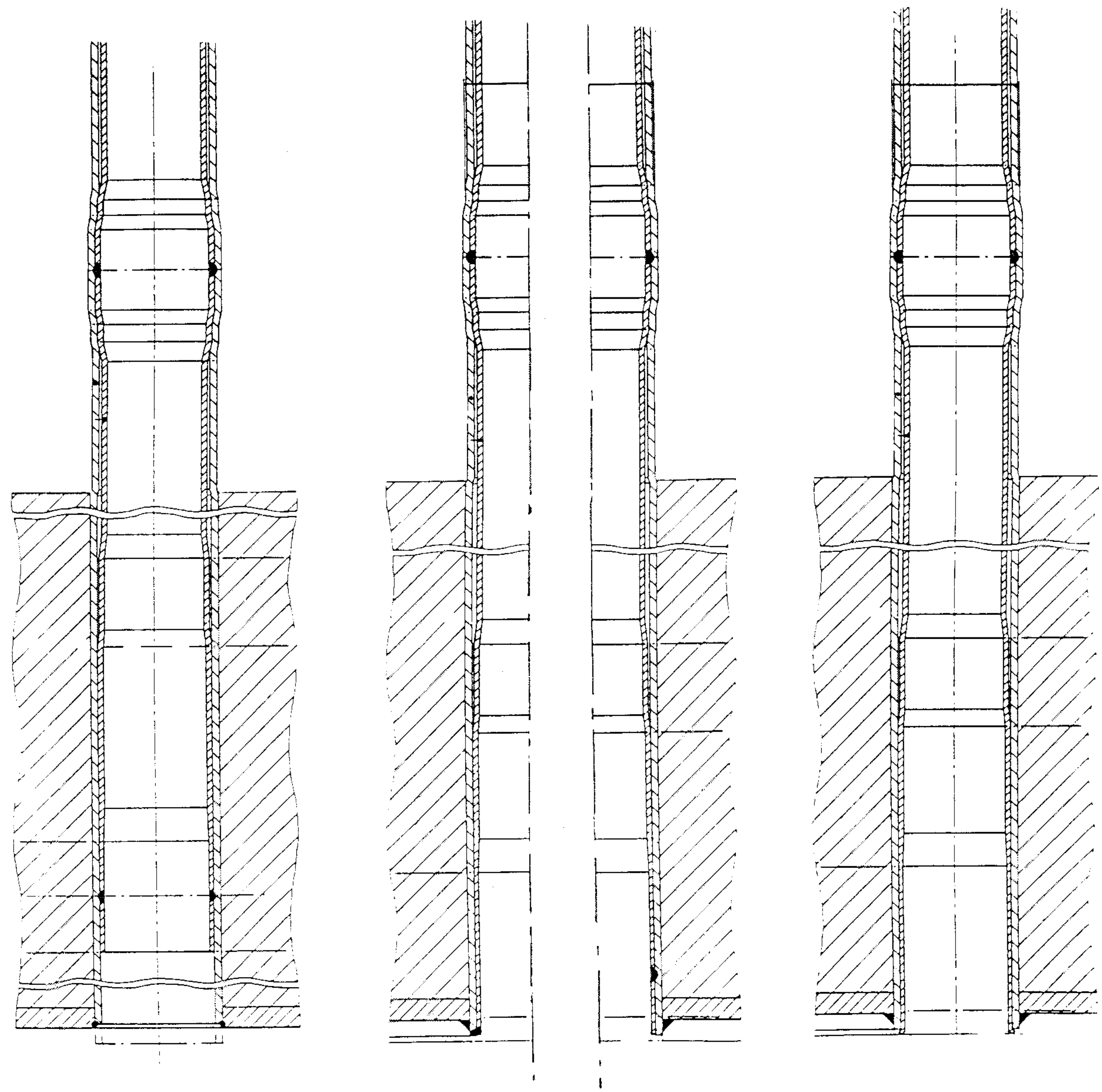


Figure 5-5. Framatome Welded Sleeves

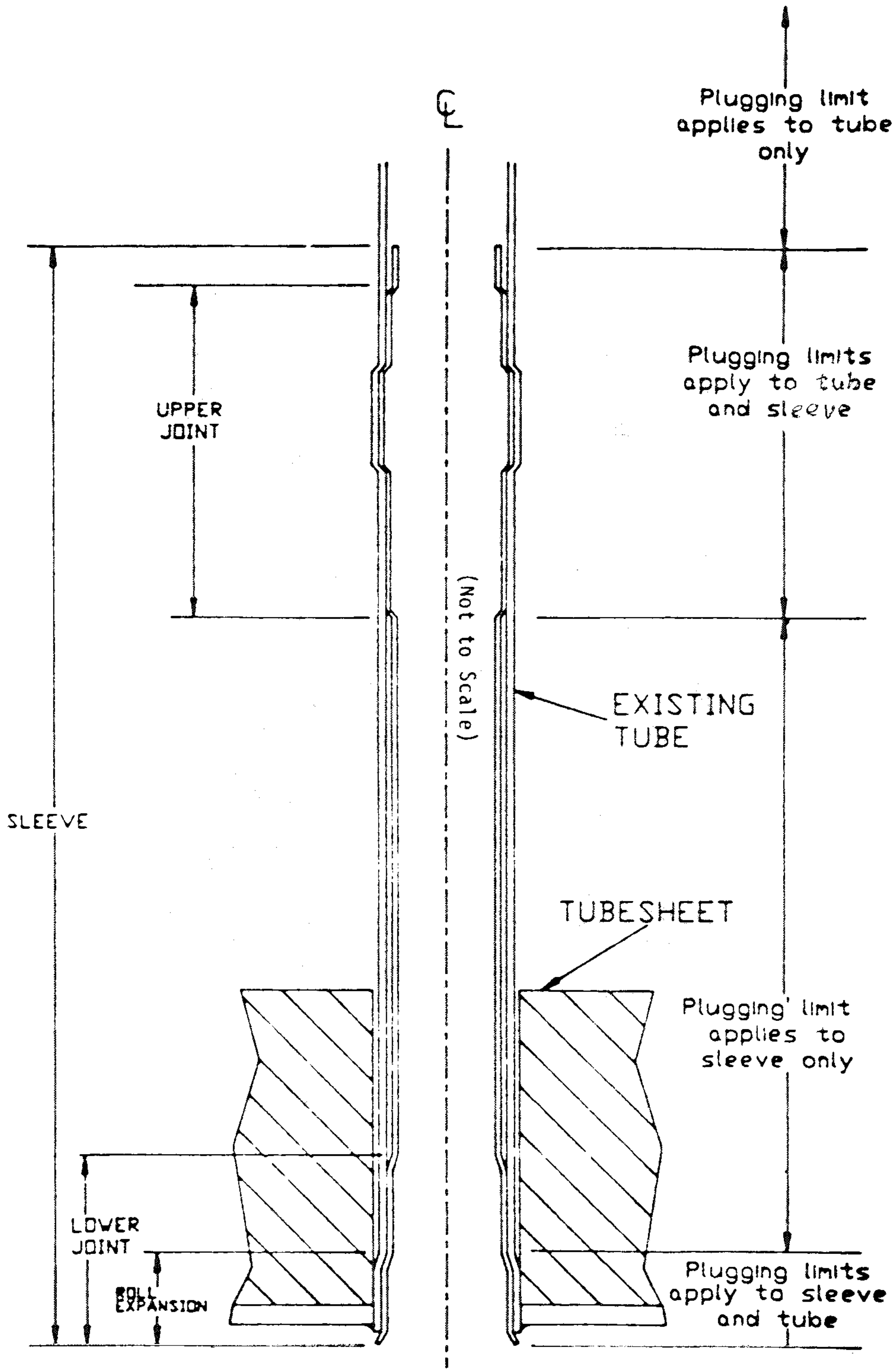


Figure 5-6. Westinghouse Hybrid Expansion Sleeve (40)

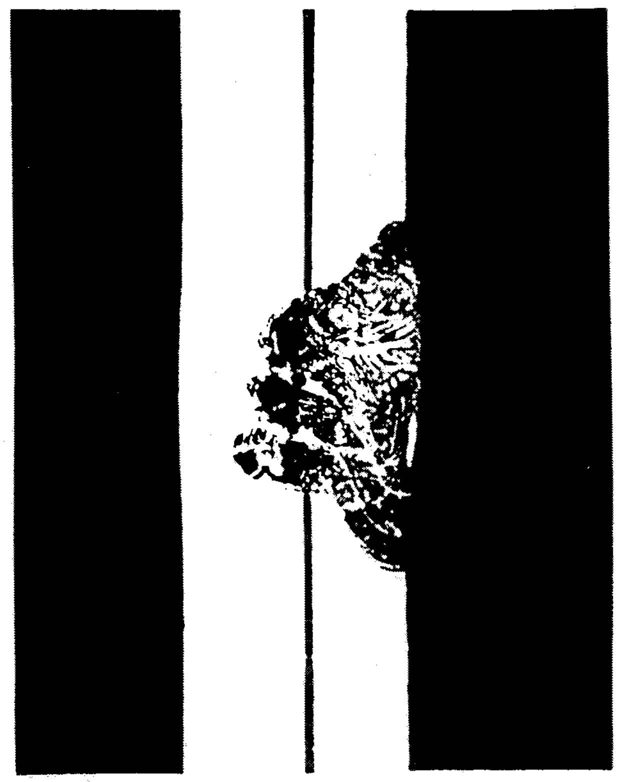


Figure 5-7. Cross Section Through Westinghouse Laser Welded Sleeve Joint (28)

Section 6

SLEEVING EXPERIENCE

Table 6-1 contains a summary of sleeving experience at a number of plants where significant numbers of sleeves have been installed. The table is intended to be representative rather than all inclusive. The design of some sleeves installed prior to 1985 differ somewhat from current designs described in this report. Descriptions of these earlier designs are contained in EPRI report NP-4296-LD (5).

