PWR Steam Generator Sleeving Assessment Document Revision 1

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Technical Report

PWR Steam Generator Sleeving Assessment Document, Revision 1

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Final Report, December 1997

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REPORT SUMMARY

Sleeving is a repair method that has been widely used for degraded steam generator tubes since 1976. An ad hoc Steam Generator Sleeving Review Committee, originally formed in 1995, reconvened in 1997 to review industry experience with installed sleeves, evaluate sleeve qualification programs, and develop a plan to address sleeve issues.

Background

As of the end of 1996, more than 64,000 steam generator tube sleeves had been installed in the United States. The vast majority of these sleeves have performed as designed without any evidence of degradation in the sleeve or parent tube. A few sleeve designs, however, have contributed to degradation of the parent tube, primarily at the sleeve-to-parent-tube joint location. There have also been several tube leak forced outages caused by sleeved tubes in which the sleeve was improperly installed or was installed in a tube that was locked at a support plate. In these instances, high residual stresses contributed to through-wall stress corrosion cracking of the parent tubing and subsequent leakage. The ad hoc Steam Generator Sleeving Review Committee was reconvened to review the most recent industry experience with installed sleeves.

Objectives

- To discuss sleeve designs, qualification programs, and joint inspection and repair efforts.

- To provide updated recommendations for managing in-service sleeves and issues to consider in the selection of new sleeves.

Approach

The ad hoc Steam Generator Sleeving Review Committee, representing 14 utilities, reconvened and assigned responsibilities for updating the industry experience with steam generator sleeves and producing a draft revision of the original PWR Steam Generator Sleeving Assessment Document. The committee revised the draft document, resolved comments, and approved publication of this revised document.

Results
The report covers steam generator tube sleeve designs, vendor qualification programs, sleeve joint inspection and repair, recommendations for managing in-service sleeves, and issues to consider in the selection and installation of new sleeves. Vendor qualification test programs, the condition of the steam generator tubes at the time of sleeve installation, and the installation process all require careful review prior to any new sleeve installation. The committee concluded that steam generator sleeving is still an effective repair process, provided all issues are identified and properly addressed.

EPRI Perspective
Steam generator tube sleeving can be an effective repair process that provides a finite increase in the useful operative life of a degraded steam generator. Experience has shown that the ability of a utility to achieve a desired steam generator life once degradation has been detected and a sleeving repair option has been selected will be determined principally by how well the degraded condition has been defined and how thoroughly the sleeving process has been qualified. This assessment document captures the lessons learned by utility personnel who have experienced the challenges of implementing the sleeving repair option in their degraded steam generators.

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ABSTRACT

As of December 31, 1996 over 64,000 steam generator tube sleeves have been installed in the United States and over 35,000 outside the United States. The vast majority of these sleeves have performed as designed without any evidence of degradation in the sleeve or the parent tube. However, some degradation has occurred in the parent tube, primarily at the sleeve to parent tube joint location. An ad hoc Steam Generator Sleeving Review Committee was formed in 1995 and initially met with each of the U.S. sleeving vendors to review industry experience with installed sleeves. The committee reconvened in 1997 to update this report which summarizes the committee findings and provides recommendations to address sleeving issues. Vendor qualification test programs, the condition of the steam generator tubes at the time of sleeve installation, and the sleeve installation process all require careful review prioir to any new sleeve installation. Steam generator tube sleeving is an effective repair process provided that issues discussed in the report are properly addressed. The report is provided to assist utilities in effectively identifying and managing these issues.

ACKNOWLEDGMENTS

Grateful appreciation is extended to the many individuals who provided information used in this report. The Steam Generator Sleeving Review Committee would like to thank the domestic sleeving vendors for their contribution. Specifically, the committee would like to thank Bob Keating, Ray Leasure, Bala Nair, Bob Gold, and Dan Malinowski from Westinghouse; David Stepnick and Wayne Gahwiller from ABB Combustion Engineering; John Helmey and John Griffith from Framatome Technology Incorporated; and Bob Vollmer from Zetec. Without their support this report would not have been possible.

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EXECUTIVE SUMMARY

PWR steam generator tubes are subject to a variety of degradation mechanisms. Corrective actions for significantly degraded tubes include removing the tube from service by plugging or installing a sleeve which bridges the degraded region of the tube. As of December 31, 1996, over 64,000 sleeves have been installed in steam generators in the United States. An additional 35,000 sleeves have been installed in steam generators outside the United States. Due to steam generator replacements and plant shutdowns, not all of these sleeves are still in service. As of December 31, 1996, approximately 27,000 of these sleeves are in service in the United States and approximately 7000 outside the United States. The vast majority of the installed sleeves have performed as designed without any evidence of sleeve or parent tube degradation. However, there have been a number of cases of sleeve and tube assembly failures related to either difficulties encountered during the sleeve installation process, or in-service degradation of the parent tube at the sleeve-to-tube joint. In a few cases the parent tube degradation has led to a tube leak forced outage.

Concerns have been expressed regarding the long term integrity of sleeved tubes based on these industry events. An ad hoc Steam Generator Sleeving Review Committee was formed in 1995 and met with each of the U.S. sleeving vendors to review the industry experience with installed sleeves, evaluate sleeve qualification programs, and develop a plan to address sleeve issues. The committee met again during 1997 and this updated report is the result of the efforts of this committee. The report covers steam generator tube sleeve design, vendor sleeve qualification programs, and sleeve joint inspection and repair. The report also provides recommendations for managing in-service sleeves and issues to consider in the selection and installation of new sleeves. The vendor qualification test programs, the condition of the steam generator tubes at the time of sleeve installation, and the installation process all require careful review prior to sleeving. Steam generator tube sleeving is an effective repair process, provided the issues mentioned above are properly addressed. The purpose of this report is to assist utilities in effectively identifying and managing steam generator tube sleeving issues.

1

INTRODUCTION

Steam generator tubes in pressurized water reactors (PWR's) are subject to several types of degradation. This degradation includes denting, wastage, pitting, intergranular attack (IGA), intergranular stress corrosion cracking (IGSCC), erosion-corrosion, fatigue, fretting, and wear. Degradation can initiate from either the primary side (inside) or the secondary side (outside) of the tube surface. Corrective action must be taken if the degradation reaches some pre-established acceptance criteria, normally 40% or greater of the tube wall thickness. Corrective actions under these conditions include removing the tube from service by plugging or leaving the tube in service by installing a sleeve which bridges the degraded region of the tube. Sleeving has been used as a repair method since 1976. Figure 1-1 shows typical locations and types of degradation within a PWR steam generator that have been repaired by sleeving (1).

Successful installation and performance of a steam generator tube sleeve requires the integration of a number of factors. These include sleeve material selection, qualified installation procedures, sleeve to parent tube joint design, and production controls. Sleeves are installed for preventative measures or because a portion of the parent tube has degraded and the utility does not want to remove the tube from service by plugging. The sleeves should be long enough to bridge the degraded portion of the parent tube to ensure that the joints are made in sound parent tube material. The sleeve material should be resistant to both primary and secondary side degradation. The most commonly used sleeving materials have been thermally treated Alloy 600 and thermally treated Alloy 690. Currently, thermally treated Alloy 690 and Alloy 800 are being offered although Alloy 800 has not yet been licensed in the United States. In addition, nickel cladding and welded tube repair processes are being developed. The location sleeves are installed in the tube bundle include the following:

- Tubesheet
- Intratubesheet
- Tube support plate

The sleeve joint is one of the most critical areas resulting from the sleeve installation process. Sleeve to parent tube joints are required at both the bottom and top of the

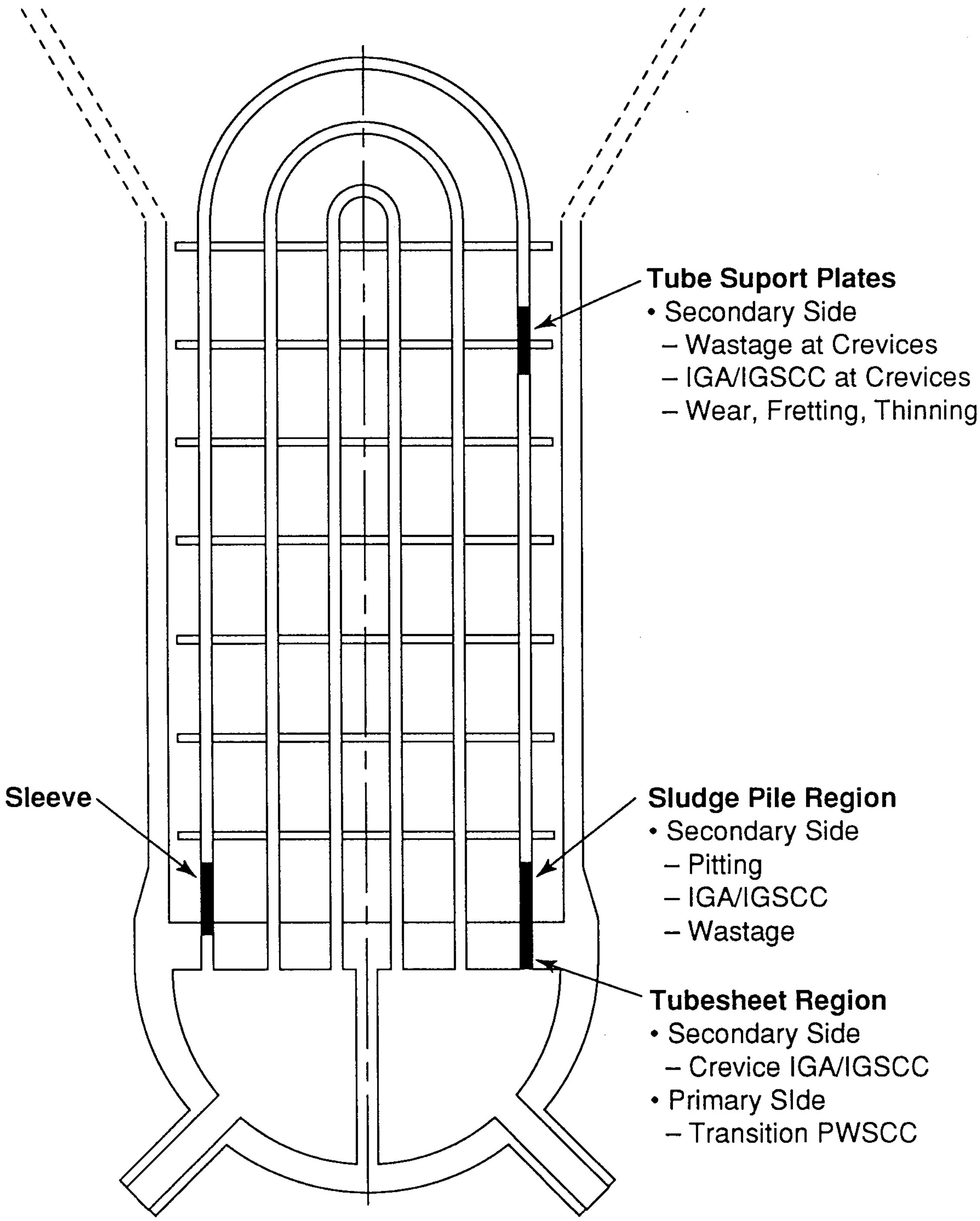


Figure 1-1
Typical Sleeve Locations in PWR Steam Generators

sleeve. A number of different types of sleeve joints have been used. These include the following:

- Brazed
- Hydraulic expansion
- Roll expansion
- Kinetic welded
- Hybrid: hydraulic plus roller expansion
- TIG welded
- Laser welded

The process of forming a sleeve joint places an additional stress on both the sleeve and the parent tube materials. The additional stress in the joint area increases the parent tube susceptibility to environmentally induced cracking. Recent improvements in the sleeving process are aimed at minimizing the residual peak stress caused by the sleeve installation process. In some cases, especially for primary water stress corrosion cracking (PWSCC) susceptible parent tube material, it may be necessary to stress relieve the joint to reduce the residual stress levels. Stress relief is normally performed in a temperature range of 1250°F to 1600°F (677°C - 871°C) for a period of several minutes. However, the stress relief process can be complicated if the tube is constrained at an adjacent support plate due to packed crevices, tube denting, or misalignment. This is referred to as a “locked” tube condition because the tube is constrained from moving in the vertical direction during joint stress relief. The locking of the tube at the support plate may contribute to unacceptably high residual stresses as a result of heating and cooling the joint during the stress relief process. The stress relief process can also be affected if lower sleeve expansion joints are made prior to stress relief.

Each sleeving installation process should be tested before it is used in the field. An adequate sleeve qualification program consists of a number of different elements including sleeve design, stress evaluation, mechanical testing, structural and vibration analysis, accelerated corrosion testing, installation verification, and sleeve inspection. Testing during the qualification program should realistically simulate the actual conditions to be experienced in the steam generator.

The sleeving installation process involves a number of steps. The sequence of performing these steps is also very important. The installation steps can vary depending on the type of sleeve and the joint process. In general the sleeve installation process has included the following:

- Tube cleaning as required
- Sleeve insertion
- Upper and lower joint expansion
- Upper and lower joint sealing
- Ultrasonic Inspection (upper welded joint)
- Stress relief of welded joints (optional)
- Final inspection (visual, eddy current)

These operations are generally performed using remote manipulators to maximize efficiency and minimize personnel radiation exposure.

As of December 31, 1996, over 64,000 sleeves have been installed in the United States. This includes approximately 46,700 Westinghouse sleeves, 9000 Asea Brown Boveri Combustion Engineering (ABB CE) sleeves, and 8900 Framatome Technology Incorporate (FTI) sleeves, formerly known as Babcock & Wilcox Nuclear Technologies (BWNT). In addition, approximately 35,000 sleeves have been installed in non-U.S. plants. Since the installation of the sleeves, a number of steam generators have been replaced and several units have been shut down. As of December 31, 1996, there were approximately 27,500 sleeves in service in plants in the United States. This includes approximately 14,600 Westinghouse sleeves, 7200 ABB CE sleeves, and 5700 FTI sleeves.

The vast majority of these sleeves have performed as designed. However, there have been a number of incidents of sleeve/tube assembly failures related to either the sleeve installation process, or in-service degradation of the parent tubing at the sleeve-to-tube joint. In a few cases the parent tube degradation has led to a tube leak forced outage. There has been only one case reported to date of in-service degradation of the sleeve material. A number of the more significant sleeving field experiences reports are contained in Appendix B.

To date the most notable problems that have been attributed to sleeve installation anomalies include the following:

> Lack of weld bond due to inadequate cleaning of the parent tube in the weld region (Prairie Island and Kewaunee)
>
> Weld discontinuities, i.e., blowholes and hot cracks, due to entrapped moisture and contaminants in the weld joint region (Maine Yankee, Doel 4 and Kewaunee)
>
> Hot cracks caused by too high of a heat input (Kewaunee and Doel 4)

Bulging and bulking of the parent tube due to stresses on the tube in the locked tube support plate configuration (Doel 4 and Maine Yankee)

Mechanical shearing of the weld during stress relief due to uneven stress loading over the weld surface (Kewaunee)

Some of the more notable problems detected in service include the following:

Degradation of the parent tube in kinetic welded sleeve joints (Trojan and McGuire 1)

Degradation of the parent tube in the upper expansion joint of mechanical sleeves (Kewaunee, Doel 4, Point Beach 2 and Cook 1)

Collapsed sleeves due to entrapped water between the sleeve and tube expanding during heat up (Farley)

Wastage of the Alloy 690 sleeve due to high concentration of boric acid entrapped between the sleeve and parent tube (Doel 4).

Utility Industry Response

The industry response to these sleeving issues has been one of pro-active monitoring, investigation, and identification of issues. As early as 1985 the utility industry, through EPRI, developed and distributed a *Design Review Checklist: Steam Generator Sleeving* (2). In 1990 the document was updated and issued in February 1991 as *Guidelines for PWR Steam Generator Tubing Specifications and Repair, Volume 3, Steam Generator Tube Sleeving: Design, Specification, and Procurement Checklist* (3). Later, as tube pulls were used to better characterize long term sleeve integrity, Volume 4, *Tube Removal and Examination Guidelines* (4), was issued. The utility industry continues to work with sleeving vendors to improve existing sleeve designs and to develop new innovative sleeving techniques.

The industry has also taken the initiative to improve sleeving reliability through enhanced inspection and leakage monitoring. Application of Appendix G of *PWR Steam Generator Examination Guidelines* (5) for personnel qualification and Appendix H for inspection technique qualification have increased the probability that degradation in the parent tube will be identified. In addition, implementation of the *PWR Primary-to-Secondary Leak Guidelines* (6) provides assurance that in the event of a leak, prompt identification and effective remedial action will be taken.

Based on recent industry events there is still a concern regarding the long term integrity of the sleeve and the parent tube in which the sleeve is installed. An ad hoc Steam Generator Sleeving Review Committee was formed and met with each of the U.S. sleeving vendors to review industry experience with installed sleeves, to review sleeve qualification programs, and to develop a management plan to address sleeving issues. This revised PWR Steam Generator Sleeving Assessment Document is the result of the continuing efforts of this committee.

Field experience to date demonstrates that sleeves and sleeve repairs can be used successfully to prevent tube plugging and keep tubes in service. However, in order for the sleeving or sleeve repairs to be successful, the utility needs to carefully review the information in this assessment document including the field experience reports in Appendix B and the recommendations provided in Section 6.

2

STEAM GENERATOR SLEEVE DESIGNS

Each of the U.S. sleeving vendors, Westinghouse, ABB CE, and FTI, offer several sleeve designs depending upon the location and nature of the parent tube degradation. The tubing from which the sleeves are fabricated is procured to the requirements of the ASME Boiler and Pressure Vessel Code Section II (SB-163) and applicable code case (N-474-1) governing yield strength requirements. The sleeve designs currently installed or being offered are described below.

Westinghouse Designs

Since 1980, Westinghouse has installed over 59,000 sleeves in the steam generators at 17 nuclear plants. The types of sleeves provided by Westinghouse in the past included the following:

- Brazed
- Mechanical hybrid expansion joint (HEJ)
- Laser welded

Presently no Westinghouse brazed sleeves are installed in an operating plant. Westinghouse is currently offering mechanical (HEJ) sleeves and laser welded sleeves.

Hybrid Expansion Joint (HEJ) Sleeves

Figure 2-1 shows a hybrid expansion joint (HEJ) sleeve installed in, and extending above, the tubesheet region. The HEJ sleeve installation sequence includes the following:

1. Tube cleaning
2. Sleeve insertion and hydraulic expansion
3. Lower hard roll
4. Upper hard roll
5. Baseline eddy current inspection

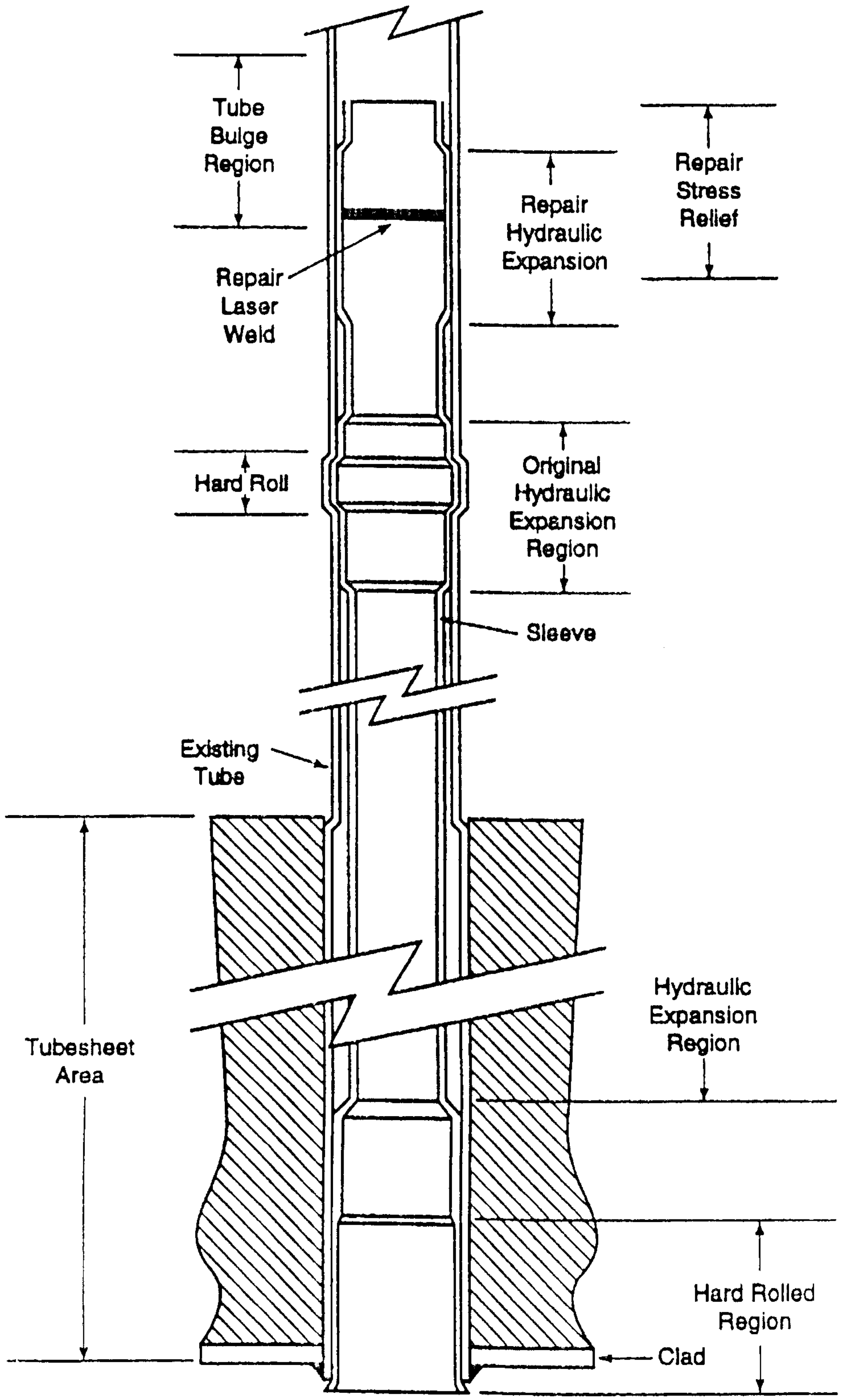


Figure 2-1
Westinghouse Hybrid Expansion (HEJ) Sleeve Installation

The tube cleaning is normally performed with a tungsten carbide tipped brush rotating at 1500 rpm. After the sleeve is inserted, a hydraulic expansion is performed simultaneously at the upper and lower ends of the sleeve to hold the sleeve in the proper position. The hydraulic expansion region is 4.0 inches in length. The hydraulic expansion is a computer controlled process which senses the start of tube bulging by a continuous measurement of the pressure ramp rate. Historically, diametrical tube bulge was limited to 10 mils maximum for HEJ sleeves. The typical tube bulges range from 4 to 7 mils. The tube bulge is confirmed through sampling eddy current profilometric measurements. Following the hydraulic expansion, a lower and upper hard roll expansion is performed. The hard roll provides the structural and leak limiting attachment of the sleeve to the parent tube. After the completion of the sleeve installation, a baseline eddy current inspection is normally performed.