Table 6-1

SUMMARY OF SLEEVING EXPERIENCE
(Thru Summer 1989)

Plant	Dates	Vendor	Sleeves Installed	Reason Sleeved	Sleeve Length (in)	Sleeve Material	Freespan Joints	Tube Sheet Joints	Total Time (weeks)	Total Exposure (Rems)
Arkansas Nuclear 1	84	B&W	10	IGA	80	TT 600	DR	R	0.7	13
	86	B&W	40	IGA	80	TT 600	DR	R	1.3	16
	88	B&W	174	IGA	80	TT 600	DR	R	1.7	24
Beznau 1	84	B&W/NOK	12	TS Crevice IGA	20	TT 600 Ni Clad	---	EW/EW	---	---
	85	B&W/NOK	64	"	20	"	---	EW/EW	---	---
	86	B&W/NOK	162	"	20	"	---	EW/EW	---	---
	87	B&W/NOK	80	"	20	"	---	EW/EW	---	---
	88	B&W/NOK	53	"	20	"	---	EW/EW	---	---
	89	B&W/NOK	17	"	20	"	---	EW/EW	---	---
Beznau 2	85	B&W/NOK	39	"	20	"	---	EW/EW	---	---
	86	B&W/NOK	86	"	20	"	---	EW/EW	---	---
	87	B&W/NOK	42	"	20	"	---	EW/EW	---	---
	88	B&W/NOK	53	"	20	"	---	EW/EW	---	---
	89	B&W/NOK	14	"	20	"	---	EW/EW	---	---
Doel 2	82/83	B&W	192	Transition PWSCC	1.5 mini	TT 600	N.A.	EW	---	---
Doel 3	88	W	55			TT 690	HE + LW	HE + R	---	---

Table 6-1 (Continued)

SUMMARY OF SLEEVING EXPERIENCE
(Thru Summer 1989)

Plant	Dates	Vendor	Sleeves Installed	Reason Sleeved	Sleeve Length (in)	Sleeve Material	Freespan Joints	Tube Sheet Joints	Total Time (weeks)	Total Exposure (Rems)
Ginna	80	B&W/RGE	5	3 IGA 2 preventive	36	TT 600 Ni Clad	HE + B	EW	---	40
	81	B&W/RGE	16	13 IGA 3 preventive	36	TT 600 Ni Clad	EE + B	EW	---	32
	83	B&W/RGE	78	IGA/IGSCC	22-28 36-41 9-28	TT 600 Ni Clad	EE + B EE + B	EW EW EW	---	26
	84	B&W/RGE	9	IGA/IGSCC	20	TT 600 Ni Clad	---	EW/EW	---	---
	85	B&W/RGE	69	IGA/IGSCC Wastage	20-36	TT 600 Ni Clad	EE + B	EW	---	---
	86	CE	36	IGA/IGSCC Wastage	27	TT 690	HE + TIG	PF + TIG	---	---
	87	CE	107	IGA/IGSCC	27	TT 690	HE + TIG	PF + TIG	---	10
	89	CE	395 rigid 109 curved	IGA/IGSCC PWSCC Wastage	27	TT 690	HE + TIG	PF + TIG R + TIG	---	---
Indian Point 3	82/83	W	2,971	Sludge Pile Pitting	36-44	TT 600	HE + R	HE + R	14	860
	85	W	635	Sludge pile pitting	36-44	TT 600	HE + R	HE + R	1.7	88
Kewaunee	88	W	1,940	TS Crevice IGA/IGSCC	30 & 36	TT 690	HE + R	HE + R	2.5	62
	89	W	1,698	TS Crevice IGA	30 & 36	TT 690	HE + R	HE + R	2.0	51

Table 6-1 (Continued)

SUMMARY OFSLEEVING EXPERIENCE
(Thru Summer 1989)

Plant	Dates	Vendor	Sleeves Installed	Reason Sleeved	Sleeve Length (in)	Sleeve Material	Freespan Joints	Tube Sheet Joints	Total Time (weeks)	Total Exposure (Rems)
Kori 1	88	ABB	558		28-36	TT 690	HE + TIG	HE + TIG	---	---
Millstone 2	83	W	~3,000	Sludge Pile Pitting	40	690 + 625 Clad	HE + R	HE + R	8	526
	85	W	~3,000	Sludge Pile Pitting	40	690 + 625 Clad	HE + R	HE + R	---	---
	86	W	~100	Sludge Pile Pitting	40	690 + 625 Clad	HE + R	HE + R	---	---
Oconee 1	87	B&W	450	Preventive	80	TT 600	DR	R	see below	see below
	87	B&W	32	TSP IGA + Erosion	15	TT 600	DR/DR	---	6	33
Oconee 3	88	B&W	247	Preventive	80	TT 600	R + DR	R + DR	2.2	9
Palisades	76	CE	14	TSP Wastage	12	600	HE	HE	8	15
	78	CE	23	TSP Wastage	12	600	HE	HE	---	---
Point Beach 1	81	W	13	TS Crevice IGA	36	TT 690	HE + B or R	HE + R	2	---
Point Beach 2	83	W	3,000	TS Crevice IGA	36	TT 600	HE + R	HE + R	10	660
Prairie Island 1	87	CE	27		30	TT 690	HE + TIG	PF + TIG	---	6
	88	CE	73		30	TT 690	HE + TIG	PF + TIG	---	4

Table 6-1 (Continued)

SUMMARY OF SLEEVING EXPERIENCE
(Thru Summer 1989)

Plant	Dates	Vendor	Sleeves Installed	Reason Sleeved	Sleeve Length (in)	Sleeve Material	Freespan Joints	Tube Sheet Joints	Total Time (weeks)	Total Exposure (Rems)
Rancho Seco	86	B&W	507	Preventive	80	TT 600	DR	R	5	47
Ringhals 2	84	CE	18	TS Crevice IGA/IGSCC	30	TT 690	HE + TIG	PF + TIG	---	5
	84	W	17	TS Crevice IGA/IGSCC	30	TT 690	HE + B	HE + R	---	3.4
	85	CE	59	TS Crevice IGA/IGSCC	27	TT 690	HE + TIG	PF + TIG	---	13
	86	CE	599	TS Crevice IGA/IGSCC	27	TT 690	HE + TIG	PF + TIG	---	53
	87	CE	571	TS Crevice IGA/IGSCC	27	TT 690	HE + TIG	PF + TIG	---	42
San Onofre 1	80/81	W	6,929	TS Crevice IGA	27-36	TT 600	HE + B or R	HE + R	30	3,496
Tricastin	??	F	22		??	TT 690	RE + TIG	RE + TIG Optional	---	---
Zion 1	86	CE	128	IGA	27	TT 690	HE + TIG	PF + TIG	---	28
	88	W	47	IGA	30	TT 690	HE + R	HE + R	---	---
	89	CE	445	PWSCC & IGA	27	TT 690	HE + TIG	PF + TIG		---

Section 7

SUMMARY

To date over 25,000 sleeves have been installed in steam generators of over 20 plants. In some cases, a few sleeves were installed as part of a qualification program with the knowledge that larger numbers of sleeves may have to be installed in the future. In other cases, relatively large numbers of sleeves (almost 7,000 in one plant) were installed to correct immediate problems.

While sleeving experience has generally been successful, it has not always been trouble free. Some installation difficulties have occurred when actual field conditions have differed from the more ideal conditions assumed for the qualification tests. Further, some of the installation methods may have induced tensile residual stresses in the joints that could possibly lead to cracking of the parent tube over the long term for plants with PWSCC susceptible tubing, although experience to date has not indicated the occurrence of cracks.

Currently offered sleeves, described in Section 5, are considered to represent significant improvement over most earlier sleeves. However, many of these designs are still undergoing qualification tests, and the total number of such sleeves installed in plants is still relatively low. Given the past history, the current development and installation status, and the economic risk associated with installing large numbers of any sleeve design, it would be prudent for utilities to remain cautious.

It is recommended that sleeving be approached in the following manner:

1) Start planning for sleeving as early as possible if plant experience and predictions suggest that sleeving may be required. Three areas should receive attention:

   - increasing the tube plugging margin based on actual plant operating conditions,
   - qualifying sleeve designs, and
   - developing a sleeving strategy taking into account the current status of sleeve development, and the extent and rate of degradation.

2) Select a sleeving vendor, or vendors, if desirable from a competitive standpoint. The draft specification in Appendix A can

be used as an aid in soliciting proposals. The sleeving checklist in Appendix B can be used in the screening of alternate proposals.

3) Complete sleeve design and installation procedures.

4) Develop and carry out a qualification test program including the following key phases:

   - Develop test procedures which addresses all known conditions which can exist in the steam generators, and the range of anticipated process variables.

   - Perform tests on stainless steel tubes/sleeves in boiling magnesium chloride or sensitized alloy 600 tubes/sleeves in sodium tetrathionate to confirm that residual stresses are low.

   - Perform tests of mill annealed alloy 600 tubes and alloy 690 sleeves in 10% sodium hydroxide or doped high temperature steam to confirm preliminary results under more representative accelerated conditions.

   - Perform tests of alloy 600 tubes and alloy 690 sleeves in elevated temperature primary water to determine long term performance under the most representative accelerated conditions.

   Control specimens should be included in all tests to confirm that tests results are as anticipated. In the case of accelerated testing of LTMA alloy 600 tubing in 10% sodium hydroxide or doped steam, the control specimens must be able to support the conclusion that the total operating stresses in the joint including residual stresses, pressure stresses, thermal stresses, bending stresses, etc. will be below 40 ksi.

5) Install small numbers of sleeves a year or two prior to having to install large numbers of sleeves. This will provide practical experience concerning all phases of the installation operation.

6) Make decision to install larger numbers of sleeves based on sleeve development status and the sleeving strategy.

Each utility need not carry out the full scope of work, but each utility should confirm that the work has been carried out and that the results are satisfactory. Finally, it is recommended that each utility should carry out a trial installation of a small number of sleeves prior to any large scale installation.

Section 8

REFERENCES

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Appendix A

DRAFT SLEEVING SPECIFICATION

1.0 Scope

2.0 References

3.0 Information to be Submitted With Proposal

4.0 Required Services

5.0 Required Equipment

6.0 Design Verification

7.0 Procedure Qualification

8.0 Training

9.0 Sleeving

10.0 Documentation

<u>Note</u>:

This draft is limited to technical requirements pertaining to sleeving operations. Other plant or utility specific contractual, administrative, and quality control requirements must be added to these draft technical requirements prior to their use in procuring sleeving services. These additional requirements include:

- A definition of who is to provide the complete range of required services, including, but not limited to: opening steam generator, installing dams, performing inspections, setting up equipment, training operators, performing sleeving, performing quality control functions, disassembling equipment, decontaminating equipment, packing equipment for shipping, providing licensing support, etc.

- A definition of who is to provide a training mockup, and where the training is to be performed. The training mockup should simulate access to the steam generator inlet and outlet plenums and the lower face of the tube sheet.

- A clear understanding of whether the sleeving is to be performed manually, or using automated equipment. If more than a few sleeves are to be installed, automated equipment should be used to complete the work faster and minimize radiation exposure.

- A clear definition of who is to approve the sleeving procedures and the required field changes.

1.0 SCOPE

1.1 This specification defines technical requirements for sleeving steam generator tubes in the tube sheet region and at tube support plates at the (utility) (station).