Laser Welded Sleeves

Figure 2-2 shows a laser welded tubesheet sleeve while Figure 2-3 shows a laser welded elevated tubesheet sleeve. Figure 2-4 shows a laser welded tube support plate sleeve. The laser welded sleeve installation sequence includes the following steps:

1. Tube cleaning
2. Sleeve insertion and hydraulic expansion
3. Lower hard roll (tubesheet sleeves)
4. Laser welding, including optional seal weld of tubesheet sleeve lower joint
5. Ultrasonic inspection of all free span welds
6. Stress relief heat treatment of free span welds
7. Baseline eddy current inspection.

The tube cleaning, sleeve insertion, hydraulic expansion, and lower hard roll process (tubesheet sleeves) for the laser welded sleeves are similar to that used in the HEJ sleeve installation process except that the hydraulic expansion is limited to 1 to 3 mils instead of 4 to 7 mils. Except for a limited campaign at Doel 3 in 1988 using a CO_2 laser, all Westinghouse laser welded sleeves in operation were welded using a Nd:YAG laser. The laser welding is a two pass process made with a N_2 cover gas. If the initial weld is rejected, a reweld is made either above or below the initial weld depending on the reason for the initial weld rejection. The optional tubesheet sleeve lower weld provides only a sealing function. This weld is made using the same parameters as a free span weld. All freespan laser welds are inspected by an ultrasonic examination.

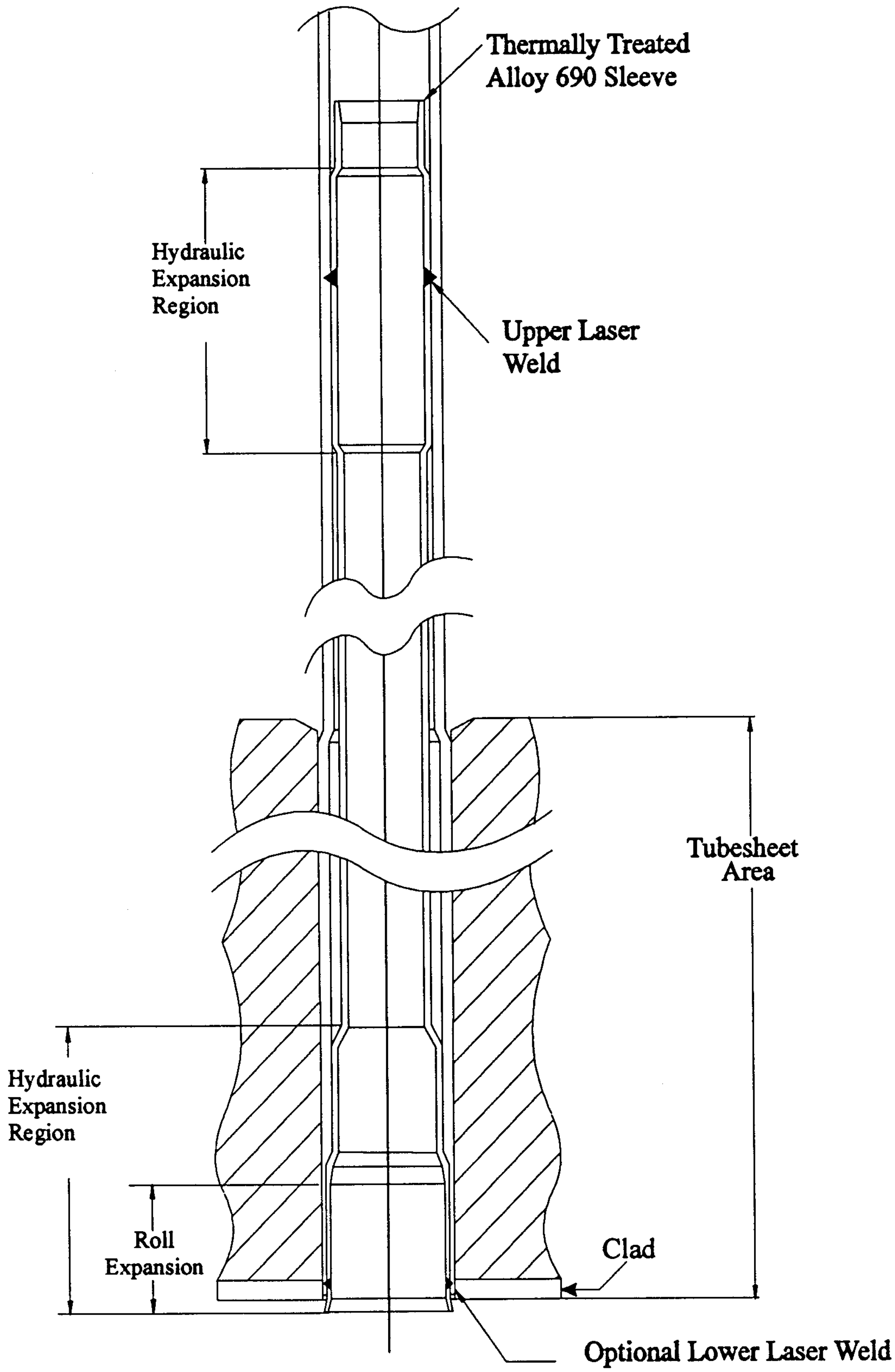


Figure 2-2
Westinghouse Laser Welded Tubesheet Sleeve Installation

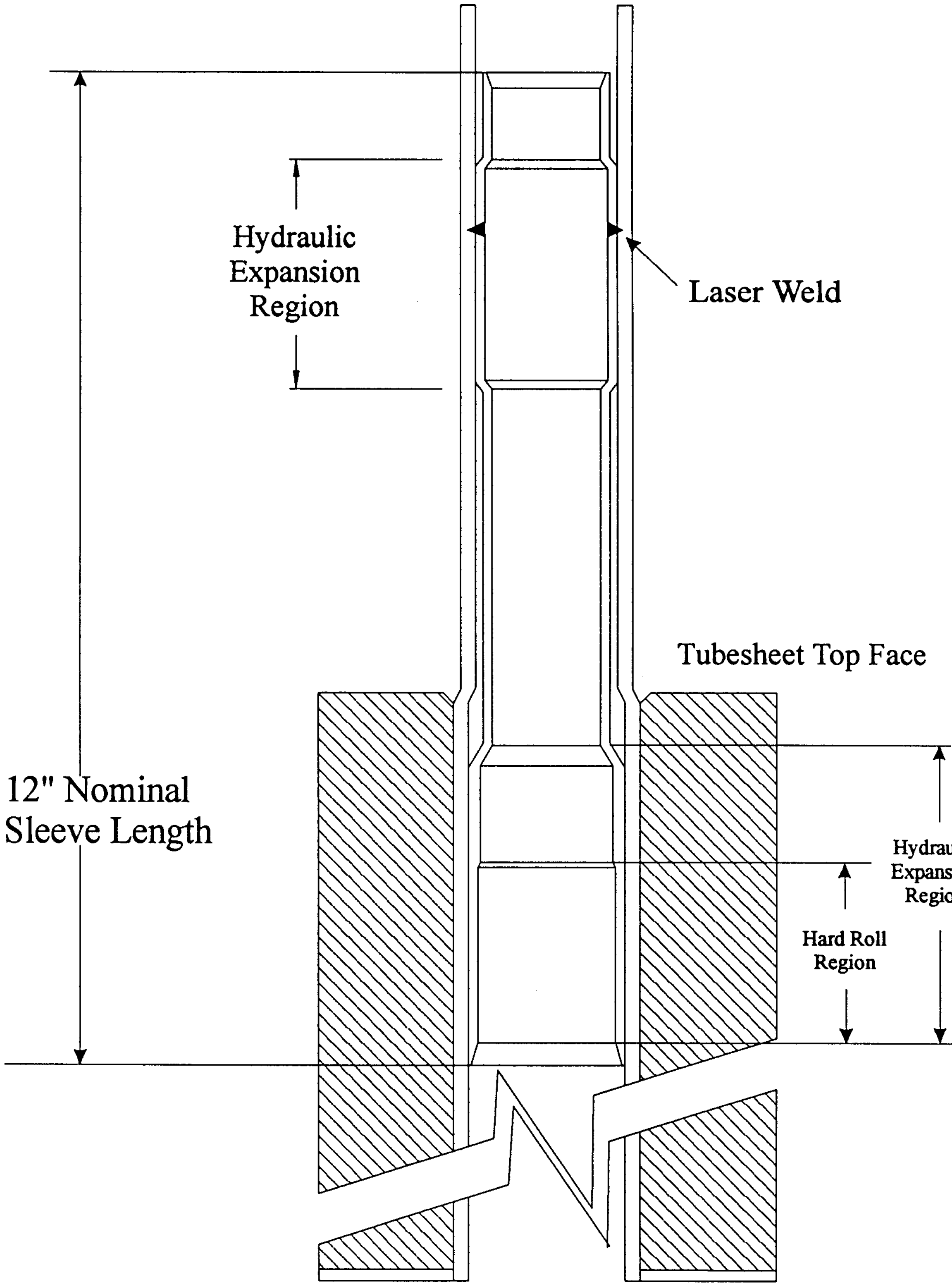


Figure 2-3
Westinghouse Laser Welded Elevated Tubesheet Sleeve Installation

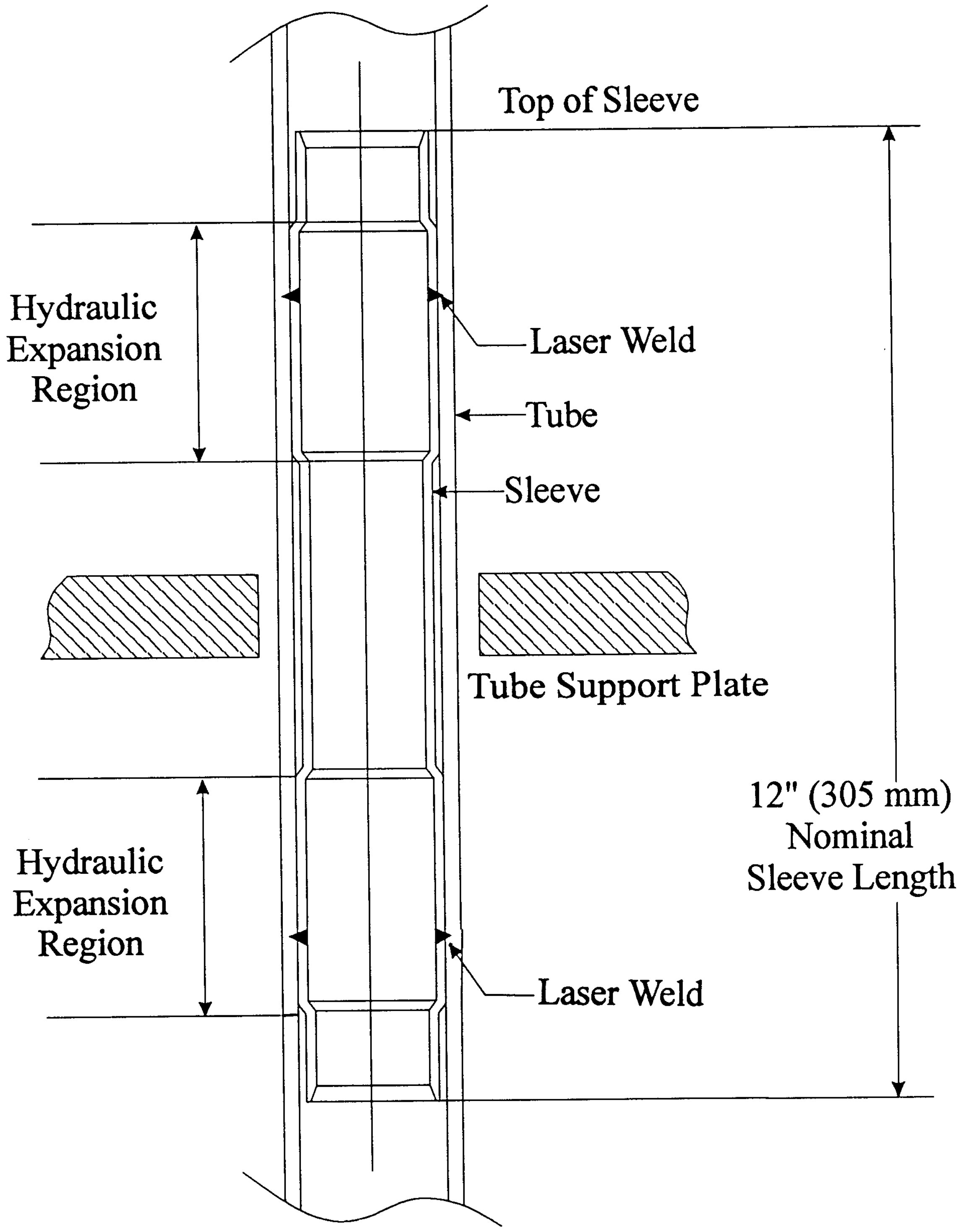


Figure 2-4
Westinghouse Laser Welded Tube Support Plate Sleeve Installation

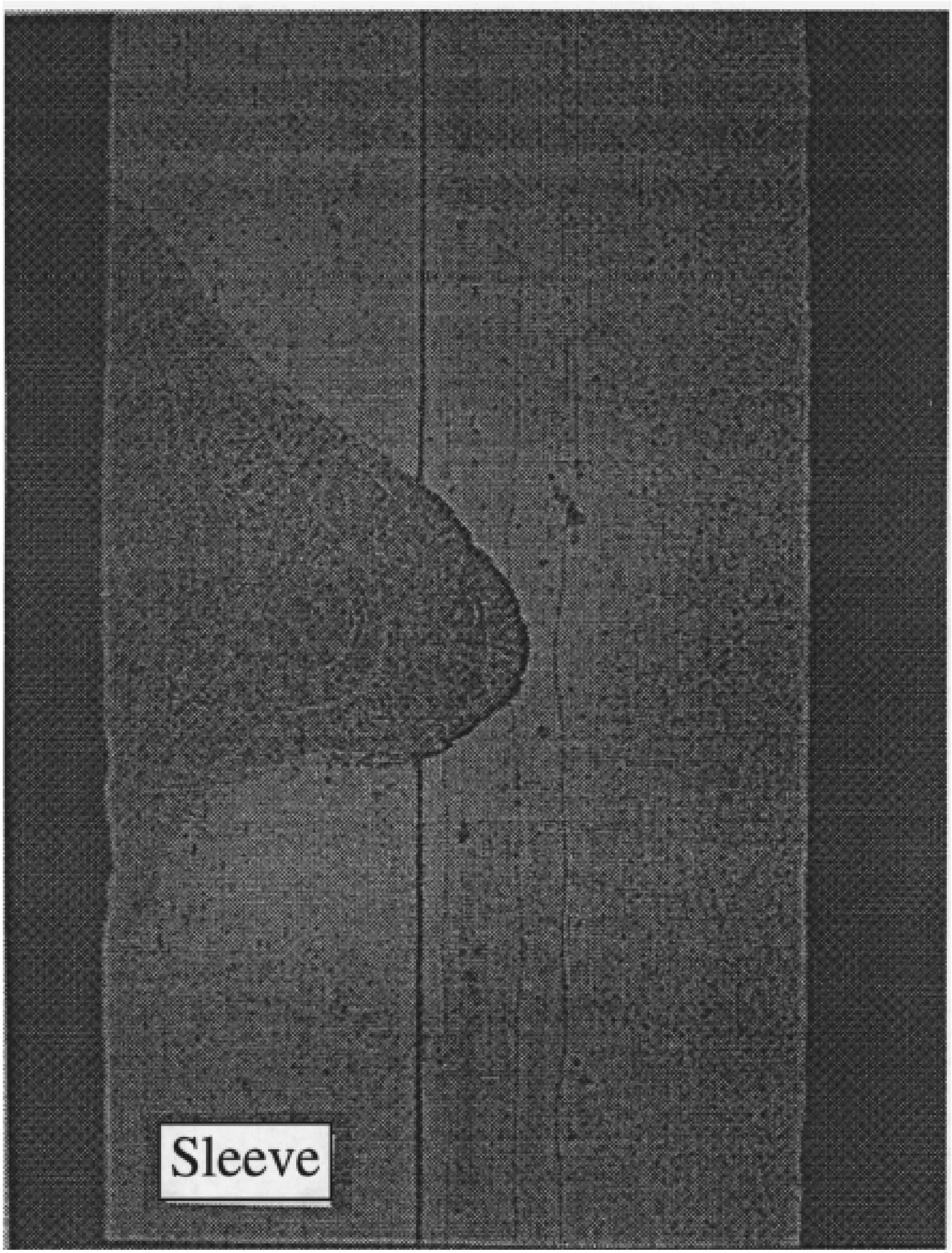


Figure 2-5
Typical Cross-Section of Westinghouse Laser Weld

The nominal weld width is 30 to 40 mils. A minimum ultrasonic inspection criterion of 18 mils ensures the 12 mil width needed for structural requirements and a 6 mil width as a safety margin. Figure 2-5 shows a typical cross section of a laser weld including its penetration into the parent tube.

FTI Designs

FTI has installed over 10,000 sleeves at twenty-one nuclear plants. FTI has a number of sleeve designs for both recirculating and once-through steam generators. The FTI sleeve designs include the following:

- Brazed
- Hydraulic Expanded
- Roller Expanded
- Kinetic
  - Minisleeve
  - Intra-tubesheet
  - Tubesheet (TS)
  - Tube support plate (TSP)

The FTI sleeves are used for (1) the tubesheet region of recirculating steam generators, (2) the tube support plate regions of recirculating steam generators, (3) the tubesheet and upper span of once-through steam generators, (4) the tube support plate region of once-through steam generators.