1.2 The intent of the sleeving is to bridge degraded sections of the original alloy 600 tubes with a sleeve which will have adequate corrosion resistance and strength to permit continued operation of the tube. It is also an intent that the sleeving operation not lead to other problems such as stress corrosion cracking of the original tube at the sleeve joints.

1.3 For purposes of this specification, the following definitions apply:

Utility - (Utility)
Contractor - Organization to perform sleeving

2.0 REFERENCES

The following documents and revisions thereto form a part of this specification to the extent referenced herein.

2.1 Plant design, operating and Technical Specification requirements applicable to sleeving (to be prepared by Utility).

2.2 Results of previous eddy current inspections and tube pull examinations (to be prepared by Utility).

2.3 EPRI Report"Steam Generator Tube Sleeving: Design, Specification and Procurement Checklist."

2.4 ASME Boiler and Pressure Vessel Code*, Section II, "Materials".

2.5 ASME Boiler and Pressure Vessel Code*, Section III, "Nuclear Power Plant Components".

2.6 ASME Boiler and Pressure Vessel Code*, Section IX, "Welding".

2.7 ASME Boiler and Pressure Vessel Code*, Section XI, "Inservice Inspection".

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

2.9 USNRC Regulatory Guide 1.83, "Inservice Inspection of Pressurized Water Reactor Steam Generator Tubes".

2.10 EPRI Specification for Alloy 690 Steam Generator Tubing.

* The applicable revision date shall be provided for all ASME Code requirements.

3.0 INFORMATION TO BE SUBMITTED WITH PROPOSAL

The following information shall be submitted with the proposal to perform steam generator sleeving.

3.1 Description of proposed sleeve design and installation procedure.

3.2 Discussion of how the proposed sleeve design and installation procedure addresses the technical concerns described in Section 3 of reference 2.3. Particular emphasis should be directed toward the following:

a. Sleeve design

b. Peripheral sleeve designs (if required)

c. Sleeve materials

d. Joint expansion

e. Joint sealing/welding

f. Joint stress relief

g. Effect of multiple heating operations on tube and sleeve materials

h. Inspections

3.3 Summary and status of design verification analyses.

3.4 Summary and status of qualification testing.

3.5 Summary and status of installation technology.

3.6 Licensing status.

3.7 List of plants which have been sleeved with the proposed sleeve design. Also a list of plants which have been sleeved with previous sleeve designs including a summary of problems encountered and how these problems have been resolved in the proposed sleeve design and installation procedure.

3.8 Outline schedule for sleeving project including a breakdown of work to be performed inside containment.

3.9 Estimated radiation exposure.

3.10 List of exceptions to requirements of this specification, along with technical justification for each exception.

3.11 Estimated productivity (sleeves per day per steam generator).

4.0 REQUIRED SERVICES

4.1 <u>Locations to be Sleeved</u>

a. Actual tubes to be sleeved will be identified during eddy current testing at the beginning of the outage. The following information is a best estimate of the sleeving which will be required based on the results of previous testing.

b. Based on the results of previous eddy current testing the proposal should be based on sleeving the following numbers of tubes.

	Radius From Generator Centerline			
	0-15 in 0-0.38 m	15-30 in 0.38-0.76 m	30-45 in 0.76-1.14 m	45-Rmax 1.14-Rmax
Sludge Pile Depth (in)				
A Generator				
B Generator				
C Generator				
D Generator				

c. Based on previous experience it is anticipated that the following number of sleeves will have to be installed at tube support plate intersections.

Location	Tube Support Plate Number					
	1	2	3	4	5	6
A Generator						
B Generator						
C Generator						
D Generator						

4.2 <u>Services to be Provided by Contractor (Typical Scope)</u>

a. Perform sleeve detailed design, or submit previously prepared and accepted design report.

b. Perform sleeving qualification tests, or submit report of previously performed qualification tests.

c. Provide technical support required to obtain NRC approval.

d. Prepare and submit a final sleeving procedure.

e. Provide equipment and supplies to perform sleeving and training in a steam generator mockup.

f. Provide training for Contractor and Utility personnel in an appropriate training mockup.

g. Ship equipment to and from the plant.

h. Perform all aspects of specified sleeving, including: equipment set-up, calibrations, initial inspections, cleaning, sleeve installation, joint expansion, joint sealing/welding, stress relief, cleaning, final inspections base line ISI (if performed by the Contractor), evaluations, process checks, quality control, and any required repairs.

i. Prepare and submit a final report on sleeving operations including the documentation specified in Section 10.0.

j. Decontaminate and pack sleeving equipment for shipment.

4.3 <u>Services to be Provided by Utility (Typical Scope)</u>

a. Move equipment between the loading dock and required locations in the reactor containment building.

b. Open the steam generator in preparation for sleeving.

c. Erect required scaffolding and platforms, etc.

d. Provide electrical service to the equipment location.

e. Provide labor (jumpers) to enter the steam generators to install required equipment.

f. Provide Quality Control and Health Physics personnel.

g. Perform baseline ISI of sleeved joints.

h. Close up the steam generator after sleeving operations are complete.

5.0 REQUIRED EQUIPMENT

5.1 The Contractor shall provide all equipment required to carry out the sleeving operations.

5.2 Equipment shall be of a rugged design in order to avoid unnecessary downtime due to equipment damage.

5.3 Equipment shall be proven out in advance to operate reliably for long periods of time. The Utility shall be notified in advance of tests to confirm equipment operation.

5.4 The equipment design shall be such that it minimizes personnel radiation exposure to set up, operate and disassemble.