Brazed Sleeves

The brazed sleeve for recirculating generators is shown in Figure 2-6. The upper freespan joint of the 36 inch long sleeve is brazed while the lower tubesheet joint is kinetically welded. Thermally treated Alloy 600 has been used for the brazed sleeves. The installation process includes the following:

1. Pre-tension tube (option for tubes with locked support plates)
2. Clean tube ID
3. Insert sleeve and kinetic expand upper joint

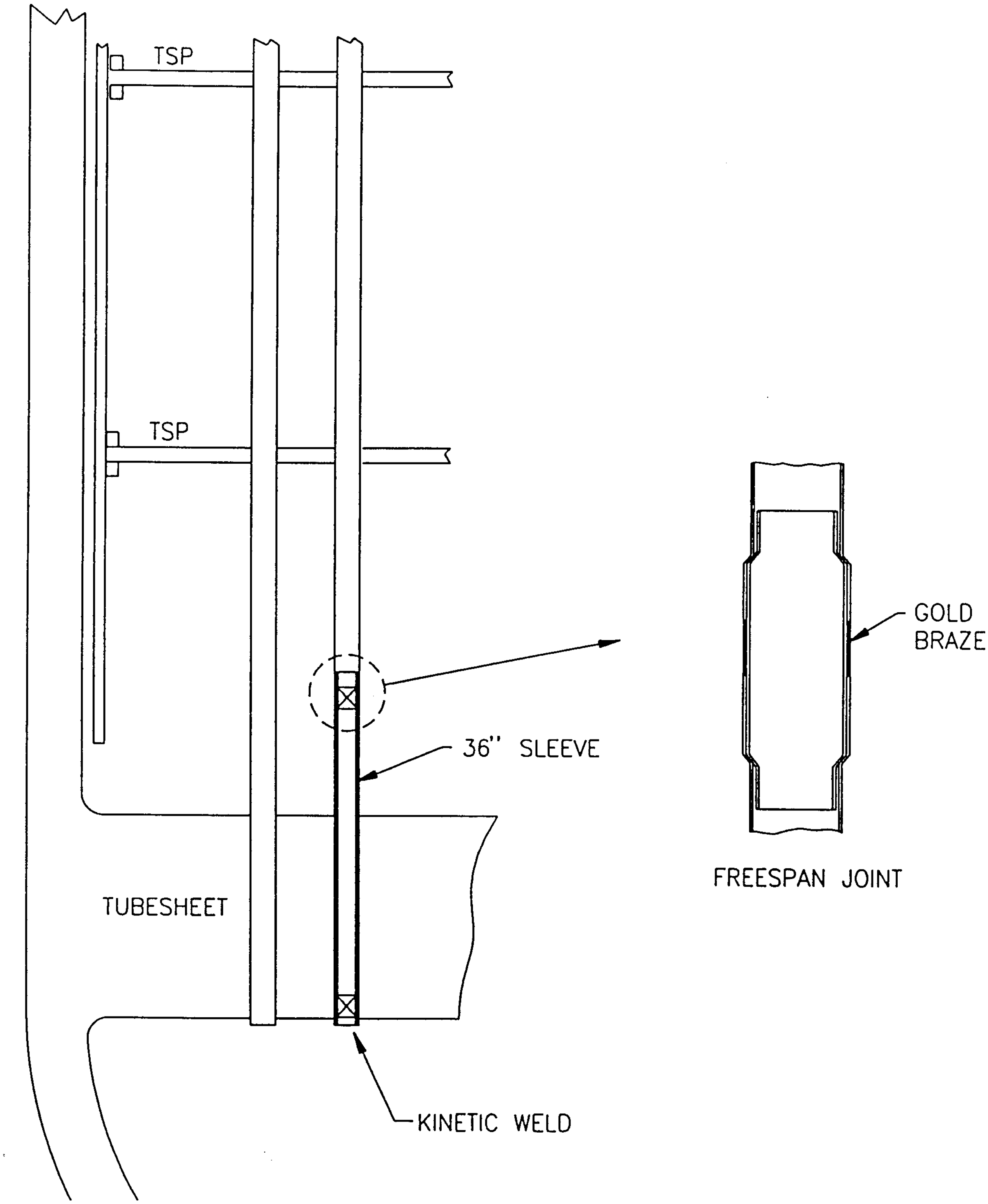


Figure 2-6
FTI Brazed Sleeve

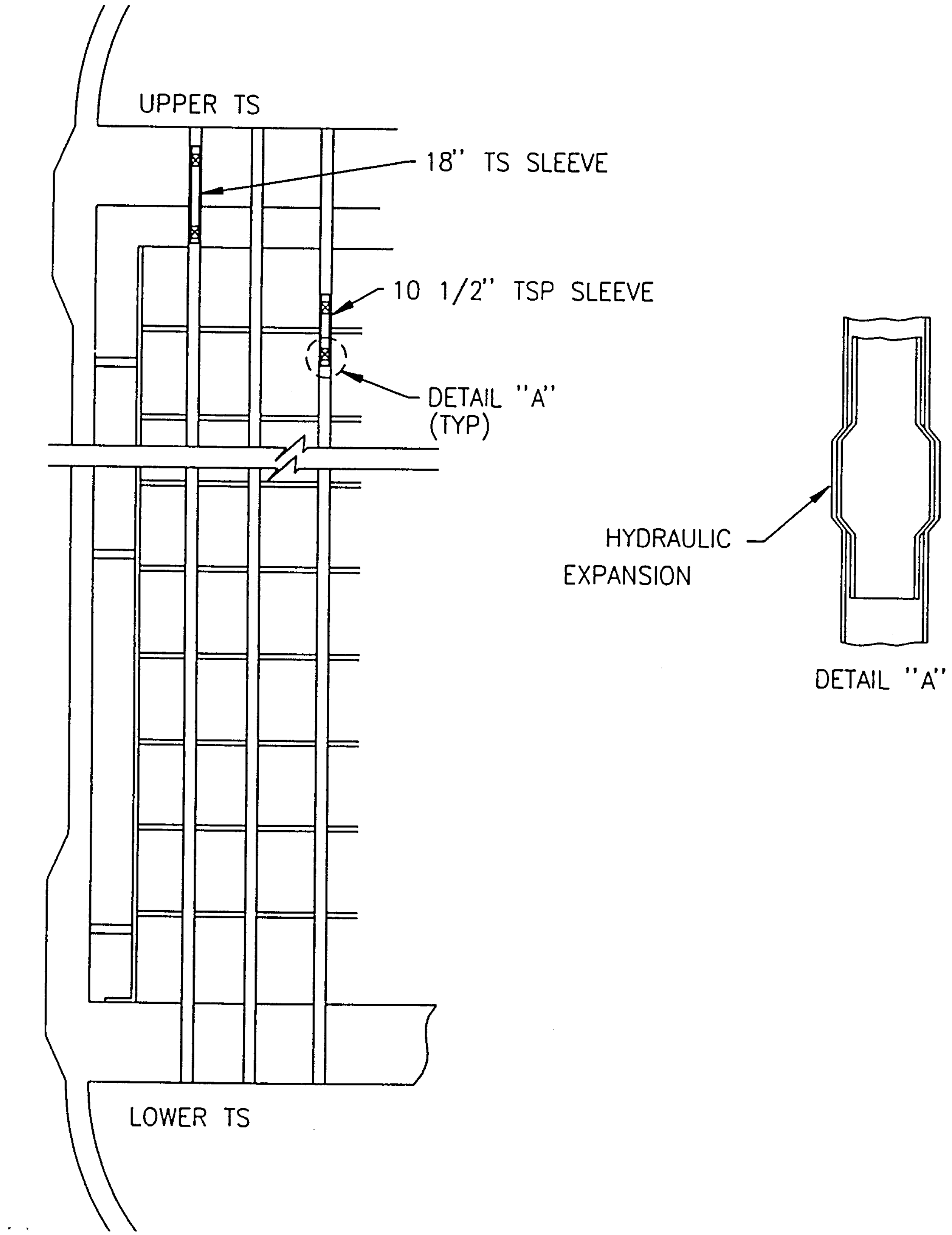


Figure 2-7
FTI OTSG Hydraulic Sleeve

4. Braze upper joint (1870°F)

5. Stress relieve upper joint (1375°F)

6. Kinetic weld tubesheet joint

Hydraulic Expanded Sleeves

Hydraulic expanded sleeves for once-through steam generators are shown in Figure 2-7. The tubesheet sleeve is 18 inches in length while the tube support plate sleeve is 10.5 inches. The installation process includes the following:

1. Insert sleeve and expand the first joint

2. Expand the second joint

Roller Expanded Sleeves

The rolled sleeves for once-through steam generators are shown in Figure 2-8. The rolled sleeves include 31 inch tubesheet sleeves, 80 inch tubesheet sleeves which extend below the upper tube support plate, and 14 inch tube support plate sleeves. Both thermally treated Alloy 600 and Alloy 690 have been used for rolled sleeves. The installation process for the rolled sleeves includes the following:

1. Straighten and insert the sleeve (80 inch sleeve only)

2. Roll expand the tubesheet joint

3. Roll expand the first freespan joint

4. Roll expand the second freespan joint

Kinetic Mini Sleeves

A FTI mini sleeve is shown in Figure 2-9. The mini sleeve was used on a trial basis to span the roll transition region of tubes which are partially expanded in the tubesheet. The mini sleeve had a full length kinetic weld and was made of thermally treated Alloy 600 material. The installation process includes the following:

1. Clean tube

2. Insert mini sleeve and perform kinetic weld

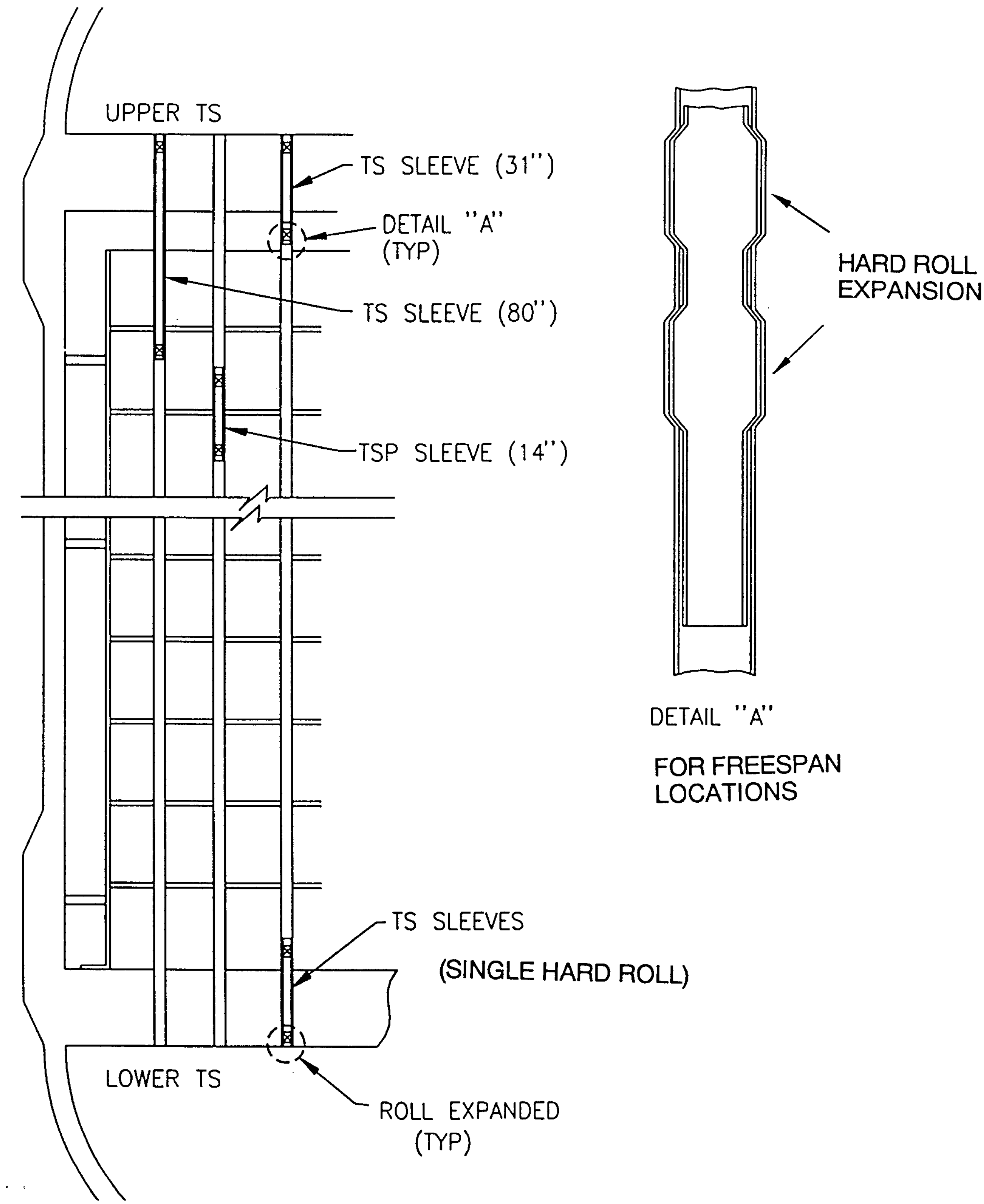


Figure 2-8
FTI OTSG Rolled Sleeve

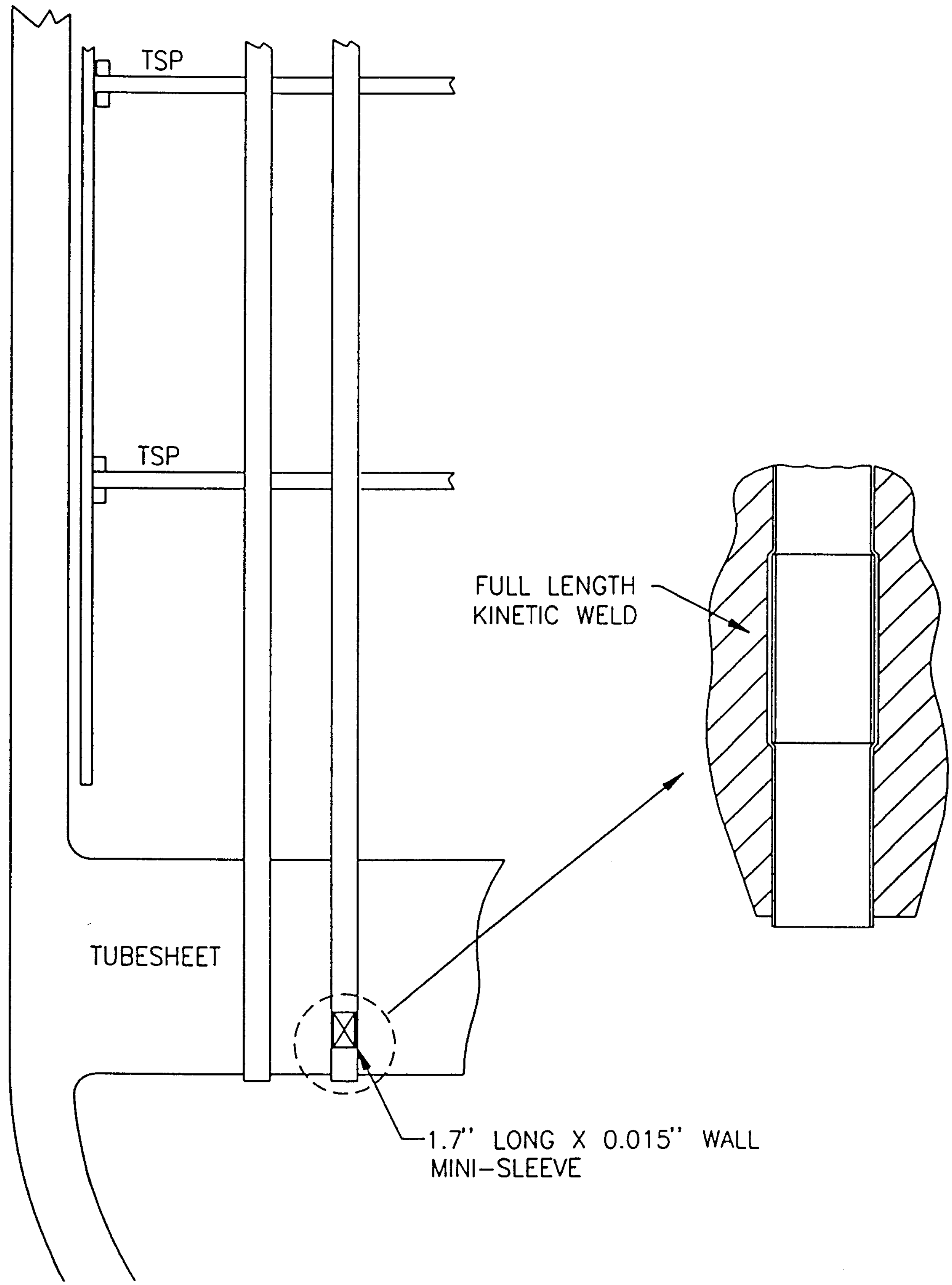


Figure 2-9
FTI Mini-Sleeve

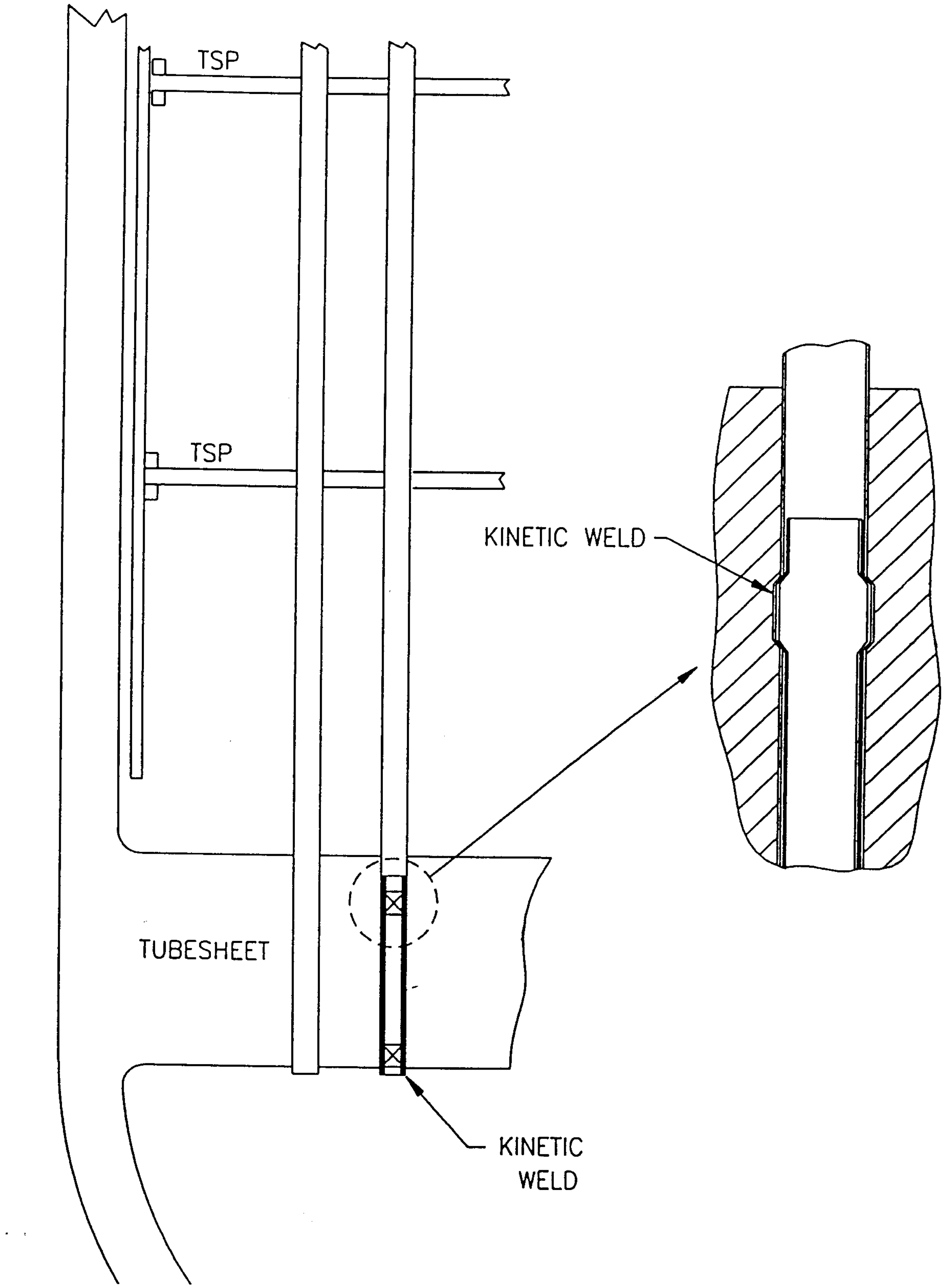


Figure 2-10
FTI Intratubesheet Sleeve

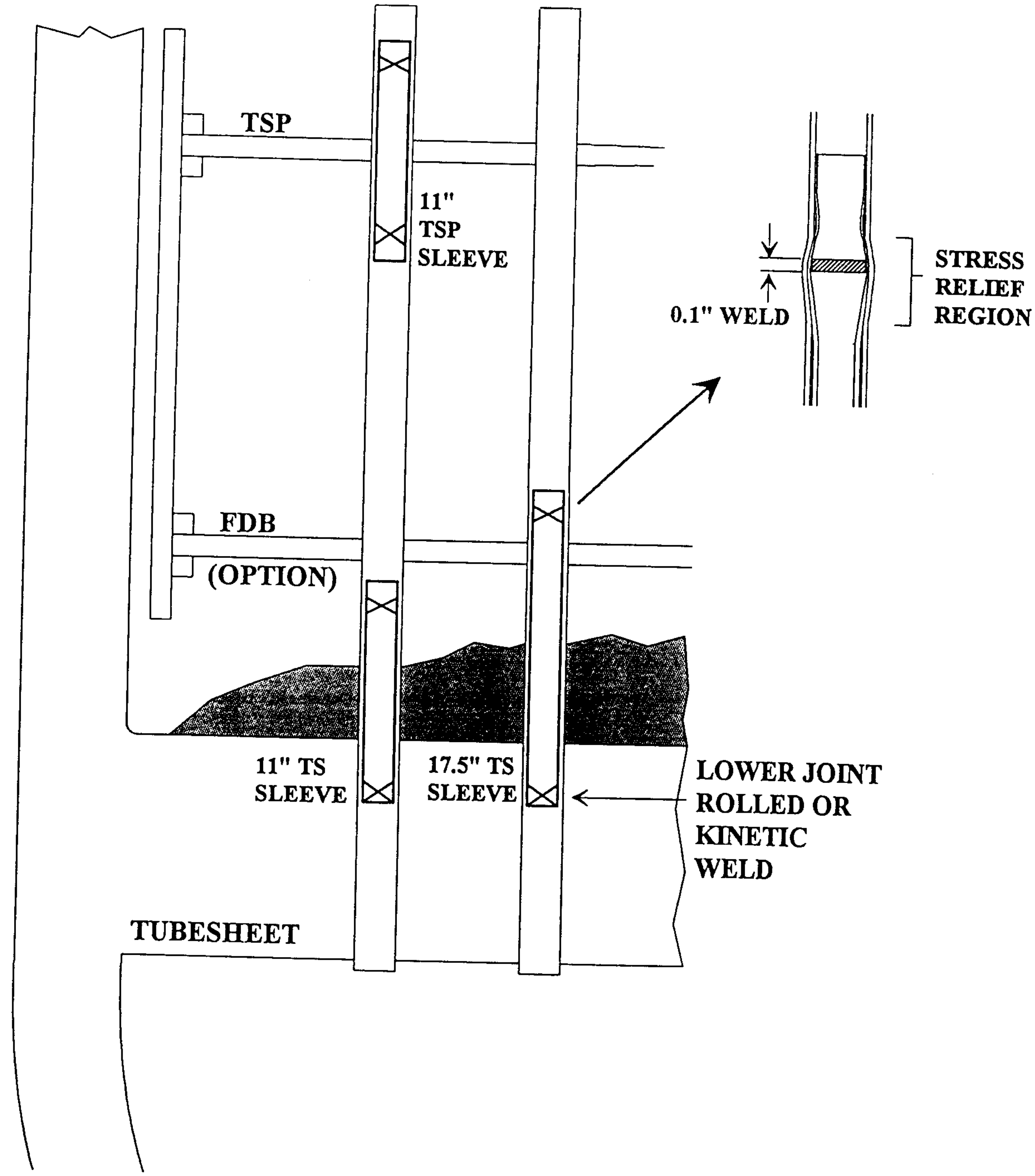


Figure 2-11
FTI Kinetic Tubesheet and Tube Support Plate Sleeves

Kinetic Intratubesheet Sleeves

The kinetic intratubesheet sleeve is shown in Figure 2-10. The intratubesheet sleeve has both an upper and lower joint kinetic weld. Both thermally treated Alloy 600 and Alloy 690 have been used for the intratubesheet sleeve. The installation process includes the following:

1. Clean tube

2. Insert sleeve and kinetic weld upper joint

3. Kinetic weld lower joint

Kinetic Tubesheet and Tube Support Plate Sleeves

Kinetic tubesheet and tube support plate sleeves are shown in Figure 2-11. The tube support plate sleeve is 11 inches in length while the tubesheet sleeves are either 11 inches or 17.5 inches. Thermally treated Alloy 690 has been used for these kinetic sleeves.