5.5 The Contractor shall develop a list of, and bring to the plant, spare parts to cover: (1) all consumables with an adequate allowance, (2) all parts required for periodic maintenance, and (3) all other parts which previous sleeving experience or test has indicated that replacement may be necessary.

6.0 DESIGN VERIFICATION

6.1 Contractor shall prepare a design verification report covering, as a minimum, the topics indicated in Section 3 of reference 2.3.

6.2 Stress analyses shall be performed in accordance with Section III of the ASME Boiler and Pressure Vessel Code, reference 2.5 and shall demonstrate that stresses do not exceed the limits of that section.

6.3 Sleeve materials shall comply with Section II of the ASME Boiler and Pressure Vessel Code, reference 2.4, and applicable Code Cases, and shall also comply with the EPRI Specification for Alloy 690 Steam Generator Tubing.

6.4 Sleeve welding shall comply with Section IX of the ASME Boiler and Pressure Vessel Code, reference 2.6.

6.5 The design verification report shall be approved by the Contractor and reviewed and approved by the Utility. The Utility review will include the topics in the Design Review Checklist in Appendix B of reference 2.3.

7.0 PROCEDURE QUALIFICATION

7.1 PSleeving Procedure

a. The Contractor shall prepare a sleeving procedure to serve as the basis for qualification testing.

b. The procedure shall include provisions for recovering from potential problems during sleeving. At the minimum, the procedure should cover the installation of removable plugs in sleeved and unsleeved tubes.

c. The sleeving procedure shall be reviewed and approved by the Contractor and Utility. The Utility will confirm that the procedure addresses the topics in the Design Review Checklist in Appendix B of reference 2.3.

7.2 Qualification Testing Plan

a. The Contractor shall review the proposed sleeve design and installation procedure relative to the potential problems outlined in Section 3 of reference 2.3. Potential problems include: PWSCC susceptibility of parent tubes, locking of tubes at tube sheet or tube support plates, presence of sludge pile, varying emissivity on tube outside diameter, denting, out-of-roundness, range of achievable process variables, etc.

b. The Contractor shall prepare a qualification test plan based on the proposed design which addresses each of the potential problems identified in paragraph a and which covers testing of the contingency measures such as installation of removable plugs.

c. At the minimum, the qualification testing shall include:

- Accelerated screening tests in boiling magnesium chloride, or sodium tetrathionate, to confirm that residual stresses following all sleeving operations are acceptable. (Note: If a thermal stress relief is included as part of the remedial measure, it must be confirmed that the thermal process has actually reduced stresses, and not just decreased the cracking susceptibility of the test materials.)
- Accelerated testing of mill annealed alloy 600 tubes and alloy 690 sleeves in 10% sodium hydroxide or doped high temperature steam to confirm preliminary results under more representative accelerated conditions.

- More representative long term testing in high temperature primary water for cases involving significant PWSCC susceptibility.

Control specimens should be included in all tests to confirm that tests results are as anticipated. In the case of accelerated testing of LTMA alloy 600 tubing and alloy 690 sleeves in 10% sodium hydroxide or doped steam, the control specimens must be capable of supporting the conclusion that the total operating stresses in the joint including residual stresses, pressure stresses, thermal stresses, bending stresses, etc. will be below 40 ksi.

d. The test plan shall include sufficient calibration specimens (e.g., stressed C-rings) to verify that the time-to-crack vs stress relationship in the test is as expected. The testing shall also include regular roll transitions in material of known PWSCC susceptibility. Consideration shall also be given to the effect of the test specimen heat treatment on level of residual stress.)

e. The test plan shall cover the range of sleeving conditions and process variables to establish acceptance criteria, or shall simulate combined worst case conditions

f. The Contractor and Utility shall approve the qualification test plan.

7.3 Qualification Testing

a. The Contractor shall carry out qualification tests in accordance with the approved plan.

b. All qualification testing shall be performed under the Contractor's Quality Control program using calibrated equipment and qualified personnel.

7.4 Final Sleeving Procedure

a. Upon completion of qualification testing, the Contractor shall evaluate the test results and propose modifications to the sleeving procedure.

b. Significant modifications to the procedure shall be confirmed by further qualification testing.

c. The final sleeving procedure shall be approved by the Contractor and submitted to the Utility for review and approval.

8.0 TRAINING

8.1 Contractor personnel assisting in the sleeving operations shall have been trained in advance of the sleeving operations. This training shall include: (1) a thorough familiarization with the sleeving objectives, (2) familiarization with the sleeving procedure, (3) familiarization with long term problems which can result from failure to follow the procedure exactly, and (4) training on the actual sleeving equipment in a mockup which simulates sleeving conditions at the plant.

8.2 The Contractor shall conduct a refresher training course prior to start of the actual sleeving effort and during the sleeving effort the effort if it is determined that procedures are not being adhered to.

9.0 SLEEVING

9.1 Document Approval

a. Sleeving shall not be initiated until required NRC concurrence has been obtained and the following documents have been reviewed, approved, and signed off by both the Contractor and the Utility.

- Sleeving Design Report
- Sleeving Procedure Qualification Report
- Sleeving Procedure

b. If changes are required to the sleeving procedure during performance of the work, the revisions shall be approved by the designated Contractor and Utility representatives.