The tube support plate sleeve installation includes the following:

1. Clean tube

2. Install sleeve with the double kinetic weld and weld

3. Perform stress relief at 1400°F-1450°F (760C°-788°C) for approximately 6 minutes

The tubesheet sleeve installation includes the following:

1. Clean tube

2. Install sleeve with double kinetic weld and weld
   or
   Install sleeve with single kinetic weld and weld freespan joint

3. Stress relieve freespan weld at 1300°F-1450 °F (704°C-788 °C) for approximately 6 minutes

4. For sleeve with single kinetic weld, roll expand lower joint

The majority of sleeves installed by FTI have been either the roller expanded tubesheet sleeve or the kinetic tubesheet sleeve.

ABB CE Designs

ABB CE has installed over 14,000 sleeves at 14 nuclear plants. ABB CE provides three types of leak tight Alloy 690 welded sleeves identified below:

- Straight tubesheet sleeve
- Peripheral tubesheet sleeve
- Tube support plate sleeve

Each sleeve is TIG welded to the parent tube near both ends of the sleeve. The steam generator tube with the welded sleeve is designed to meet the structural requirements of tubes which are not degraded.

The thermal treatment for the Alloy 690 tubing is specified at 1300°F (704°C) to impart greater corrosion resistance in potential faulted secondary environments. The enhanced corrosion resistance is achieved in the thermal treatment by insuring the presence of chromium healed grain boundary carbides and by reducing the residual stress levels in the tubing. During sleeve fabrication for a peripheral sleeve, an intermediate stress relief anneal is employed to reduce residual stress induced during the forming process. Each of the sleeve types includes a chamfer at both ends to prevent hang-up of equipment used to install the sleeve and to inspect the steam generator tube end and sleeve. The principal sleeving criteria for the sleeve material is its resistance to stress corrosion cracking in primary and faulted secondary environments.

The general sequence of the remotely controlled installation process includes:

1. Brushing and cleaning of the parent tube in the region of both upper and lower sleeve joints
2. Sleeve insertion (includes straightening for the peripheral sleeve)
3. Hydraulic expansion of the sleeve free span joint regions
4. Weld the upper and lower sleeve joints
5. Non-destructive examination
    - Visual inspection of the lower (and upper, when necessary) tubesheet sleeve welds
    - Ultrasonic examination of the free span welds
6. Post weld heat treatment of the free span welds when appropriate
7. Baseline eddy current examination

Straight Tubesheet Sleeves

The first type of sleeve, the straight tubesheet sleeve shown in Figure 2-12, spans the degraded area of the parent tube from the tube end to a variable distance above the top of the tubesheet. The lower end of the sleeve is tapered to provide a tight fit between the sleeve and tube to facilitate welding the lower joint. At the upper end of the sleeve, a hydraulic expansion is done to provide sleeve to parent tube contact for the upper sleeve weld.

Peripheral Tubesheet Sleeves

The second type of ABB CE sleeve, the peripheral tubesheet sleeve shown in Figure 2-13, also spans the degraded area of the parent tube. The sleeves are initially curved during fabrication and straightened during the installation process. The ends of the peripheral sleeve are always straight to prevent welding difficulties. When installed, the peripheral sleeve duplicates the straight sleeve including material, diameter, wall thickness, length, lead-in and weld joints.

Tube Support Plate Sleeves

The third type of ABB CE sleeve, the tube support plate sleeve shown in Figure 2-14, spans degraded areas of the steam generator tube and tube support plate. The tube support plate sleeve can be installed up to the sixth support plate in a Westinghouse Model D steam generator. The leak tight sleeve is welded to the parent tube near each end of the sleeve. The tube support plate sleeve is approximately 8 inches in length. The number of support plate sleeves which can be installed in one leg of a tube depends on the condition of the support plate intersection and the need for stress relief.

PLUSS Sleeves

Recently, ABB CE has introduced and offered a mechanical expansion, leak limiting Alloy 800 sleeve known as the “PLUSS” Sleeve. This sleeve is hydraulically expanded and several expansion schemes have been tested. One design has two hydraulic expansions which result in a 2.5% deformation of the parent tube. The hydraulic expansion is then stress relieved. After hydraulic expansion of the sleeve into the steam generator tube, the spring-back effect of the sleeve will be less than that of the tube because of the lower yield strength of the sleeve. The different spring-back effects of the sleeve and tube cause an interference fit between the ID of the tube and the OD of the sleeve. The sleeve is leak tight at operating temperature due to the higher coefficient of expansion of the Alloy 800. Approximately 1300 of these sleeves have experienced at least one cycle of operation and, to date, have performed satisfactorily.

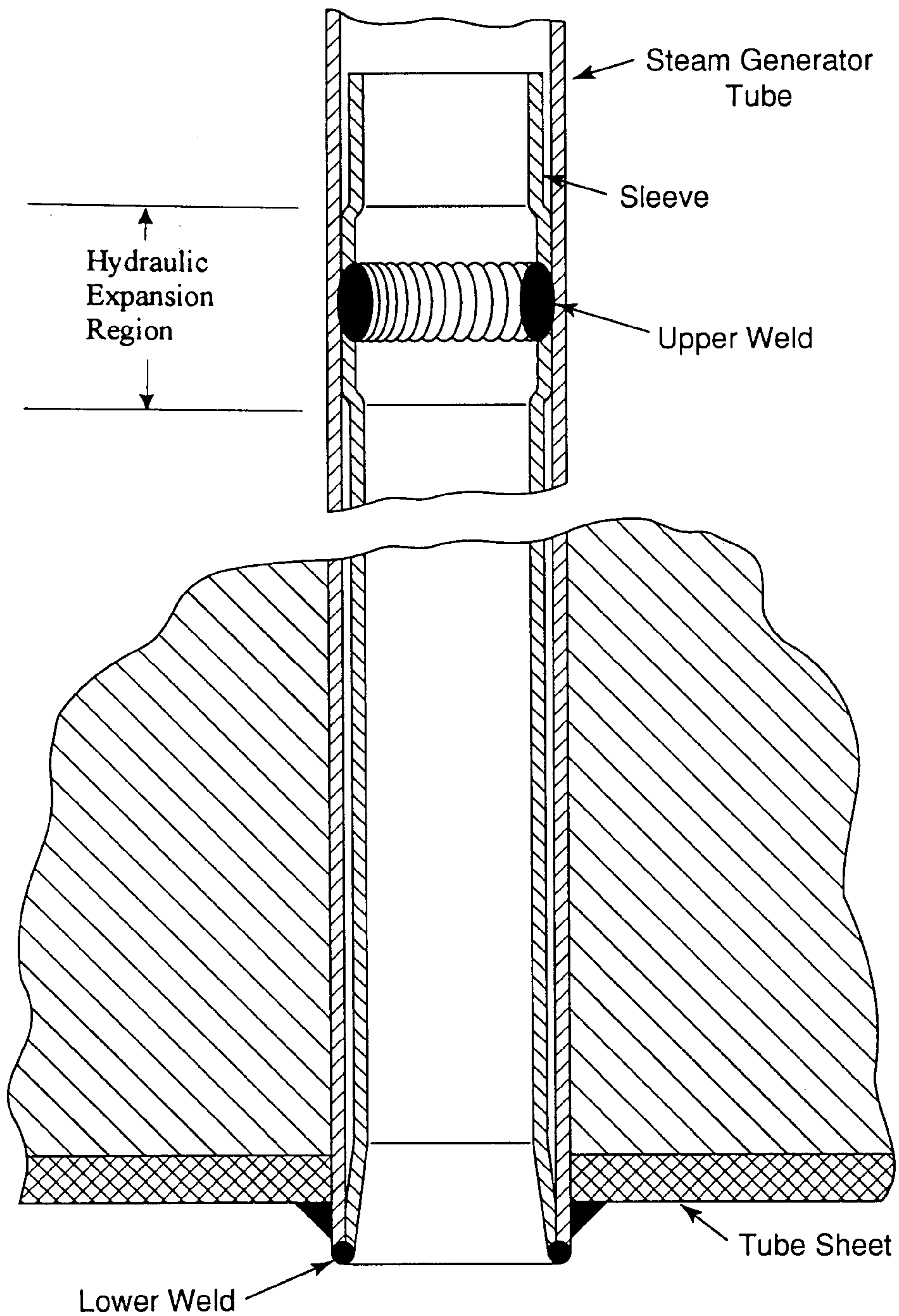


Figure 2-12
ABB CE TIG Welded Sleeve Installation

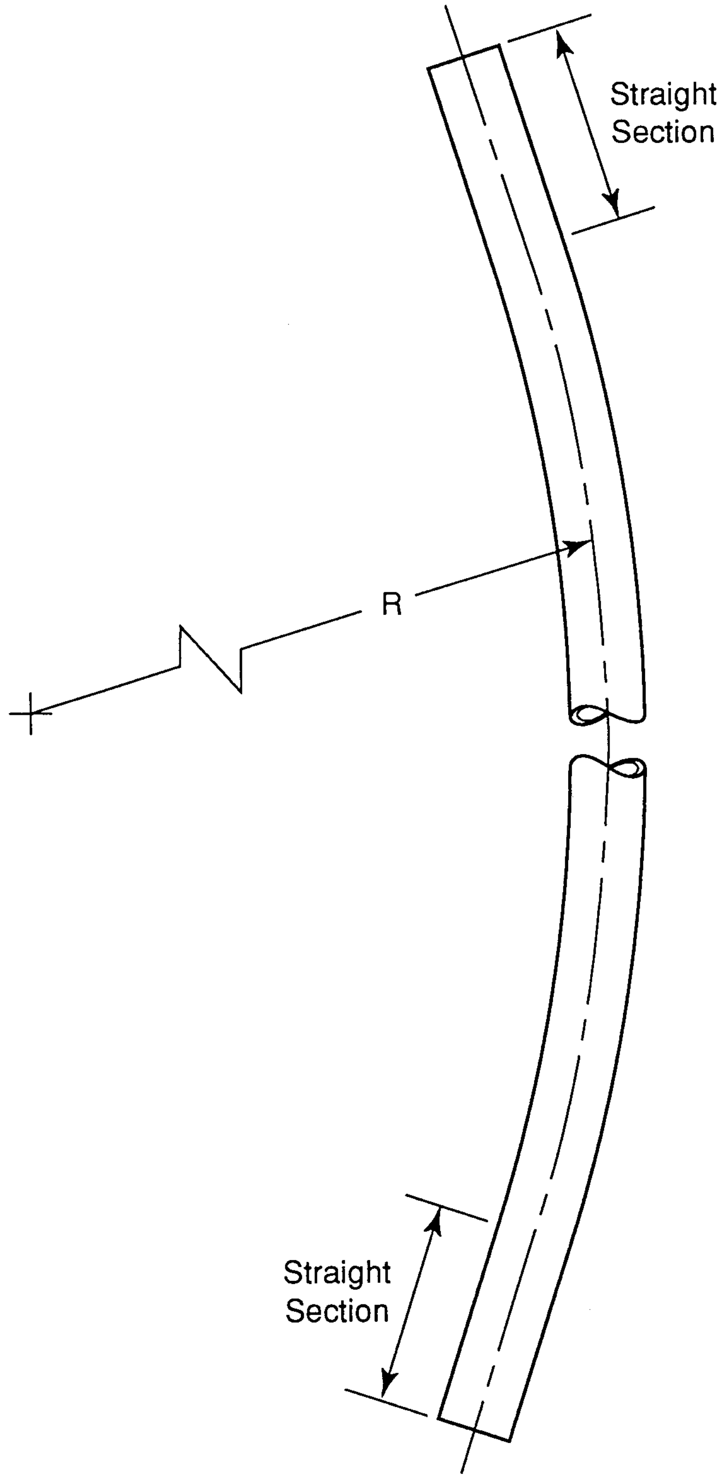


Figure 2-13
ABB CE Peripheral Sleeve

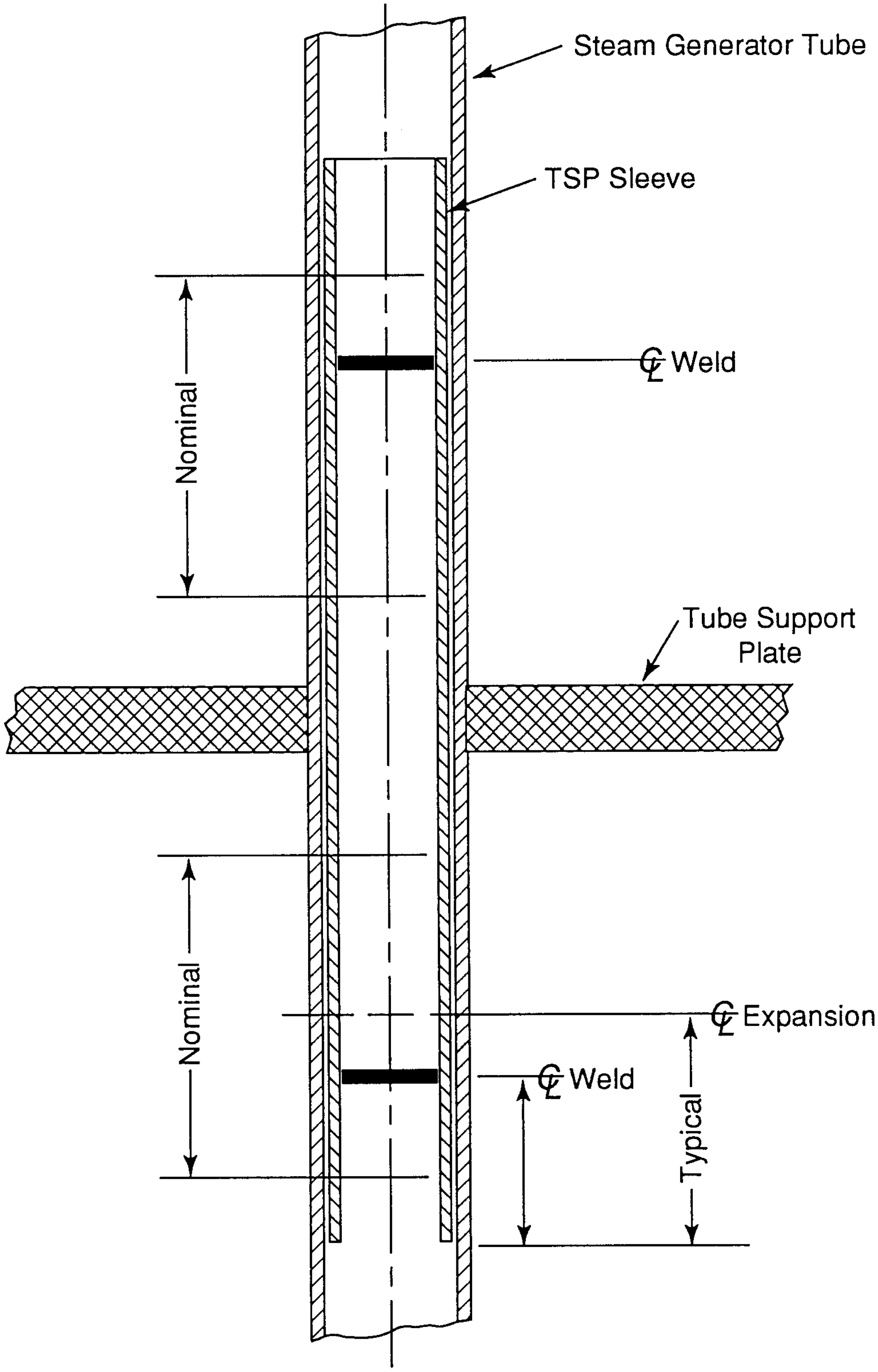


Figure 2-14
ABB CE TIG Welded Tube Support Plate Sleeve Installation

Another "PLUSS" Sleeve design has an upper joint which is called a "zero expansion" process. In this case only a minor amount of plastic deformation of the parent tube occurs such that heat treatment is not required. At operating temperatures this design is leak limiting with a sufficiently low leak rate that a large percentage of tubes with through-wall defects could be sleeved without exceeding a plant's technical specification limit. This design can be applied both in the parent tube expansion transition zone at the tubesheet or at the tube support locations. The lower joint of the tubesheet sleeves is provided by a hard roll in the tubesheet identical to the TIG welded sleeve.

Proposed Sleeve Designs

Several sleeve designs have been proposed as an alternative to the more standard designs which place a sleeve in the tube and connect it with an upper and lower joint. The alternative designs include a nickel deposition electrosleeve and two laser welded direct tube repair techniques. These alternative designs are discussed in more detail below.

FTI Electrosleeve

The FTI Electrosleeve is a structural repair for steam generator tubing. The electrosleeve process provides a continuous bond of high-strength micro-alloyed nickel to the parent tube internal diameter, spanning the defective region. Since no deformation of the parent tube occurs, stress relief is not required.

The present electrosleeve is an advancement based on earlier nickel electroplating performed on European steam generators starting in 1985. Framatome performed nickel plating on over 2000 steam generator tubes at several nuclear plants. The nickel plating in these applications was used as a corrosion protection layer and was also used to minimize primary to secondary leakage. Nickel was selected due to its excellent corrosion performance but was not used as a structural load-carrying repair because of its low mechanical strength. However, advances in nanocrystalline technology have led to the development of a high-strength, micro alloyed nickel electroforming process. This process, known as electrosleeving, was developed by Ontario Hydro to repair Monel 400 steam generator tubing at the Pickering plants. The process has been adapted by Ontario Hydro and FTI to repair Alloy 600 steam generator tubes. The electrosleeve process provides a structural bearing, high strength, microalloyed nickel sleeve. The steps for installing an Electrosleeve include the following:

- Mechanically clean the tube region to be repaired
- Insert an electroforming probe into the tube

- Introduce acid to clean the parent tube
- Introduce a nickel strike solution to electroform a transitional bonding layer
- Introduce a nickel plating solution to form the electrosleeve

- Remove the electroforming probe from the tube

The corrosion performance of nanostructured nickel is equal to or better than polycrystalline nickel. Qualification corrosion testing demonstrated that nanostructured nickel is not susceptible to stress corrosion cracking or intergranular attack under normal steam generator primary or secondary environments. However, ultrasonic inspections are generally required to inspect the parent tube behind the Electrosleeve.

The first field demonstration of the Electrosleeve was the installation of eighteen sleeves at Pickering Unit 5 in May 1994. The Electrosleeves were inspected in 1995 after twelve months of operation and were found acceptable for continued operation. A second demonstration was performed at Oconee 1 in November 1995. A total of nine eight inch sleeves were installed in one steam generator at the first support plate. The sleeves were examined by ultrasonic inspection and found to be acceptable. Since the Electrosleeve was not licensed at the time of installation, the nine sleeved tubes were removed from service prior to startup.

ABB CE Direct Tube Repair

The ABB CE Direct Tube Repair process was initially developed by EPRI and has been licensed to ABB CE. Direct Tube Repair is a process for repairing cracked steam generator tubes by depositing a highly corrosion resistant layer of weld metal on the inner tube surface where the tube is cracked. The deposited layer restores the full integrity of the defective tube with a corrosion resistant alloy. The ABB CE Direct Tube Repair is performed with a continuous wave Nd:YAG laser using a fiber optic delivery system. Fine Alloy 72 weld wire is transported to the weld area through a flexible conduit. The conduit also contains the laser fiber optics and a shielding gas.

Initial development work concentrated on repair of 7/8 inch tubing at the tube support region. Present development includes a system capable of cladding in sleeved 3/4 inch tubing at the tube support location and unsleeved tubes at the tubesheet region. Qualification efforts have evaluated the stress state of the weldment including the residual welding stresses in the heat affected zone in the Alloy 600 tubing adjacent to the weld deposit, corrosion performance in primary and secondary side environments, and mechanical properties of the repair. Ultrasonic and eddy current inspection procedures are also being developed.

Westinghouse Direct Tube Repair

Westinghouse has also developed a laser welded Direct Tube Repair process for restoring degraded steam generator tubing. This process represents an extension of the Westinghouse Laser Welded Sleeve process discussed earlier. In the Westinghouse Direct Tube Repair process, the degraded region of the tube is melted to a depth of thirty to eighty percent of the tube wall thickness from the ID surface using the focused energy of a laser beam and a spiral overlapping weld pattern. The chemistry of the melted material is enriched by the addition of a high chromium filler metal. Two different approaches for adding the filler metal have been qualified. One approach uses a consumable insert which is expanded in place prior to the welding and the other approach uses a filler wire which is fed to the weld area.

The primary advantage of the Direct Tube Repair process is the ability to repair tube degradation above a sleeved location. The smaller restriction in the flow area and the length of the repair compared to a sleeve provides for a minimal impact on the thermal-hydraulic performance of the steam generator. The nominal repair length is approximately one inch.

The Direct Tube Repair qualification testing includes determining mechanical properties such as tensile, burst, low and high cycle fatigue, and corrosion testing using doped steam and caustic solutions. The accelerated corrosion tests were performed under tensile preloads derived from making the Direct Tube Repair welds and applying post-weld stress relief heat treatment under conditions simulating locking of the tube at tube support plate intersections.

Acceptance testing of the repair is performed using ultrasonic testing and eddy current testing. Plans are to perform in-service inspections using only eddy current techniques. The Direct Tube Repair effort for 7/8 inch tubing is essentially complete with the exception of on-going NDE qualification to *PWR Steam Generator Examination Guidelines* (7). It is anticipated that a utility license amendment package for field implementation will be submitted to the NRC by the end of 1997.

3

STEAM GENERATOR SLEEVE QUALIFICATION PROGRAMS

Vendor qualification testing is performed for new sleeve designs and for modifications and installation changes to previously tested designs. A typical test program is intended to accomplish the following:

- Confirm that the installation method produces the required joint strength and leak tightness
- Confirm that the joint in both the sleeve and parent tube has sufficiently low stresses to provide acceptable resistance to stress corrosion cracking
- Test the entire range of anticipated process variables
- Confirm that the installation equipment and procedures perform satisfactorily

A test program can consist of a number of different elements including mock-up testing, sleeve design, mechanical testing, structural and vibration analysis, stress evaluation, accelerated corrosion testing, installation verification, and sleeve inspection. Since in-service failures have been driven by high residual stress resulting in stress corrosion cracking, this report will concentrate on the corrosion qualification testing performed.

Accelerated corrosion testing is used to demonstrate the effectiveness of the proposed sleeving process. The purpose of the testing is to demonstrate that the residual stresses in the sleeve and parent tube are low enough that the potential for stress corrosion cracking is reduced to a low level. There are, however, several limitations with accelerated corrosion testing. The accelerated corrosion tests may not accurately simulate in-generator tube degradation mechanisms and the accelerated tests may not accurately duplicate the same stress threshold for cracking as the actual mechanical conditions and operating environment. However, these accelerated tests are the only practical way to get laboratory corrosion information in a timely manner.

Previous EPRI work indicates that a practical threshold for PWSCC in susceptible Alloy 600 tubing is very close to the conventional proportional limit, roughly 80% of the engineering yield strength (8) . A typical value is 40 ksi. The stress threshold for stress corrosion cracking in the secondary crevice or sludge pile is not well known but may be closer to 25 ksi. Consequently, accelerated corrosion tests used to evaluate sleeve designs should also have a stress threshold not greater than these values. Many accelerated tests have very low threshold stress levels and can be extremely conservative. If a sleeve design is tested under extremely aggressive conditions and found resistant, it is likely that the design will perform well in service provided that the mock-up simulates all known inservice stresses.

A number of accelerated test methods have been used . These include the following:

- Stainless steel tubes in boiling magnesium chloride

  Specimens which have tensile stresses in excess of roughly 15 ksi will fail by stress corrosion cracking in less than one day. The test is simple to run and is effective in identifying regions of residual stress, However, since Alloy 600 will not crack in this environment this test should not be used for combinations of complex materials with different thermal expansion characteristics, *i.e.*, Alloy 690 or Alloy 800 in combination with Alloy 600, which can impose additional operational loads. In addition, it would be extremely difficult to impose stresses due to heat transfer.

- Sensitized tubing in polythionic acid or sodium tetrathionate

  Sensitized Alloy 600 specimens which have tensile stresses in the order of 8 - 10 ksi will fail by intergranular stress corrosion cracking in as little as 24 hours. Intergranular attack can also be found on the test specimens and can complicate the interpretation of results. Test environments and techniques have been developed to reduce this complication (9). The test requires that the tubing be in a “sensitized” (grain boundary chromium depleted) condition which can require heat treatments which may lower the yield strength. Since the magnitudes of residual stresses developed after any fabrication steps are directly related to the starting yield strength, mockup samples made using sensitized tubing may not contain prototypic residual stresses. In addition, if stress relief treatment is to be applied, the treatment could “desensitize” the parent tube and become less sensitive to cracking even though stresses are still present. Stresses imposed from a joint with other materials, i.e., Alloy 690 or Alloy 800 during a stress relief treatment might be evaluated. However, differential expansion or thermal stresses during operation cannot be simulated since the test is run near room temperature.

- Ten percent sodium hydroxide

  With this test an electric potential can be applied to the specimen to accelerate the corrosion attack. Specimens which have tensile stresses on the order of 10 ksi have failed by stress corrosion cracking in as little as 36 hours. Without an electric potential, elevated temperatures are used to accelerate corrosion attack. Tests in this environment are usually performed in an autoclave at a temperature in the range of 600°F-662°F (316°C-350°C). Cracking in this environment is intergranular and steam generator tubing does not require a special heat treatment to make it sensitive to stress corrosion cracking. The test does, however, appear to work better for tubing with high yield strengths. Tubing with chromium depleted grain boundaries (sensitized) can be quite resistant to cracking. Capsule tests can be designed which will provide stresses due to differential expansion and pressure, but stress due to heat transfer is difficult, if not impossible, to simulate.

- Primary water tests at elevated temperatures

  Primary water tests at temperatures between 600°F-662°F (316°C-350°C) have also been used. The control of dissolved hydrogen gas and concentrations of lithium and boric acid can also influence aggressiveness. The increased temperature can accelerate the time to cracking by roughly a factor of two for every 18°F (10°C) above the steam generator operating temperature. The threshold stress for cracking should be close to that of service, however, the time required for cracking may exceed the patience of the investigator or the resources of the funder. Parent tube material susceptibility plays an important role in determining whether this test condition produces results within the constraints of the test program. The accelerating factor and stress threshold levels need to be verified using control standards such as C-rings, U-bend samples, or expansion transition mockups. Tests in this environment can provide the opportunity to simulate stresses imposed by both differential expansion and heat transfer if designed properly.

- Elevated temperature steam tests

  Elevated temperatures on the order of 750°F (400°C) have been used to accelerate corrosion attack. The accelerating factor and stress threshold levels need to be verified using control standards. This test can accelerate the time to cracking by factors of at least 10 compared to steam generator service at threshold levels close to that of service. A concern expressed about tests performed at 750°F (400°C) is that residual stresses which have not caused cracking in the short term might relax after prolonged exposure. Good evidence to support this concern is limited. Tests performed under these conditions could overemphasize the influence of differential expansion stresses, and may not have been performed with realistic heat transfer conditions. However, without this heat transfer, the inside diameter stresses will become more tensile than with heat transfer and should be more conservative.

- Elevated temperature doped steam tests

  Elevated temperature steam tests with contaminates such as Cl^-, F^-, and $SO_4^=$ have been used to accelerate the corrosion attack of the steam tests. The accelerating factor and stress threshold levels need to be verified using control standards. The doped steam tests can accelerate the time to cracking by a factor of 200 compared to service. Since the time to cracking in this environment is accelerated even more than the pure steam test, the concern for relaxation over the test period is reduced. As with the pure steam tests, stresses due to the lack of heat transfer and higher differential expansion stresses could be conservative.

Westinghouse Qualification Testing

Westinghouse sleeve test programs cover a number of different areas including the following:

- Physical positioning of the sleeves
- Tube cleaning
- Sleeve expansion
- Joint structural integrity
- Joint leak-tightness
- Welding (Laser Welded Sleeves)
- Thermal stress relief (Laser Welded Sleeves)
- Residual Stresses
  - HEJ Sleeve
  - Laser Welded Sleeve

The sleeves have been tested using prototypic Alloy 600 mill annealed tubing and in tubing having known low resistance to PWSCC.

Testing of Westinghouse HEJ sleeves was performed in the early 1980’s. Early testing in boiling magnesium chloride and polythionic acid environments were used to evaluate the residual stress in the HEJ upper joints. The results of these early tests are summarized in Table 3-1.

Table 3-1
Estimates of Maximum Residual Stresses (Axial) in the Expansion Transitions of an Alloy 600 HEJ Sleeved Joint from Early Laboratory Qualification Testing

	Hydraulic Expansion	Mechanical Expansion
Sleeve ID		~ 35-40 ksi
Parent Tube ID	~ 30 ksi	~ 35 ksi
Parent Tube OD		~ 20 ksi

In addition to the expansion residual stresses, the joint experiences operational stresses. The principle operational stresses are those from the pressure differential across the tube. These can be 5-6 ksi in the axial direction and 10-12 ksi in the hoop direction. Heat transfer can also apply stresses in the joint which are slightly compressive on the ID and slightly tensile on the OD. The absolute value of the heat transfer stresses are difficult to determine since exact temperatures have not been measured. However, they are probably less than 5 ksi and can be ignored from primary stress calculations since they are compressive which would add a degree of conservatism. Estimates of sleeve joint life from these early stress results gave factors of 7 to 8 times that of a roll transition. The worst case estimate (i.e., 46 ksi for an HEJ sleeve joint and 66 ksi for a roll transition) gave a factor for the HEJ sleeve of 4.4 times that of the roll transition.

Accelerated testing was also performed with primary water at 680°F (360°C), a temperature higher than normal hot leg temperatures. For mill annealed tubing, the multiplier on life between a 615°F (324°C) hot leg condition and the autoclave temperature of 680°F (360°C) has been reported to be 6-20 times (10).

Outside diameter corrosion tests were performed under caustic conditions using a 10% sodium hydroxide solution at 600°F (316°C) with an applied potential of 140 mv to accelerate the cracking. Results of the above tests indicated acceptable corrosion resistance for the HEJ assemblies in the test environment. Experience shows that higher than anticipated residual stresses are occurring in operating steam generators and corrosion degradation can proceed at a much faster rate than the qualification tests would indicate.

A series of corrosion tests were also performed for the Laser Welded Sleeves. In the first series of tests the Laser Welded Sleeves were tested in a 750°F (399°C) doped steam test environment with a 1500 psi pressure differential. A portion of the Laser Welded Sleeves were stress relieved either with a fixed heater or in a furnace. Roll transition mock-ups were used as a reference condition for resistance to PWSCC. The Laser Welded Sleeve mock-ups cracked at approximately 1.4 times longer than the roll

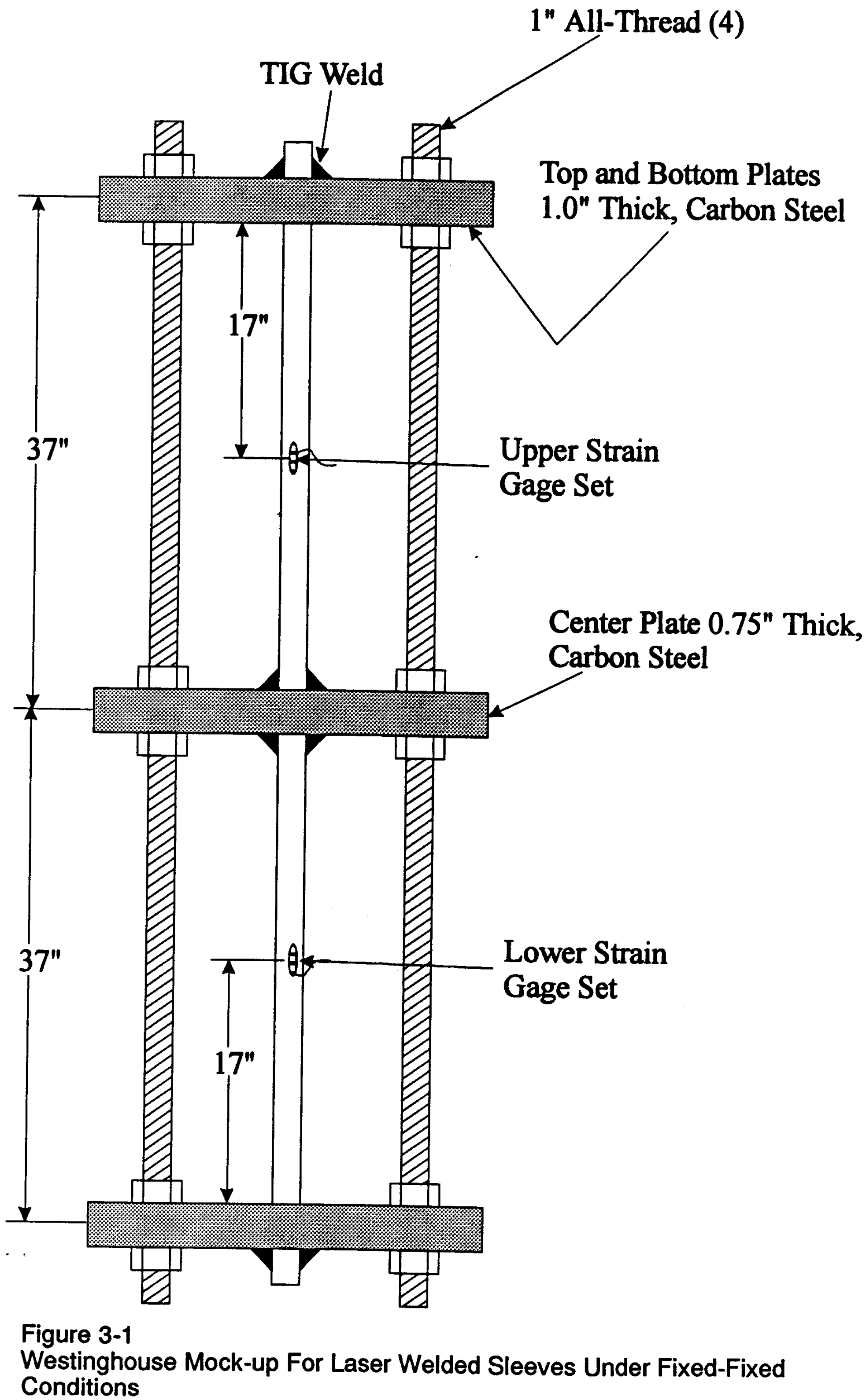


Figure 3-1
Westinghouse Mock-up for Laser Welded Sleeves Under Fixed-Fixed Conditions

transition mock-ups. The stress relieved Laser Welded Sleeve mock-ups exhibited approximately 10 times the corrosion resistance compared to the roll transition mock-ups.

In the second series of tests, the Laser Welded Sleeves were stress relieved with a vertically oscillating heater to minimize the temperature gradients. Testing was again done in a doped steam environment with a 1500 psi pressure differential. The stress relieved specimens exhibited less than 20 percent through-wall cracking at approximately 2 times the time-to-crack for roll transition specimens.

In the third series of tests, Laser Welded Sleeve mock-ups were fabricated under fixed-fixed conditions (see Figure 3-1) and thermally stress relieved with a fixed heater in the range of 1400°F -1600°F (760°C - 871°C) for five minutes. Testing was again performed at 750°F (399°C) with a pressure differential of 1500 psi. Axial loads of 17 ksi derived from the mockup test were applied to these corrosion samples. The time for cracking for the Laser Welded Sleeve specimens was approximately 3 times that for the roll transition specimens. Subsequent mock-up testing showed that even higher axial loads are obtainable and these higher loads will be factored into future tests.

FTI Qualification Testing

The qualification of FTI sleeves was performed to address the many technical issues associated with sleeving including determination of residual stresses and corrosion resistance of the sleeved tube assembly. Tests were performed to both qualitatively and quantitatively determine stresses at joint locations. These included x-ray diffraction measurement of residual stress, finite element modeling of the sleeve installation process, and stress indexing corrosion tests. Both sodium hydroxide and magnesium chloride were used for stress indexing corrosion tests. In some instances, sodium tetrathionate was also used. C-rings stressed to various levels were used to index stress severity.

Corrosion testing of the FTI OTSG mechanically rolled sleeves was performed in the early 1980’s. The initial sleeve was designed utilizing Alloy 600, thus these sleeves focused on both the sleeve and tube performance. Current sleeves are fabricated from Alloy 690. The original corrosion tests were performed exposing all areas of the installed Alloy 600 sleeve and parent tube in a 10% NaOH solution at 550°F (288°C) with an applied potential of +190mV. Samples were exposed for durations of 360 hours and 480 hours. The tests indicated SCC formed on the sleeve ID in the roll transitions after 480 hours of exposure. No SCC was found in the parent tube material. The tests indicate that these Alloy 600 sleeves may require repair sometime during their service life. X-ray diffraction residual stress measurements were also performed on the parent tube ID in the freespan roll transitions. The maximum residual tensile stress measured was approximately 30 ksi. This stress level combined with the OTSG tubing indicates acceptable performance should be expected in regard to stress corrosion cracking.

Extensive corrosion testing was performed on the FTI kinetic sleeve. However, a key aspect to the original tests was that the sleeves were tested in mock-ups where the tube was free to expand, *i.e.*, locked tubes in the steam generator were not modeled in the original corrosion tests.

The first kinetic sleeve test was performed in sodium tetrathionate in order to estimate residual stress in the kinetic weld joint. Six specimens were tested for an exposure time of 29.5 hours. The results indicated that residual stresses in the parent tube at the stress relieved joint are approximately 8 ksi. A second stress indexing test was performed on the kinetic weld joint utilizing a caustic environment. Five specimens were tested for up to 480 hours in 10% NaOH at 550°F (288°C) with +190mV potential applied and no differential pressure. Parent tube C-rings in the test with stress as low as 11 ksi exhibited SCC as well as the non-stress relieved kinetic welded parent tube. No stress relieved joints had SCC.

Two separate caustic tests were performed on kinetic sleeved tubes with applied operating differential pressure. The test environments were 10 % NaOH at 550°F (288°C) with +190mV applied potential. Stress relieved and non-stress relieved samples were included as well as reference tube roll transitions and stressed C-rings. The samples were exposed for 360 hours. Original tube roll transitions cracked with SCC as well as C-rings stressed to 20 ksi. Stress relieved kinetic welds exhibited no SCC.

An additional longer term corrosion test was independently performed by Laborelec on kinetic welded sleeves. Two specimens, one stress relieved and one not stress relieved, were tested in 10% NaOH at 598°F (350°C) and 1300 psig differential pressure. Four tube roll transitions were also included in the test. The tube roll transition samples cracked 100% throughwall in 55 to 116 hours, the non-stress relieved sleeved tube cracked 100% throughwall in 160 hours. The stress relieved kinetic weld sample was removed from the test after 2821 hours. A 40% throughwall stress corrosion crack was found. The stress relieved kinetic joint lasted more than 25 times longer than a roll transition.

The original corrosion tests indicated that the kinetic sleeve was acceptable. However, tests were performed in tubes not locked at the tube support plate. Subsequent corrosion tests, along with mock-up strain tests and finite element analysis, showed that if the tube is locked at the tube support plate, the stress relieved joint will have high stresses in the parent tube and is not acceptable for long term operation.

ABB CE Qualification Testing

Extensive tests have been performed on the ABB CE welded sleeve design. Sleeves were welded into steam generator tube mock-ups to confirm that the welded joints were leak tight. Weld parameters were established by performing a series of welds and sectioning the welds to ensure that the sleeve design requirements were met. The welded joint process was qualified to ASME Section XI requirements where applicable. In addition, site specific qualification testing was performed for tube cleaning using mock-ups with pot boiler and inservice tubes. Additional site specific qualification was performed for sleeve expansion and for weld variables including electrode standoff, tube thickness, and tube ovality. A series of corrosion tests, including capsule and autoclave tests, were performed to estimate residual stress and corrosion resistance. A summary of a series of capsule corrosion tests is provided in Table 3-2.

Pure water autoclave tests were performed on as-welded sleeves in susceptible Alloy 600 tubing. No cracking was observed in the sleeve or parent tube in times approximately twice that required to crack reverse U-bend (RUB) samples.