9.2 Sleeving Operations

a. A program shall be implemented to ensure that all equipment taken into the steam generators is logged and cleaned prior to entry.

b. Sleeving equipment shall be set up in the containment building in preparation for sleeving operations. This shall include the installation of a TV camera and lighting in the steam generator plenum.

c. Prior to performing the initial sleeving, and at pre-determined intervals during the sleeving operations, the equipment shall be calibrated. Results of the calibrations shall be signed off by personnel performing the work and a Quality Control representative.

d. Specimen sleeves shall be installed in a mockup prior to performing the initial sleeving and after each subsequent day of sleeving work. The sample sleeves shall be examined by NDE methods and destructively to ensure that the joints meet the established acceptance criteria.

e. A log sheet shall be prepared for each tube sleeved including: steam generator number; tube location, profilometry results, cleaning signoff; initial eddy current inspection sign-off; sleeve number; sleeve inspection results; range of key process variables such as rolling torque, welding current and stress relief conditions; final inspection sign-off. Records shall be retained for key process variables such as welding current, welding speed, and stress relief time-temperature. The data shall be filled in by personnel overseeing the work and the record shall be signed off by the responsible Quality Control representative.

f. The Contractor shall have qualified contingency plans to cover sleeve installation problems. The contingency plans shall include the installation of qualified temporary plugs. No remedial actions shall be performed which are not qualified.

9.3 Sleeving Evaluations

a. A summary of sleeving progress, problems and observations shall be prepared at the end of each shift. This evaluation shall be submitted to the Utility.

b. A technical evaluation of the sleeving operation shall be performed upon completion of the sleeving project. This evaluation shall be approved by the Contractor and submitted to the Utility. The evaluations shall indicate problems which were encountered and resolved and make recommendations regarding future sleeving.

10.0 DOCUMENTATION

Upon completion of sleeving, the Contractor shall prepare and submit a final report which compiles all documentation pertaining to the sleeving operation including but not limited to the following:

10.1 Information submitted in the proposal and outlined in paragraph 3.0.

10.2 Final approved revision of sleeving design report, including any changes required by the field operations.

10.3 Final approved revision of the qualification testing report, including any supplemental testing required as a result of problems encountered during sleeving.

10.4 Final approved revision of sleeving procedure, including all field changes.

10.5 Complete set of sleeve fabrication records including: identification of tubes sleeved, material heat numbers, sleeve markings, sleeve dimensional inspections, mechanical property tests, and QC acceptance of sleeves.

10.6 Copy of sleeving log book including results of all calibrations, inspections and process variables.

10.7 Summary engineering evaluation of sleeving operation including lessons learned and recommendations regarding required further testing and process development.

Appendix B

SLEEVING CHECKLIST

Note:

The following checklist is intended to be used as an aid in evaluating vendor sleeving proposals and in planning for sleeving repairs. Further discussion of these topics is contained in Sections 2, 3 and 4 of the accompanying report.

1. PROJECT CONSIDERATIONS

a. Suitability for Sleeving Repairs

- Can the tube plugging margin be increased in lieu of sleeving?
- Are potential sleeving designs qualified and tested to the extent that they can be installed with confidence?
- Is the parent tubing material at the high or low end of the PWSCC susceptibility range?
- Is the degradation at a location where sleeves can be installed using available tooling?
- Is it likely that future sleeves will have to be installed at an elevation above the subject sleeves?
- Is the extent and rate of degradation such that large scale sleeving can be deferred until the intended sleeving process is better proven?

b. Prior Experience

- Has the proposed vendor previously installed sleeves?
- How many sleeves of the proposed design have been installed?
- Are the proposed sleeves similar to sleeves previously installed, or if not, are the differences significant?
- What was the installation and operating experience with the previously installed sleeves?

c. Licensing Status

- Has the proposed sleeve design been accepted by the NRC?
- Does the proposed sleeve design meet general regulatory requirements?
    - Design
    - Installation
    - Inspection
    - ALARA
- What work remains to obtain NRC acceptance, and how much time is required to accomplish the remaining work?
    - Analyses
    - Tests
    - Submittals
    - Schedule

d. Required Resources

- How long will it take to install equipment, install sleeves, and remove equipment?
- What will the sleeving program cost?
- What level of utility and vendor support will be required?
- What level of radiation exposure is predicted and can this be reduced by automation, decontamination, or training?

e. Quality Control/Quality Assurance

- Does the vendor have a quality control and quality assurance program covering all aspects of sleeve design, testing, and installation?
- Has the utility audited the quality control and quality assurance program to ensure that the vendor is following the program?

2. DESIGN

a. Design Objectives

- What are the tube/sleeve strength requirements?
- What are the tube/sleeve corrosion requirements?
- What are the tube/sleeve leak tightness requirements?

b. Base Line Sleeving Data

- Has a reasonable estimate been made regarding the number and location of sleeves to be installed?
- Has background work been performed to obtain all relevant data regarding the condition of the tubes to be sleeved including: material properties, inside surface profilometry; crevice conditions; sludge pile location, depth and thermal properties; sludge on outside surface of the tube; tube emissivity; locking of tube at tube sheet or tube support plates, etc?

c. Length

- Where are the degraded sections of tube located?
- What sleeve length is required to bridge the degraded location, provide for top and bottom joints and leave room for a possible backup joint?
- Where will the lower joint be located relative to the bottom surface of the tube sheet?
- Is there sufficient headroom between the channel head and bottom of the tube sheet to permit rigid sleeves to be installed or are flexible or segmented sleeves required?