Table 3-2
ABB CE Capsule Corrosion Tests

Environment	Exposure Time	Test Results
Cl^-	120 days	No attack in weld or heat affected zone
SO_4=	120 days	No attack in weld or heat affected zone
Anion and Cation Resin	90 days	No attack in weld or heat affected zone
10 % NaOH	30 days	No attack in weld or heat affected zone
Mod. Huey		No attack in weld or heat affected zone Attack to parent tube

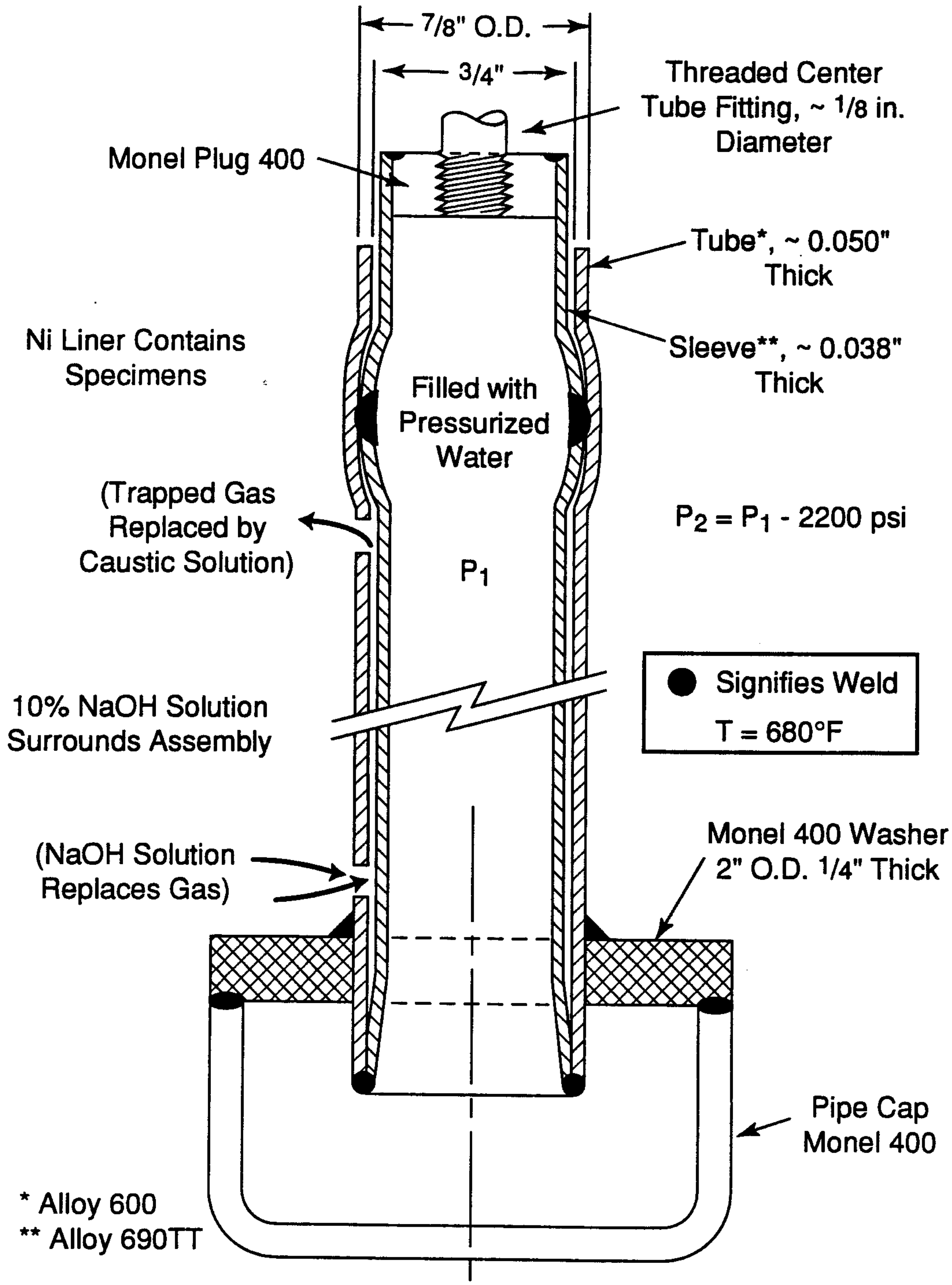


Figure 3-2
Typical ABB CE Caustic Corrosion Autoclave Test Specimen

Caustic corrosion autoclave tests were performed with a 10% NaOH solution at 660°F (349°C). A typical autoclave test specimen is shown Figure 3-2. These tests demonstrated that post weld heat treatment resulted in an increase in the time to cracking of 2.5 to 5 compared to non-post weld heat treated specimens. The post weld heat treated samples cracked at times equivalent to C-ring specimens having an axial stress of 40 ksi.

Tests on pulled sleeved tubes were also performed. Five non-post weld heat treated sleeved tubes installed in Ringhals 2 in 1985 and 1986 were removed and examined in 1990. The sleeved tubes had accumulated up to 916 effective full power days (EFPD) and showed no evidence of field service degradation.

Independent Qualification Testing

A number of independent sleeve qualification tests have also been performed. Laborelec undertook a comparative test program on tubes repaired by laser, TIG, and kinetic welding. Mock-ups were manufactured from the same parent tube by different vendors including ABB CE, FTI, and several European vendors (11). The results of the Laborelec test program showed that a post weld heat treatment was necessary for the tubing which was sensitive to PWSCC. The temperature and method of the heat treatment were also important. Within the heat treatment range specified, the highest temperatures provided the best results.

Laborelec also performed an independent qualification of the Westinghouse Laser Welded Sleeves prior to their installation at Doel 4. Caustic corrosion tests were performed on two series of test specimens. In the first series, a fixed heater was used to stress relieve the laser weld. In the second series, an oscillating heater was used to increase coverage. The results of the testing showed that the oscillating heater provided the best results and that the heat treatment range specified by the vendor must be strictly followed. The highest stresses occurred at the toe of the weld which extends into the parent tube. Laborelec concluded that these stress levels were acceptable for the time period the sleeves were to be installed prior to the planned Doel 4 steam generator replacement.

The life of the installed HEJ sleeves at Doel 4 has been roughly the equivalent to that of roll transitions. This implies that the stresses in an HEJ sleeve joint are equivalent to those in a roll transition (i.e., roughly 65 ksi). The Westinghouse testing program discussed earlier indicated that the life of the HEJ sleeve joint should be 7 to 8 times that of a roll transition. This testing, although extensive, evaluated only the joint and did not account for all sources of stress as in the full sleeve. When determining the root cause for the Doel 4 HEJ sleeve failures, Laborelec performed caustic stress corrosion tests on different types of mock-ups and showed that high residual stresses resulted mainly from a hydraulic expansion and that the sleeve installation sequence, *i.e.*, mechanical rolling of upper and lower joints, can modify the stresses. The stress levels found were in the range of the stress levels for roll transitions, in agreement with the rapid failures of the sleeves at Doel 4. However, other factors may have further decreased the life time in the plant. These include lockup of the parent tube at the first support plate, operational interaction with the flow distribution baffle, IGA on the inner surface of the parent tube, and differential thermal expansion of the Alloy 600 tube and Alloy 690 sleeve.

Laborelec determined that the sleeve installation sequence was a significant factor and estimated that an additional 28 ksi could be added to the upper hydraulic expansion. This additional stress could bring the stress levels of the HEJ sleeve in the range of the stress levels for the roll transition. The early qualification testing of the HEJ sleeves did not include the influence of the installation sequence, *i.e.*, the simultaneous expansion of both the upper and lower joints, mechanical hard rolling of the lower joint, and the mechanical roll of the upper joint. One of the lessons from the Doel 4 experience is that testing of the full sleeve and tube assembly needs to account for the same installation procedures as those used in the field.

Since the observation of bulging in laser repair welded HEJ sleeves and the laser welded sleeves, both given a stress relief treatment, the initial assumption that tubes were not locked in the tube support plates was put into question. During removal of sleeve samples at a following outage in 1995, it was determined that the tubes were in fact locked at the support plates due to deposits which filled the annulus between the drilled support plate holes and the tubes. This occurrence was unexpected because 1) both the support plate and tubing material are highly resistant to general corrosion, and 2) it is believed the corrosion deposits were not due to these parent materials but were the result of crevice deposition.

4

STEAM GENERATOR SLEEVE INSPECTION

Eddy Current Sleeve Inspections

Just as the steam generator sleeve designs have evolved, so to have the techniques used to inspect the sleeves. The original focus on sleeve inspection was to verify that the sleeve installation was properly performed and to provide a baseline inspection for parent tube integrity. The current emphasis is on providing the most sensitive and reliable inspection techniques to detect and size degradation in the parent tube behind the sleeve and at the sleeve joints.

Rotating Probe Driver

Initial sleeve examinations in the late 1970's and early 1980's were performed using a Zetec SM-6 Rotating Probe Driver with a fixed probe head. The probe driver rotated on an assembly and was retracted by a racking or moving of the probe driver away from the fixed snorkel assembly. This technique was very slow and radiation exposure intensive. One plant in 1983 developed an alternative technique which used basically the same technology placed on a wand assembly which was controlled at the tube sheet face and used a pair of pancake coils connected differentially. This technique could detect a 40% ASME hole at the transitions and free span of the parent tubing. Because axial flaws were the expected damage mechanism, this technique was replaced with a faster cross wound bobbin technique.

Cross Wound Bobbin Probe

In 1981 the Cross Wound Bobbin Probe was developed to detect discontinuities and variations in sleeved tubing. This probe was composed of differential bobbin coils crossing at mid point as shown in Figure 4-1. This technique was very similar to the bobbin coil in that it was differently connected, but the upper 180 degree segment and the lower 180 degree segment were on two different planes. The second coil was offset just opposite the first. This meant that on each side of the probe the coils crossed like an "X". This also meant that at those locations where the coils crossed there was a blind spot. To compensate for this, an additional set of coils was added with the "X" 90 degrees from the previous set of coils. The Cross Wound Bobbin Probe was capable of

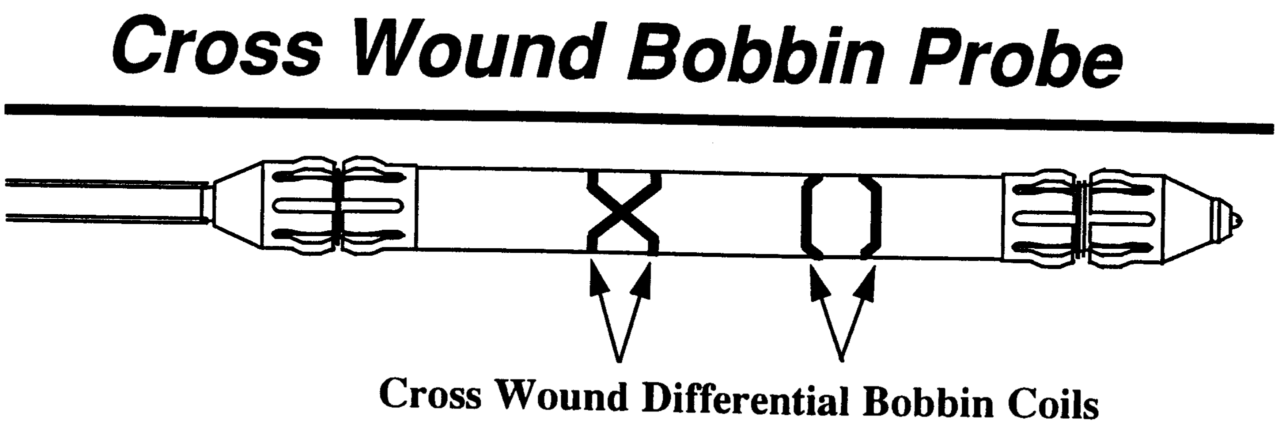


Figure 4-1
Cross Wound Bobbin Probe

achieving high inspection speeds and provided both diametric data and flaw detection. This technique was qualified to detect ASME 40% flat bottom holes at expansion transitions, freespan, and weld interfaces in the parent tubing. The data from this probe was fairly complex. The two sets of coils were separated by an axial distance and had to be analyzed separately. Non-symmetric expansion transitions could mask flaw indications or could be interpreted as a flaw (false positive). The Cross Wound Bobbin Probe was also insufficient for detection of circumferential indications.

Axial Differential Rotating Coils

In 1985, axially oriented directional coils which are differentially connected were also used by one utility for sleeve examinations. This provided detection of 40% ASME flat bottomed holes in the parent tube at the tube to sleeve interface where the parent tube is part of the pressure boundary. The differential connected coils would eliminate any axisymmetric condition. This technique was inherently noisy at geometrical interfaces. The coils are orthogonal to the circumferential cracking, but being differently connected, a 360 degree flaw would not be detected. This process was the first attempt using rotating probe heads for sleeve examinations.

AKTS MRPC

The AKTS motorized rotating pancake coil (MRPC) was developed for the inspection of laser welded sleeves and is shown in Figure 4-2. This probe design takes advantage of two coils entering geometry and weld affected zones at the same time thus eliminating their effect. A bobbin coil was also included to provide location information and geometry changes. The probe showed good sensitivity to circumferential flaws and had a high signal to noise ratio. The probe was not sensitive to non-circumferential flaws and had a relatively slow inspection speed.

"I" Coil MRPC

The "I" Coil MRPC was developed to offer the detectability of both axial and circumferential oriented flaws and is shown in Figure 4-3. The probe body contains two directionally wound coils that induce current into the sleeve and parent tube in both the axial and circumferential direction. The coil size and shape were modified from previous designs to enhance the probes sensitivity to both ID and OD flaws. This technique provided detection of 40% EDM notches at the transition zones in the parent tubing behind the sleeve. Geometric conditions provided challenges to detection and the inspection speed was relatively slow. This coil was superseded by the MRPC Plus Point Probe to enhance detection capabilities at geometric locations.

MRPC Plus Point Probe

The MRPC Plus Point Probe, shown in Figure 4-4, was developed to add to the capabilities of the "I" Coil MRPC by eliminating unwanted signals due to geometry conditions. The probe design takes advantage of two directionally wound coils differentially paired to cancel non-relevant indications. By differentially connecting the directional coils, a better signal to noise ratio is achieved with this probe. This technique provides detection of 40% EDM notches at the expansion transitions in the parent tubing and has been qualified to the requirements of Appendix H of the *PWR Steam Generator Examination Guidelines* (12) for HEJ sleeves. Like other MRPC probes, the Plus Point has a relatively slow inspection speed.

A magnetic bias MRPC Plus point Probe has also been used on several occasions to inspect welded sleeves. A magnetic bias is added to the probe to eliminate permeability effects caused by the welding process. The appearance of the magnetic bias is essentially the same as the non magnetic bias probe. The magnetic bias probe has typically not provided substantial improvement and has only seen limited use.

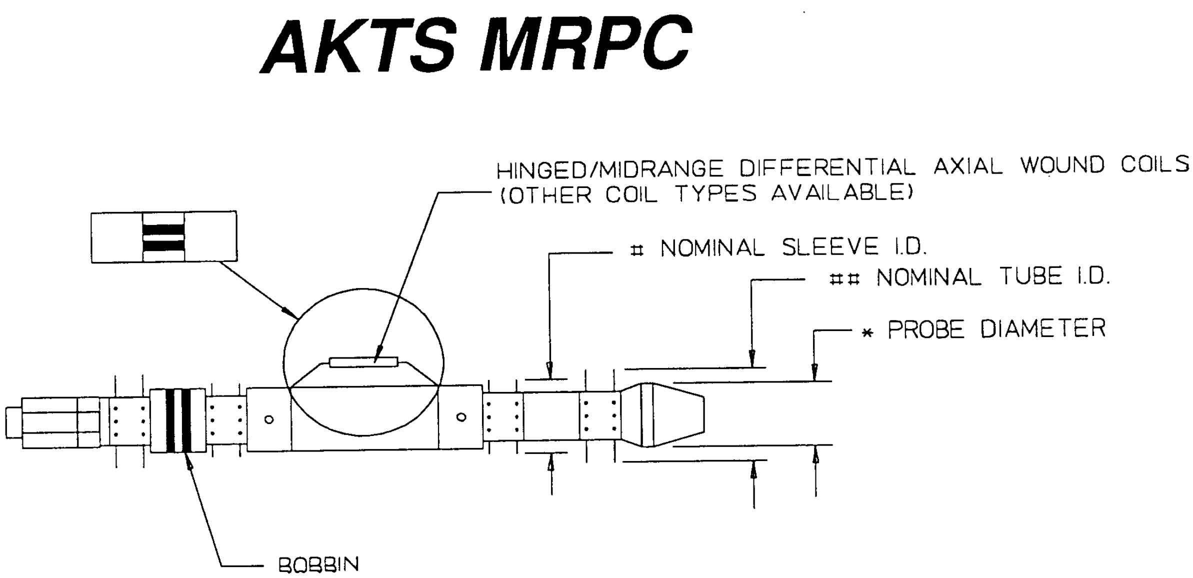


Figure 4-2
AKTS MRPC Probe

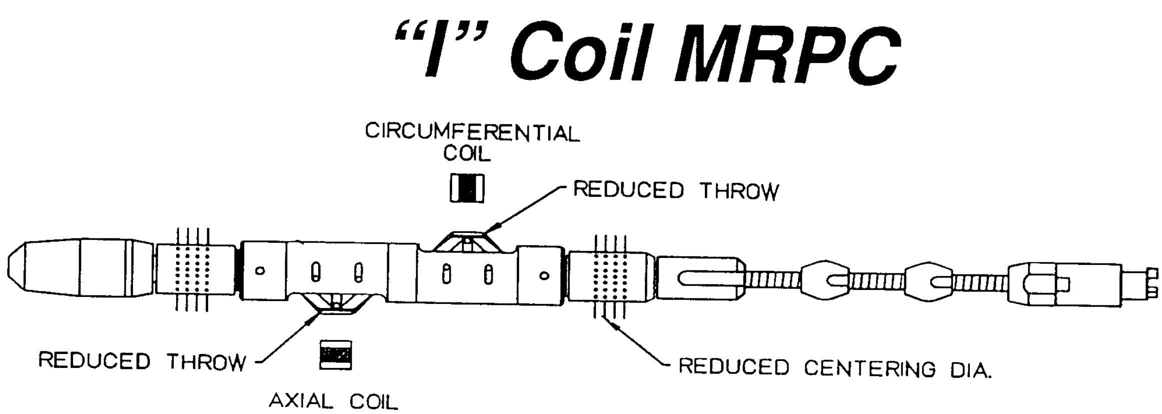


Figure 4-3
"I" Coil PRPC Probe

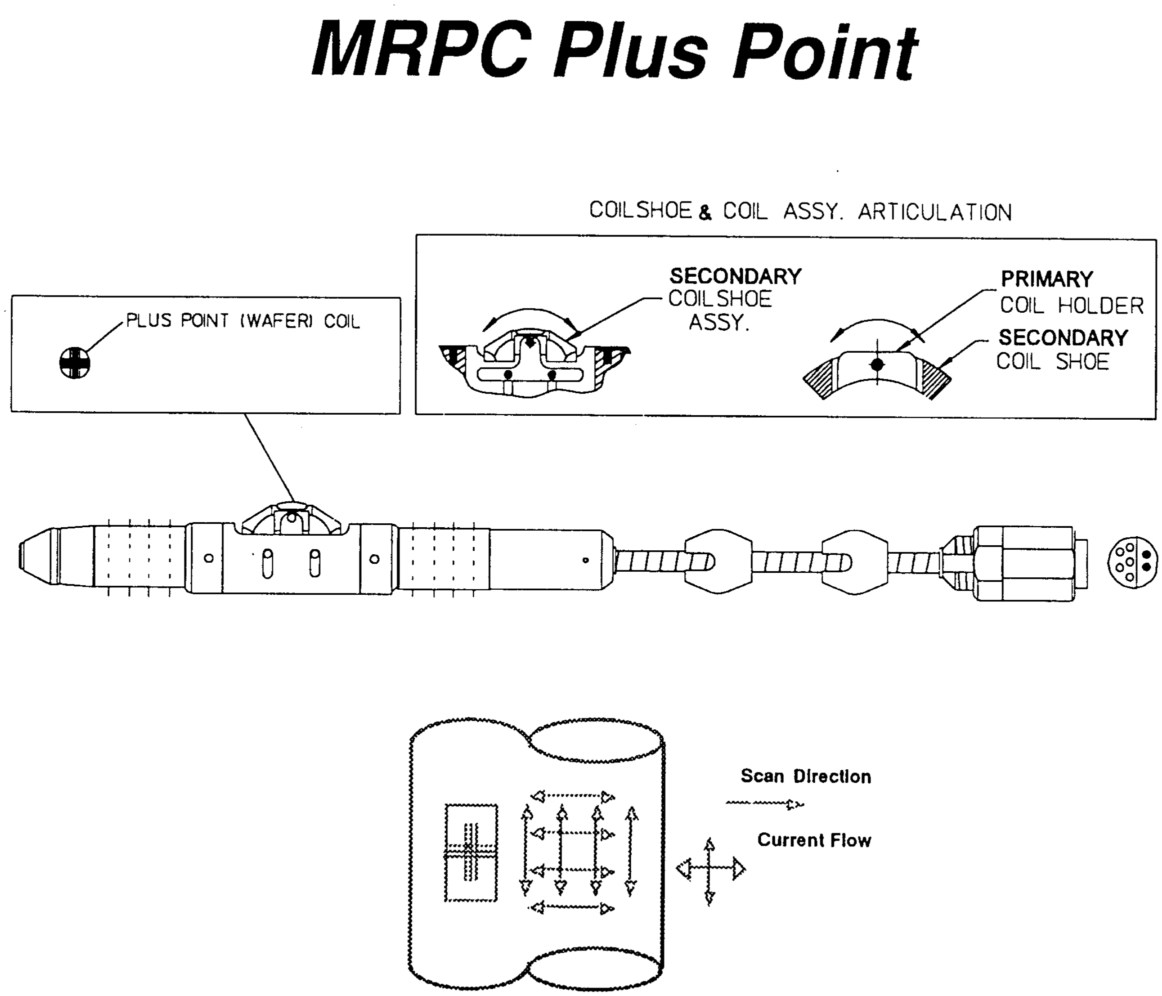


Figure 4-4
MRPC Plus Point Probe

Combination Probe

The Plus Point Sleeve Combination Probe shown in Figure 4-5 contains two absolute bobbin coils with a plus point coil located between the absolute coils. The separation distance between the plus point coil and the absolute coils is the same in each direction. The absolute bobbin coils provide inner diameter profile measurements on the sleeve expansion. Additionally, the plus point coil can provide flaw position with respect to the transition as detected by the bobbin coils. Due to the geometry of the coils and a constant inspection speed, accurate flaw position with respect to roll transitions can be determined.

CECCO Probes

The CECCO family of probes are non-rotating probes and offer the advantage of faster inspection speeds. The CECCO-3 probe uses the driver-pickup (transmit-receive) technique with the coil connectivity providing axisymmetric compensation. CECCO-3 probes have been used for detection of circumferential cracks in the parent tubing but are not sensitive to axial indications. This probe has detected 50% through-wall circumferential cracks at expansion transitions in the parent tube behind the sleeve and has been qualified to the requirements of Appendix H of the *PWR Steam Generator Examination Guidelines* (13) for Westinghouse HEJ and laser welded sleeves.

The CECCO-5 probe has been used for detection of both axial and circumferential cracks. This probe also uses the driver-pickup technology and uses a number of pancake type coils for drivers and receivers. This technology has been enhanced by the development of new instrumentation to handle the multiple transmit and receive coils. Analysis software allows for additional data manipulation. This technique has detected 50% throughwall cracks at expansion transitions in the parent tube behind the sleeve and has been qualified to the requirements of Appendix H of the *PWR Steam Generator Examination Guidelines* (14) for Westinghouse HEJ and laser welded sleeves. A Westinghouse combined CECCO-Bobbin probe is shown in Figure 4-6.