d. Outer Diameter and Diametral Clearance

- Is the diametral clearance between the sleeve and tube as small as practical to minimize expansion strains and flow interference?
- Can the sleeve be inserted to the required elevation in the parent tube without the need for reaming the inside diameter of the parent tube, or is reaming required?
- Is the diametral clearance between the sleeve and tube similar to that on previous designs?
- Are there known abnormalities in tube inside diameter which could affect sleeve installation?

e. Wall Thickness

- Does the sleeve wall thickness meet the same design criteria as the parent tube, considering: internal pressure, external pressure, potential accidents, reduced diameter, etc.?
- Is the sleeve wall thickness as small as possible, considering other countervailing constraints, to minimize expansion problems?

f. Materials

- Is the proposed sleeve material alloy 690?
- If not alloy 690, is the proposed sleeve material resistant to: primary side IGSCC, secondary side IGSCC and IGA, and secondary side pitting?
- Is the sleeve material thermally treated? If not, what is the basis for not using thermally treated material?
- Does the alloy 690 material conform to the EPRI alloy 690 tubing guideline?
- Are additional materials added to the joints such as braze material, or flux, and if so, are they compatible with the base materials and resistant to primary side IGSCC, secondary side IGSCC and secondary side pitting?

g. Joint Design

- Will the proposed joint designs have adequate strength to transfer loads from the sleeve to the tube?
- Will the proposed joints meet the design leakage requirements?
- Will residual tensile stresses in both the top and bottom joints be less than 20% of yield which can be detected by the boiling magnesium chloride and sodium tetrathionate tests? If not, what is the basis for accepting higher residual tensile stresses?
- Has the joint design considered the full range of variables which can exist in an operating plant such as: (1) sludge, (2) axial lockup due to denting, (3) deposits in crevices, and (4) variable emissivity?
- Can the joints be inspected after installation and during subsequent inservice inspection?

h. Analytical Verification

- Have the sleeve/joint designs been analyzed per ASME code static strength and fatigue requirements for all normal and postulated accident conditions?
- Will the proposed sleeve have an adverse affect on tube vibration?
- What is the effect of the sleeve on the steam generator thermal/hydraulic analysis, including the tube plugging margin?
- What is the effect of the proposed sleeves on the plant seismic analysis?
- Is there any mode by which the sleeve could increase the risk of accidents such as a double ended tube rupture?

3. QUALIFICATION TESTS

a. Detailed Test Procedure

- Has the vendor prepared a comprehensive test plan?
- Has the test plan been reviewed within the vendor's own organization, and by utility personnel who are knowledgeable regarding sleeve problems?

- Has the testing followed the plan, including approved field changes?

b. Mockup

- Do the qualification test mockups accurately simulate tube, crevice, weld conditions?
- Do the qualification test mockups accurately simulate features known to have caused past installation problems such as: dented TSP's, dented tube sheets, sludge, deposits in tube sheet crevices, variable OD emissivity, oval tubes/sleeves, etc? For example:
  - With and without axial lockup at TSP and tube sheet
  - With and without tube sheet crevice deposits
  - With and without simulated sludge pile
  - Minimum and maximum expansion
  - Minimum and maximum welding current and speed
- Are mockups fabricated of materials which will point out design/installation problems? In this regard, some tests have been conducted in the past using materials which are not particularly susceptible to attack.
- Are mockups made using the same tooling as to be used in production installations? If not, how can differences in equipment affect the test results?

c. Mechanical Testing

- Does the mechanical testing confirm joint pull out strength?
- Does the mechanical testing cover a sufficient range of process variables to establish process acceptance criteria?

d. Corrosion Testing

- Do corrosion tests include accelerated tests of all sleeve and joint details to confirm residual tensile stresses are less than about 20% of material yield?
- Do corrosion tests include longer term testing in more representative conditions?
- Do corrosion test results confirm that proposed sleeve designs will have long life?

e. Test Results

- Are test specimens checked using accepted visual and nondestructive techniques? For guidance see the test plan used by Laborelec on page 3-22 of the accompanying report.
- Do the results confirm that the proposed sleeve design will have acceptable performance?

f. Independent Review

- An independent technical review should be performed of the vendors qualification test program and test results to confirm that the testing and results are in accordance with the recommendations herein.

4. INSTALLATION

a. Material Controls

- Does sleeve material conform to vendor's specification and EPRI draft specification for alloy 690?

- Has the sleeve been procured in conformance with the vendor's quality control and quality assurance program?

b. Training

- Does the vendor have a full size training mockup of the channel head, tube sheet and portion of tube to be sleeved?
- Does the vendor have a training program for supervisory and installation personnel?
- Does the training program include emphasis on key process variables?
- Have the personnel performing the installation been trained?

c. Process Controls

- Does the vendor have a sleeving procedure?
- Does the sleeving procedure reflect criteria proven during the qualification testing?
- Does the sleeving procedure cover the following operations including manpower requirements, work description, acceptance criteria, and quality control hold points?
  - Equipment requirements
  - Equipment setup
  - Equipment calibrations
  - Trial sleeving off line
  - Tube cleaning
  - Sleeve cleaning
  - Tube inspection and gaging (profilometry, visual & ECT)
  - Sleeve inspection and gaging (profilometry, visual & ECT)
  - Sleeve installation
  - Joint expansion
  - Joint sealing/welding
  - Joint stress relief
  - Joint inspection (visual, other NDT)
  - Baseline eddy current testing

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