Combination Probe

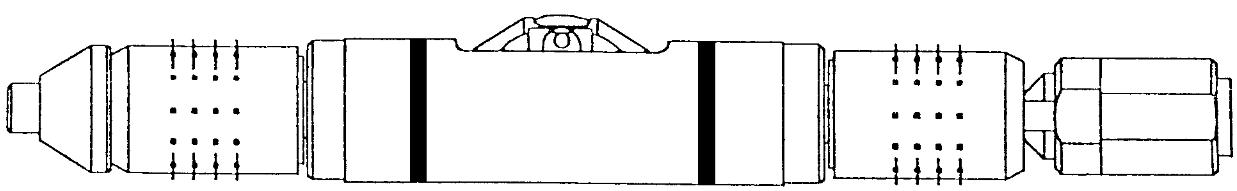


Figure 4-5
Combination Probe

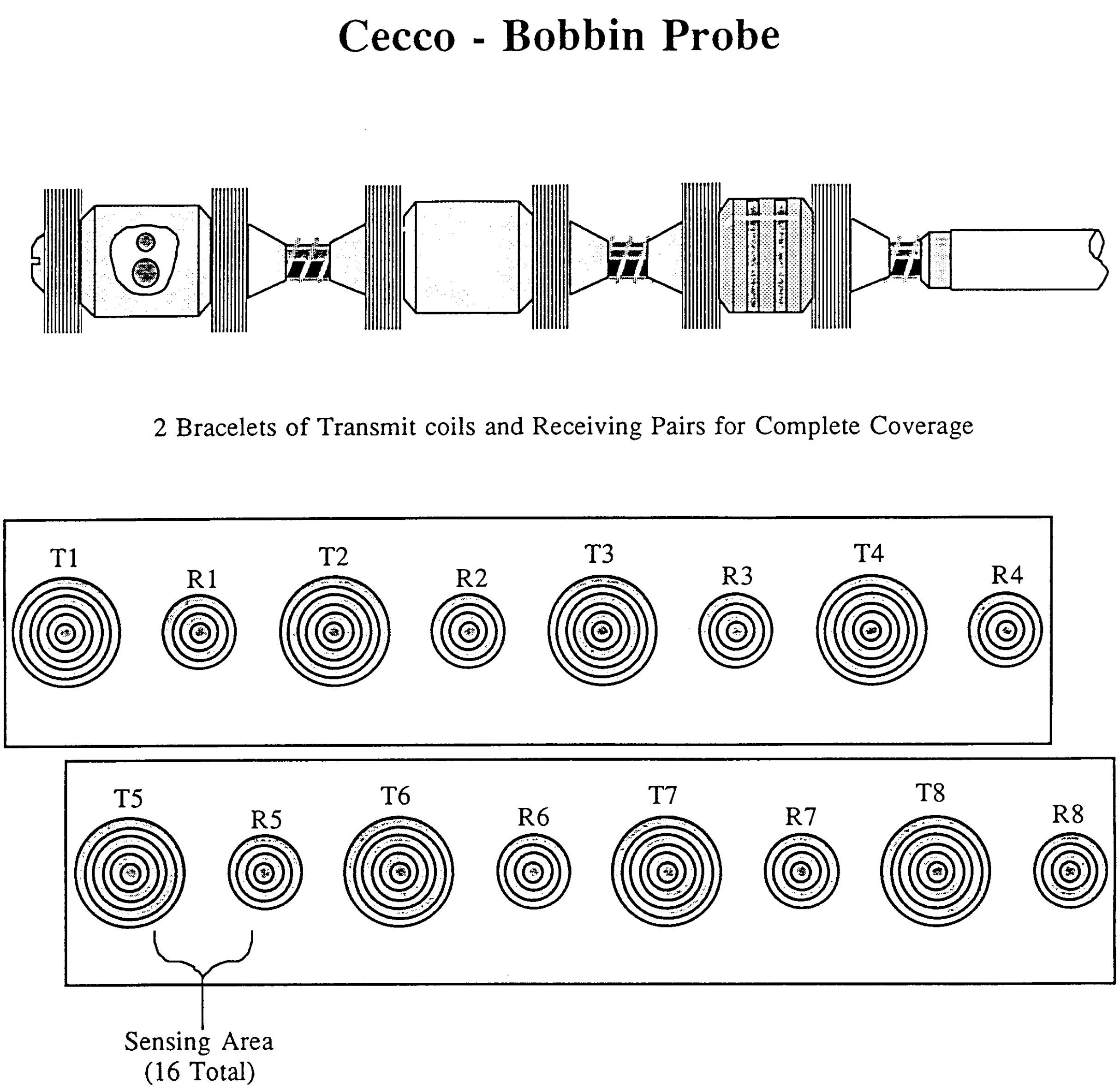


Figure 4-6
Combined CECCO-Bobbin Prove

Sleeve Inspections for Welded Sleeves

In order to assure high quality welds, inspections are required both during the sleeving process and at the completion of the process. The examination techniques commonly used are visual testing (VT), infrared examination (IR), ultrasonic testing (UT), and eddy current testing (ET) at different states of the installation process.

Sleeve Cleanliness

Successful sleeve welds are highly dependent on the cleanliness of the welded surfaces prior to welding. Visual inspection of the inside surface of the tubes should be conducted sufficiently often to assure the effectiveness of the cleaning process. Parent tube cleanliness is a critical feature of the welding process. Miniature remote cameras can be installed into the tube to the elevation where welding will be performed. The VT inspectors must be trained using examples of acceptable and unacceptable cleaning. Generally, the cleanliness requirement is the presence of bright, shinny metal. In the special case of resleeving where explosives were used for old sleeve joint expansion, residue from the explosives remained after cleaning presenting a bright, shinny surface that was not adequate. Consequently, special sleeving processes must be carefully evaluated. If adequate cleaning is not confirmed by the remote VT, the cleaning process should be repeated until suitable cleanliness is achieved. The extent of this inspection varies by vendor and can be 100% of the tubes sleeved. If 100% cleanliness VT is not conducted, a sampling program should be established to verify the cleaning step is satisfactory, such as the inspection of the last tubes cleaned each shift. Cleanliness inspection should be expanded if unacceptable welds are being made. One vendor invokes an infrared feedback testing system during the welding process to immediately determine acceptable weld quality.

Post Weld Inspections

Equipment should be available to conduct a post weld VT-1 inspection of the sleeve weld. The VT-1, as defined by ASME Section XI, should be qualified for the detection of incomplete welds, blow holes, surface cracks, and weld splatter geometric irregularities in the weld. Typically UT and ET inspections are capable of detecting these conditions. However, the VT is useful to aid in resolving uncertainties in surface conditions detected by the UT or ET examinations. In sleeves which have a lower edge weld, a VT-1 inspection is required.

The UT examination is conducted on all sleeve welds (except lower edge sleeve welds) to confer that a leak tight bond has been made by the welding process. Confirmation of the 360 degrees of weld bond is the acceptance criteria for the UT inspection. Normally, weld height is controlled by the welding process, but UT examination can provide information on weld height and may be used to confirm minimum weld height requirements when properly qualified.

If lack of fusion is identified by UT, typically the weld qualification process allows a limited number of rewelds. After a reweld, the UT is repeated to confirm the leak tight weld.

If Post Weld Heat Treatment (PWHT) is required, UT is done before PWHT since rewelds need to be done prior to PWHT. However, in the resleeving experience at

Kewaunee, the PWHT induced weld failures. Therefore, it may be necessary to conduct UT after PWHT on a sample of tubes, especially if it is known that tubes are locked at the tube support plates.

Final Inspection

The final inspection done on all new sleeves is an ET examination. This examination is normally done with rotating coil technology or equivalent. Acceptance criteria must be established for the ET examination and qualified per the *PWR Steam Generator Examination Guidelines* (15). The entire length of the sleeve pressure boundary must be examined and the inspection technique must be capable of identifying flaws in the parent tube above the sleeve weld and behind the sleeve.

Sleeving Inspection Qualification and Use

During the critical test batch conducted at the beginning of each sleeve campaign, all of the inspection techniques should be used. In addition, the ET examination should be done prior to and following the PWHT during the test batch. It has been shown by experience at Prairie Island that both the UT and ET examination are required to ensure acceptable welds.

Examination analysis should be conducted by two independent persons for all of the inspections used. All examinations should be permanently recorded. For UT examinations, the ultrasonic signal should be digitized and stored in order to provide a permanent record. All scans (A, B, and C) should be evaluated.

The Eddy Current technology has evolved from the cross wound bobbin coil design to the current Plus Point design and the CECCO probe design. The ET method used should be qualified per the requirements of Appendix H of the *PWR Steam Generator Examination Guidelines* (16). The method(s) used need to be able to detect flaws in the following four distinct sleeve regions:

- The sleeve between its upper and lower joints
- The pressure boundary region of the parent tube behind the sleeve
- The welded joints
- The hard roll joints

The ET inspection can be done before PWHT, but should in all cases also be done after PWHT.

Qualifications for sleeve joints should include a wide variety of indications and should included welds with contamination, weld cracking, weld blow holes, weld suck back, as well as cracks generated by the corrosion process. Magnetically biased probes should be considered to reduce interference from local permeability variations. Qualifications should distinguish between indications in or above the weld zone and surface or subsurface indications. Acceptance criteria should distinguish between indications in or outside the pressure boundary of the weld. Site specific training and performance demonstrations for sleeve inspection should also be conducted for each sleeve inspection outage.

Sleeve Inspection Summary

Sleeve inspection techniques are continually being developed to meet specific requirements. It is important to use a technique that has been demonstrated to be capable of finding the degradation of concern. Techniques which have been qualified to the requirements of Appendix H of the *PWR Steam Generator Examination Guidelines* (17) should be used.

5

STEAM GENERATOR SLEEVE REPAIR

The options for dealing with degraded sleeved tubes include removing the sleeved tube from service by plugging or attempting to repair the sleeved tube. Doel 4 and Kewaunee have both performed extensive sleeved tube repairs.

Doel 4 Sleeve Repair

The Doel 4 began experiencing top of tubesheet indications in 1991. The utility pulled several tubes and confirmed secondary side circumferential stress corrosion cracking. Due to an increase in the number of indications at the end of the operating cycle in 1993, the utility installed 1738 Westinghouse HEJ sleeves. During the next operating cycle, a primary to secondary leak occurred and reached the technical specification limit at the end of the cycle. A hydrostatic test was performed on the steam generators and the utility identified several leaking sleeved tubes. The utility pulled a sleeved tube with a confirmed leak and removed one additional sleeved tube which had no indication of cracking by NDE. The subsequent examination revealed primary side initiated circumferential cracks in the parent tubes at the upper transition of the hydraulic expansion of both tubes. An extensive evaluation of the installation and qualification process indicated that the cracks in the parent tube were due to high residual stress, high operating temperature, and susceptible parent tube material. The HEJ sleeves were repaired by hydraulically expanding the sleeve above the existing HEJ joint, performing a laser weld, and then performing a stress relief heat treatment. This method of repair was unique to Doel 4 because the sleeve extended approximately 6 inches above the hybrid expansion joint. In most HEJ sleeves, the hybrid expansion joint is much closer to the sleeve end. An important aspect of the laser weld repair is assuring that the moisture in the annulus between the parent tube and the sleeve is removed. During the 1994 outage the utility also installed 11,232 Westinghouse Laser Welded and stress relieved sleeves in the remaining unsleeved tubes.

In June of 1995, both the laser welded and repaired HEJ sleeves were inspected and ten samples (six repaired HEJs and four LWSs) were pulled for laboratory examination and testing. The laboratory examination revealed a bulging, or outward expansion of the parent tube, in the region just above the welded joint. In addition, weld defects, either hot weld cracks or porosity, were detected in many of the repaired HEJs and some of the laser welded sleeves. Wastage of both the sleeve (Alloy 690) and parent tube

(Alloy 600 LTMA) was also observed in the trapped crevice region between the original upper HEJ joint and the repair joint. Three of the six repaired HEJ samples that were removed due to NDE indications in this area showed volumetric wastage. The utility elected during that outage to plug all of the repaired HEJ tubes. The sleeve repair at Doel 4 is more fully described in the Doel 4 Field Experience of Appendix B.

Kewaunee Sleeve Repair

Wisconsin Public Service Corporation began detecting secondary side tubesheet indications at Kewaunee in the mid 1980's. Several hundred tubes were plugged and in 1988 the utility began a preventive sleeving campaign. Between and 1988 and 1991 approximately 4328 Westinghouse Hybrid Expansion Joint (HEJ) sleeves were installed. During the 1994 refueling outage, sleeve inspections were performed. A total of 77 indications were reported. A majority of these indications were located at the lower hardroll transition in the upper joint and most were circumferential in nature. Tubes with indications located above or within the hardroll lower transition were plugged. During the 1995 refueling outage, over 700 parent tube indications were detected. Three sleeve / tube joint samples were removed for examination and root cause determination. The examination results confirmed that the parent tubes were cracked in the lower hard roll transition. The cracks were on the inside diameter of the parent tube caused by PWSCC. Again, tubes with indications located above or within the hardroll lower transition were plugged.

During the 1996 / 1997 outage over 1350 new parent tube indications were detected. Seven sleeve-tube upper joints were removed from service for further laboratory testing. Due to the significant number of new parent tube indications, sleeve joint repairs were necessary to return the plant to operation. The first repair technique attempt was to place a laser weld in the center of the existing hardroll joint. This repair method had a very low success rate. Of approximately 650 welds attempted, only 198 were determined to be acceptable following UT and eddy current inspection. The cause of the weld failure was two-fold. First, due to the confined geometry of the hardroll, there was not a vent path for hot weld gases and contaminants volitized during the welding to escape. This resulted in a significant number of blowholes forming on the weld inner diameter. Therefore, as allowed by the welding procedure, subsequent re-weld passes were made. These re-weld passes resulted in hot weld cracks forming on the inner diameter of the weld due to too much heat input. All welds with hot cracks or blowholes were either plugged or re-sleeved.

The second attempt to repair sleeves with laser welding was to re-locate the weld to the upper hydraulic expansion (HE) location. Approximately 1250 welds were made in the upper HE location with an initial weld acceptance rate of over 80% following the UT and ECT examination. The sequence for weld repair was typical of new sleeve installation, *i.e.*, welding, UT, re-welding if needed, post-weld heat treatment (PWHT) and then a baseline ECT.

In preparation for plans to startup, the secondary side of the steam generators were filled with water and a number of the repaired tubes with hydraulic expansion welds were noted to be dripping water during a visual inspection of the primary tubesheet. A video probe was run up a number of the tubes and the leaks were re-examined with both ECT and UT. The ECT showed no change, but the re-UT inspection showed a significant number of the welds had “debonded” after the post weld heat treatment. Six laser welded HEJs with a variety of weld conditions were removed for laboratory testing. The testing confirmed two items. First, the presence of small (below detection) hot weld cracks at the sleeve / tube / weld interface due to contaminants present during the weld pool cooling. Second, during the post weld heat treatment there were uneven forces applied over the hydraulic expansion weld which caused a mechanical shearing of the weld. The welds in the hardroll location were not affected by the uneven stress distribution and did not fail during the post weld heat treatment.

A number of HEJs were also repaired by resleeving the tube. This was a multiple step process discussed in more detail in the Kewaunee Field Experience of Appendix B. First, the lower section of the existing HEJ sleeve was TIG relaxed, and the HEJ sleeve was whip cut below the upper joint and the lower section of the sleeve was removed. Once the lower sleeve section was removed, the upper sleeve joint was expanded to allow passage of a new sleeve. A number of expansion processes were tested and the most successful was a kinetic expansion. After the expansion , the lower section of the parent tube was cut within the tubesheet to relieve the residual and far field stresses. After the tube preparation steps, a new longer re-sleeve was installed and welded into place using normal sleeve installation techniques. For the 1997 repair campaign, 39 inch ABB CE TIG welded sleeves were used. During the initial performance demonstration on 25 tubes, the weld acceptance rate was lower than expected. This was due to additional deposits left on the tube inner diameter surface by the kinetic expansion step which had prevented the use of the normal tube cleaning process. The vendor developed additional tube cleaning steps and was able to successfully clean the tubes. The final re-sleeving process had a satisfactory acceptance rate.

6

RECOMMENDATIONS AND SLEEVE MANAGEMENT PLAN

The goal of the sleeve management plan is to identify known problems with sleeves and develop appropriate actions. The plan includes revising *Guidelines for PWR Steam Generator Tubing Specification and Repair, Volume 3, Steam Generator Tube Sleeving: Design, Specification, and Procurement Checklist* (18), performing increased sleeve inspection with the most appropriate NDE techniques, and repairing or taking out of service those sleeved tubes as required.

Recommendations for Utilities with Sleeved Tubes in Service

1. Review the types of sleeves, variances in installation methods, and susceptibility to corrosion attack of the parent tubing for sleeved tubes still in service.

2. Develop site specific guidelines based upon laboratory testing and analysis techniques to establish acceptability of flaw types and sizes that can remain in service and establish repair thresholds for flaws requiring repair or removal from service.

3. Inspect sleeves using the *PWR Steam Generator Examination Guidelines* (19).

4. Put procedures in place which implement the *PWR Primary-to-Secondary Leak Guidelines* (20).

5. Monitor the condition of the sleeved tubes and develop qualified repair techniques or take the sleeved tubes out of service if indications requiring repair are detected.

6. Representative tube pulls should be performed to verify key assumptions such as the following:

   - Incubation times for crack initiation
   - Relative susceptibility for cracking at different locations in the parent sleeved tubing

- Crack growth rates
- Qualification of NDE techniques to detect and size cracks

7. Keep closely informed and up to date on industry experience with sleeve inspections, sleeve degradation, and sleeve repair.

Recommendations for Utilities Considering Sleeve Installation

1. Review the sleeve designs, sleeve performance, sleeve qualification programs, sleeve installation sequence, and experience of the sleeving vendors under consideration for the sleeve installation.

2. Determine the susceptibility of the parent tubing to primary and secondary stress corrosion cracking.

3. Consider using an outside independent review team to assist in these evaluations.

4. Select the sleeve design and installation process most appropriate for the condition of the steam generator and the desired sleeve performance life.

5. Develop a site specific qualification program based upon mock-up and analytical testing which bounds the expected site conditions.

6. Determine if a stress relief treatment is needed to achieve performance life.

7. Maintain accountability for, and closely monitor, all aspects of the sleeve installation process . Deviations from the qualified process parameters or sequences should not be permitted. All repair techniques should be qualified prior to implementation.

8. For larger sleeving campaigns, consider an in-plant demonstration of a small number of sleeves.

9. For all new sleeve installations, use a qualified NDE technique for the baseline examination.

10. Keep closely informed and up to date on industry sleeve experience.

The performance of the vast majority of sleeves in service has been excellent. By following the above recommendations, utilities can build upon this experience and further enhance steam generator sleeve performance.

An example of one utility building on this experience is Maine Yankee . Maine Yankee reviewed the sleeving experience of both foreign and domestic plants with special attention to developments at Doel 4. Maine Yankee utilized an independent review team to review their sleeving test programs and plans prior to selecting a sleeving design and sleeving vendor. Some of the recommendations which were implemented included the following:

- Thorough mock-up testing of steam generator conditions and sleeving process steps were performed.

- Stress relief parameters were carefully chosen to minimize post stress relief tensile stresses. This effort was aided by the fact that the tube spans were considerably longer than at Doel 4 which resulted in less heat shrinkage and lower tensile stresses.

- Sleeve process steps were altered from those utilized at Doel 4 to minimize tensile stresses. These included the introduction of a “hard roll” at the lower sleeve joint which slightly lengthens the sleeve and counters a portion of the shrinkage effect.

- The composite effect of the above efforts gives a sleeve joint with “far-field” stress intensities of less than 17 ksi.

Prairie Island also used the experience gained at other utilities to improve the sleeve inspection process for welded sleeves. This included sleeve cleanliness inspection, post weld inspection, and final sleeve inspection. In addition, site specific training and inspection performance demonstrations were conducted. These efforts, among others, demonstrate that utilities are carefully considering industry experience and incorporating this experience in current sleeving campaigns.

7

REFERENCES

1. *Guidelines for PWR Steam Generator Tubing Specifications and Repair, Volume 3, Steam Generator Tube Sleeving: Design, Specification, and Procurement Checklist*, EPRI NP-6743-L, February 1991.

2. *Design Review Checklist: Steam Generator Sleeving*, EPRI NP-4296 LD, November 1985.

3. *Id*. 1.

4. *Guidelines for PWR Steam Generator Tubing Specifications and Repair, Volume 4, Guideline for Tube Section Removal and Examination*, EPRI NP-6743-L, February 1991.

5. *PWR Steam Generator Examination Guidelines, Revision 5*, EPRI TR-107569-V1R5, September 1997.

6. *PWR Primary-to-Secondary Leak Guidelines*, EPRI TR 104788, May 1995.

7. *Id*. 5.

8. *Strain-Rate Damage Model for Alloy 600 in Primary Water*, EPRI NP-7008, October 1990.

9. *Stress Relief Treatment of Alloy 600 Steam Generator Tubing*, EPRI TR-103645, January 1994.

10. *Id*. 1.

11. E. Pierson and J. Stubbe, "SCC Testing of Steam Generator Tubes Repaired by Welded Sleeves," Sixth International Symposium on Environmental Degradation of Materials in Nuclear Power System Water Reactors" San Diego, 1993.

12. *Id*. 5.

13. *Id*. 5.

14. *Id*. 5.

15. *Id*. 5.

16. *Id*. 5.

17. *Id*. 1.

18. *Id*. 1.

19. *Id*. 5.

20. *Id*. 6.

A

SLEEVING SURVEY RESULTS

United States
Sleeves In-Service

	Year	Sleeved	Vendor	Type	Reason	Length	Material	Top_Joint	Bot_Joint	Time	Exposure
ANO 1	84	10	FTI	Roll Exp TS	OD SCC/IGA TS	80	I600 TT	R	DR		
ANO 1	86	40	FTI	Roll Exp TS	OD SCC/IGA TS	80	I600 TT	R	DR		
ANO 1	88	174	FTI	Roll Exp TS	OD SCC/IGA TS	80	I600 TT	R	DR		
ANO 1	90	106	FTI	Roll Exp TS	OD SCC/IGA TS	80	I690 TT	R	DR		
ANO 1	92	572	FTI	Roll Exp TS	OD SCC/IGA TS	80 & 31	I690 TT	R	DR		
ANO 1	93	77	FTI	Roll Exp TS	OD SCC/IGA TS	80	I690 TT	R	DR		
ANO 2	92	467	FTI	Kinetic TS	OD SCC/IGA TS	11	I690 TT	KE	KE		
CRYSTAL RIVER 3	94	326	FTI	Roll Exp TS	Other	80	I690 TT	R	DR		
DAVIS BESSE	93	213	FTI	Roll Exp TS	Other	80	I690 TT	R	DR		
DAVIS BESSE	94	199	FTI	Roll Exp TS	Other	80	I690 TT	R	DR		
MC GUIRE 1	90	397	FTI	Kinetic TS	ID SCC/IGA TS	17.5	I690 TT	KE	R		
MC GUIRE 1	91	444	FTI	Kinetic TS	ID SCC/IGA TS	17.5	I690 TT	KE	R		
MC GUIRE 2	90	478	FTI	Kinetic TS	ID SCC/IGA TS	17.5	I690 TT	KE	R		
MC GUIRE 2	92	137	FTI	Kinetic TS,TSP	ID SCC/IGA TS	17.5 & 11	I690 TT	KE	R		
OCONEE 1	78	10	FTI	Hydraulic TSP, TS	Other	10.5 & 18	I600 TT	HE	HE		
OCONEE 1	87	482	FTI	Rolled TS, TSP	Other	80 & 15	I600 TT	R	DR	6	33
OCONEE 2	90	247	FTI	Rolled TS	Other	80	I690 TT	R	DR		
OCONEE 2	94	300	FTI	Rolled TS	Other	80	I690 TT	R	DR		
OCONEE 3	88	247	FTI	Rolled TS	Other	80	I600 TT	R	DR		
OCONEE 3	95	311	FTI	Rolled TS	Other	80	I690 TT	R	DR		
TMI 1	91	250	FTI	Rolled TS	Other	80	I690 TT	R	DR	2	14
TMI 1	93	252	FTI	Rolled TS	Other	80	I690 TT	R	DR		
		5739									
ANO 2	95	622	ABB CE	Welded,Standard	OD SCC/IGA TS	17.5	I690 TT	HE+TIG	R		
BYRON 1	96	3526	ABB CE	Welded, Standard	OD SCC/IGA TS	12	I690 TT	TIG	Rolled		52
KEWAUNEE	92	16	ABB CE	Welded,Peripheral	OD SCC/IGA TS	27	I690 TT	TIG	TIG	1	12
PRAIRIE ISLAND 1	87	27	ABB CE	Welded,Standard	OD SCC/IGA TS	27	I690 TT	HE+TIG	TIG		6
PRAIRIE ISLAND 1	88	74	ABB CE	Welded,Standard	OD SCC/IGA TS	27	I690 TT	HE+TIG	TIG		4
PRAIRIE ISLAND 1	90	63	ABB CE	Welded,Standard	OD SCC/IGA TS	27	I690 TT	HE+TIG	TIG		2.5
PRAIRIE ISLAND 1	92	158	ABB CE	Welded,Standard	OD SCC/IGA TS	27	I690 TT	HE+TIG	TIG	1	3
PRAIRIE ISLAND 1	94	118	ABB CE	Welded,Standard	OD SCC/IGA TS	27	I690 TT	HE+TIG	TIG		3.5
PRAIRIE ISLAND 1	96	285	ABB CE	Welded,Standard	OD SCC/IGA TS	27	I690 TT	HE+TIG	TIG	2	6.1

United States
Sleeves In-Service

	Year	Sleeved	Vendor	Type	Reason	Length	Material	Top_Joint	Bot_Joint	Time	Exposure
ZION 1	86	127	ABB CE	Welded,Standard	ID SCC/IGA TS	27	I600 TT	HE+TIG	TIG		
ZION 1	89	445	ABB CE	Welded,Standard	ID SCC/IGA TS	27	I600 TT	HE+TIG	TIG		
ZION 1	92	125	ABB CE	Welded,Standard	ID SCC/IGA TS	27	I600 TT	HE+TIG	TIG		
ZION 1	93	61	ABB CE	Welded,Standard	ID SCC/IGA TS	27	I600 TT	HE+TIG	TIG		
ZION 1	95	911	ABB CE	Welded,Standard	ID SCC/IGA TS	27	I690 TT	HE+TIG	TIG		
ZION 2	90	82	ABB CE	Welded,Standard	ID SCC/IGA TS	27	I600 TT	HE+TIG	TIG		
ZION 2	92	170	ABB CE	Welded,Standard	ID SCC/IGA TS	27	I690 TT	HE+TIG	TIG		
ZION 2	95	162	ABB CE	Welded,Standard	ID SCC/IGA TS	27	I690 TT	HE+TIG	TIG		
ZION 2	96	226	ABB CE	Welded,Standard	ID SCC/IGA TS	27	I690 TT	HE+TIG	TIG		20
		7198									
BRAIDWOOD 1	96	897	W	Welded, Standard	OD SCC/IGA TS	12	I690 TT	LW	Rolled		
BYRON 1	95	2046	W	Welded, Standard	OD SCC/IGA TS	12 & 27	I690 TT	LW	Rolled		43
CALLAWAY	95	77	W	Laser Welded	OD SCC/IGA TS	12	I690 TT	LW	Rolled		
COOK 1	92	1840	W	HEJ	OD SCC/IGA TS	27 & 30	I690 TT	HE+HR	HE+HR	3	48.5
FARLEY 1	92	186	W	Laser Welded TS	ID SCC/IGA TS	30 & 12	I690 TT	HE+LW+SR	HE+HR+SR		55
FARLEY 1	94	83	W	Laser Welded TS	ID SCC/IGA TS	30 & 12	I690 TT	HE+LW+SR	HE+HR+SR		11
FARLEY 2	92	85	W	Laser Weld TS/TSP	ID SCC/IGA TS	30 & 12	I690 TT	HE+LW+SR	HE+HR+SR		26
FARLEY 2	93	259	W	Laser Weld TS/TSP	ID SCC/IGA TS	30 & 12	I690 TT	HE+LW+SR	HE+HR+SR		36
FARLEY 2	96	849	W	Laser Weld TS/TSP	OD SCC/IGA TS	30, 20, 12	I690 TT	HE+LW+SR	HE+HR+SR		
KEWAUNEE	88	1940	W	HEJ	OD SCC/IGA TS	30 & 36	I690 TT	HE+HR	HE+HR	4	66.8
KEWAUNEE	89	1698	W	HEJ	OD SCC/IGA TS	30 & 36	I690 TT	HE+HR	HE+HR	2	41.2
KEWAUNEE	91	692	W	HEJ	OD SCC/IGA TS	27, 30, 36	I690 TT	HE+HR	HE+HR	4	100
POINT BEACH 2	83	3001	W	HEJ	OD SCC/IGA TS	36	I600 TT	HE + B or HR	HE + HR	10	660
POINT BEACH 2	87	87	W	HEJ	OD SCC/IGA TS	36	I690 TT	HE+HR	HE+HR		
POINT BEACH 2	88	509	W	HEJ	OD SCC/IGA TS	30	I690 TT	HE+HR	HE+HR		
POINT BEACH 2	89	298	W	HEJ	OD SCC/IGA TS	36	I690 TT	HE+HR	HE+HR		
ZION 1	88	47	W	HEJ	ID SCC/IGA TS	30	I600 TT	HE+HR	HE+HR		
		14594									
Total		27531									

United States
Sleeves Not In-Service

	Year	Sleeved	Vendor	Type	Reason	Length	Material	Top_Joint	Bot_Joint	Time	Exposure
CATAWBA 1 (ORIG)	91	75	FTI	Kinetic TS	ID SCC/IGA TS	17.5	I690 TT	KE	R		
CATAWBA 1 (ORIG)	92	108	FTI	Kinetic TSP	ID SCC/IGA SP	11	I690 TT	KE	KE		
GINNA (ORIG)	84	9	FTI	Intratubesheet	Wastage	20 & 36	I600 TT,Ni Clad	KE	KE		
GINNA (ORIG)	85	69	FTI	Intratubesheet	Wastage	20 & 36	I600 TT,Ni Clad	KE	KE		
GINNA (ORIG)	94	246	FTI	Intratubesheet	Wastage	20.75	I690 TT	KE	KE		
GINNA (ORIG)	95	166	FTI	Intratubesheet	Wastage	20.75	I690 TT	KE	KE		
RANCHO SECO	86	507	FTI	Rolled TS	Other	80	I600 TT	R	DR	5	47
SUMMER (ORIG)	90	125	FTI	Kinetic TS	ID SCC/IGA TS	11 & 17.5	I690 TT	KE	R		10
SUMMER (ORIG)	91	610	FTI	Kinetic TS	ID SCC/IGA TS	11 & 17.5	I690 TT	KE	R	2	27.5
TROJAN	90	4	FTI	Kinetic TS,TSP	Other	11	I690 TT	KE	R		6
TROJAN	91	1111	FTI	Kinetic TSP	OD SCC/IGA SP	11	I690 TT	KE	KE	10	120
GINNA (ORIG)	80	5	FTI/RG&E	Brazed TS	OD SCC/IGA TS	36	I600 TT,Ni Clad	HE+B	KE		40
GINNA (ORIG)	81	16	FTI/RG&E	Brazed TS	OD SCC/IGA TS	36	I600 TT,Ni Clad	HE+B	KE		32
GINNA (ORIG)	83	78	FTI/RG&E	Brazed TS	OD SCC/IGA TS	22 & 36	I600 TT,Ni Clad	HE+B	KE		26
		3129									
GINNA (ORIG)	86	39	ABB CE	Welded,Standard	Wastage	27	I690 TT	HE+TIG	TIG		
GINNA (ORIG)	87	104	ABB CE	Welded,Standard	OD SCC/IGA TS	27	I690 TT	HE+TIG	TIG		10
GINNA (ORIG)	89	511	ABB CE	Welded,Standard-Peripheral	OD SCC/IGA TS	27	I690 TT	HE+TIG	TIG		
GINNA (ORIG)	90	247	ABB CE	Welded,Standard-Peripheral	OD SCC/IGA TS	27	I690 TT	HE+TIG	TIG		
GINNA (ORIG)	91	211	ABB CE	Welded,Standard-Peripheral	OD SCC/IGA TS	27 & 30	I690 TT	HE+TIG	TIG		
GINNA (ORIG)	92	432	ABB CE	Welded,Standard	OD SCC/IGA TS	27 & 30	I690 TT	HE+TIG	TIG		
GINNA (ORIG)	93	268	ABB CE	Welded,Standard	Wastage	27	I690 TT	HE+TIG	TIG		
PALISADES (ORIG)	76	14	ABB CE	Hydraulic TSP	Wastage	12	I600	HE	HE	8	15
PALISADES (ORIG)	78	23	ABB CE	Hydraulic TSP	Wastage	12	I600	HE	HE		
		1849									
INDIAN POINT 3 (ORIG)	82	2971	W	HEJ	Pitting	36 & 44	I600 TT	HE+HR	HE+HR	14	860
INDIAN POINT 3 (ORIG)	85	635	W	HEJ	Pitting	36 & 44	I600 TT	HE+HR	HE+HR		
MAINE YANKEE	95	16429	W	Laser Welded	ID SCC/IGA TS		I690 TT	LW			
MILLSTONE 2 (ORIG)	83	2022	W	HEJ	Pitting	40	I690TT + I625 Clad	HE+HR	HE+HR	8	526
MILLSTONE 2 (ORIG)	85	2917	W	HEJ	Pitting	40	I690TT + I625 Clad	HE+HR	HE+HR		
MILLSTONE 2 (ORIG)	86	225	W	HEJ	Pitting	40	I690TT + I625 Clad	HE+HR	HE+HR		
POINT BEACH 1 (ORIG)	81	13	W	HEJ	OD SCC/IGA TS	36	I600 TT	HE + B or HR	HE + HR	2	
SAN ONOFRE 1	80	6929	W	HEJ	OD SCC/IGA TS	27 & 30	I600 TT	HE + B or HR	HE+HR	30	3496
		32141									
Total		37119									

Non United States
Sleeves In-Service

	Year	Sleeved	Vendor	Type	Reason	Length	Material	Top_Joint	Bot_Joint	Time	Exposure
KORI 1	88	558	ABB CE	Standard	Pitting	28 & 37	I690 TT	Weld	Weld	8	278
KORI 1	89	184	ABB CE	Standard	Pitting	28 & 37	I690 TT	Weld	Weld	3.5	91
KORI 1	90	415	ABB CE	Standard	Pitting	28 & 37	I690 TT	Weld	HR	6	62
KORI 1	92	330	ABB CE	Standard	Pitting	28 & 37	I690 TT	Weld	HR	4	51
KORI 1	93	97	ABB CE	Standard	Pitting	28 & 37	I690 TT	Weld	HR	4.5	65
KORI 1	94	300	ABB CE	Standard	OD SCC/IGA TS	28 & 37	I690 TT	Weld	HR	8.5	96
KORI 1	96	1197	ABB CE	PLUSS	OD SCC/IGA TS	23	I690 TT	HE	HR	3.5	22
KORI 2	88	2	ABB CE	Standard	OD SCC/IGA TS	28	I690 TT	Weld	Weld		
KRSKO	93	166	ABB CE	Welded TSP, ETZ	ID SCC/IGA TS	9 & 15.5	I690 TT	HE+TIG	R or HE+TIG		
KRSKO	96	461	ABB CE	Welded TSP, ETZ	ID SCC/IGA TS	9 & 15.5	I690 TT	HE+TIG	R or HE+TIG		
TIHANGE 3	95	20	ABB CE	PLUSS	ID SCC/IGA TS	23	I690 TT	HE	HR		
TIHANGE 3	96	104	ABB CE	PLUSS	ID SCC/IGA TS	23	I690 TT	HE	HR		
		3834									
BEZNAU 2	83	17	BEZNAU	Welded	OD SCC/IGA TS	27	I600 TT	TIG	TIG		
BEZNAU 2	84	17	BEZNAU	Welded	OD SCC/IGA TS	27	I600 TT	TIG	TIG		
		34									
BEZNAU 2	85	39	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT+Ni Clad	KE	KE		
BEZNAU 2	86	86	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT+Ni Clad	KE	KE		
BEZNAU 2	87	42	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT+Ni Clad	KE	KE		
BEZNAU 2	88	13	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT+Ni Clad	KE	KE		
BEZNAU 2	89	14	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT+Ni Clad	KE	KE		
BEZNAU 2	90	20	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT+Ni Clad	KE	KE		
BEZNAU 2	91	15	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT+Ni Clad	KE	KE		
BEZNAU 2	92	13	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT+Ni Clad	KE	KE		
BEZNAU 2	93	39	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT+Ni Clad	KE	KE		
BEZNAU 2	95	147	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT	KE	KE		
BEZNAU 2	96	81	FTI	Intatubesheet	OD SCC/IGA TS	20	I690 TT	KE	KE		
DOEL 2	82	185	FTI	Minisleeve	ID SCC/IGA TS	1.7	I600 TT	Full Length KE			
DOEL 2	85	10	FTI	Minisleeve	ID SCC/IGA TS	1.7	I600 TT	Full Length KE			
DOEL 2	86	81	FTI	Minisleeve	ID SCC/IGA TS	1.7	I600 TT	Full Length KE			
		785									

Non United States
Sleeves In-Service

	Year	Sleeved	Vendor	Type	Reason	Length	Material	Top_Joint	Bot_Joint	Time	Exposure
DOEL 2	88	33	FRA	Nickel Plate	ID SCC/IGA TS	4	Nickel				
DOEL 2	90	345	FRA	Nickel Plate	ID SCC/IGA TS	4	Nickel				
FESSENHEIM 1	84	10	FRA	FRA	ID SCC/IGA TS		I600 TT	HE+TIG	HE+TIG		
TIHANGE 2	92	606	FRA	Nickel Plate	ID SCC/IGA TS	4	Nickel				
TIHANGE 2	93	556	FRA	Nickel Plate	ID SCC/IGA TS	4	Nickel				
TIHANGE 2	95	117	FRA	Nickel Plate	ID SCC/IGA TS	4	Nickel				
TIHANGE 2	96	602	FRA	Nickel Plate	ID SCC/IGA TS	4	Nickel				
TRICASTIN 2	88	22	FRA	FRA	Other	15.7 & 31.4	I600 TT	HE+TIG	HE+TIG		
		2291									
IKATA 1	84	14	MHI	Rolled TS	ID SCC/IGA TS	20	I600 TT	HR	HR		
MIHAMA 3	95	201	MHI	Laser Welded	OD SCC/IGA TS	6 & 25	I690 TT	LW	LW		
OHI 2	84	8	MHI	Rolled TS	ID SCC/IGA TS	20	I600 TT	HR	HR or W		
		223									
PICKERING 5	94	18	OH	Electrosleeve	Pitting		Nickel				
		18									
Total		7185									

Non United States
Sleeves Not In-Service

	Year	Sleeved	Vendor	Type	Reason	Length	Material	Top_Joint	Bot_Joint	Time	Exposure
BEZNAU 1 (ORIG)	81	3	BEZNAU	Welded	OD SCC/IGA TS	27	I600 TT	TIG	TIG		
BEZNAU 1 (ORIG)	82	24	BEZNAU	Welded	OD SCC/IGA TS	27	I600 TT	TIG	TIG		
BEZNAU 1 (ORIG)	83	37	BEZNAU	Welded	OD SCC/IGA TS	27	I600 TT	TIG	TIG		
		64									
ALMARAZ 1 (ORIG)	89	3	FTI	Kinetic TS	ID SCC/IGA TS		I690 TT	KE	R		
ALMARAZ 1 (ORIG)	90	100	FTI	Kinetic TS	ID SCC/IGA TS		I690 TT	KE	R		
ASCO 1 (ORIG)	91	115	FTI	Kinetic TS	OD SCC/IGA TS		I690 TT	KE	R		
ASCO 1 (ORIG)	93	87	FTI	Kinetic TSP	OD SCC/IGA SP		I690 TT	KE	KE		
BEZNAU 1 (ORIG)	84	35	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT+ Ni Clad	KE	KE		
BEZNAU 1 (ORIG)	85	79	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT+ Ni Clad	KE	KE		
BEZNAU 1 (ORIG)	86	174	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT+ Ni Clad	KE	KE		
BEZNAU 1 (ORIG)	87	80	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT+ Ni Clad	KE	KE		
BEZNAU 1 (ORIG)	88	53	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT+ Ni Clad	KE	KE		
BEZNAU 1 (ORIG)	89	12	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT+ Ni Clad	KE	KE		
BEZNAU 1 (ORIG)	90	24	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT+ Ni Clad	KE	KE		
BEZNAU 1 (ORIG)	91	10	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT+ Ni Clad	KE	KE		
BEZNAU 1 (ORIG)	92	11	FTI	Intratubesheet	OD SCC/IGA TS	20	I600 TT+ Ni Clad	KE	KE		
		783									
RINGHALS 2 (ORIG)	84	18	ABB CE	Welded,Standard	OD SCC/IGA TS	30	I690 TT	HE+TIG	TIG		1.7
RINGHALS 2 (ORIG)	85	50	ABB CE	Welded,Standard	OD SCC/IGA TS	30	I690 TT	HE+TIG	TIG		13
RINGHALS 2 (ORIG)	86	596	ABB CE	Welded,Standard	OD SCC/IGA TS	30	I690 TT	HE+TIG	TIG		53
RINGHALS 2 (ORIG)	87	554	ABB CE	Welded,Standard	OD SCC/IGA TS	30	I690 TT	HE+TIG	TIG		42
RINGHALS 3 (ORIG)	91	22	ABB CE	Welded,ETZ/RTZ	ID SCC/IGA SP	8	I690 TT	HE+TIG+SR	R		
RINGHALS 3 (ORIG)	91	46	ABB CE	Welded,ETZ/RTZ	ID SCC/IGA TS	37.5	I690 TT	HE+TIG+SR	R		
		1286									
GENKAI 1 (ORIG)	85	147	MHI	Brazed	OD SCC/IGA TS	11 & 29	I600 TT	B	W or B or M		
GENKAI 1 (ORIG)	86	353	MHI	Brazed	OD SCC/IGA TS	11, 17, 29	I600 TT	B	W or B or M		
GENKAI 1 (ORIG)	87	408	MHI	Brazed	OD SCC/IGA TS	11, 17, 29	I600 TT	B	W or B or M		
GENKAI 1 (ORIG)	89	886	MHI	Laser Welded	OD SCC/IGA TS	5.9, 8.3, 24.8	I690 TT	LW	LW		
GENKAI 1 (ORIG)	90	829	MHI	Laser Welded	OD SCC/IGA TS	5.9, 8.3, 24.8	I690 TT	LW	LW		
GENKAI 1 (ORIG)	91	475	MHI	Laser Welded	OD SCC/IGA TS	5.9, 8.3, 24.8	I690 TT	LW	LW		
GENKAI 1 (ORIG)	93	182	MHI	Laser Welded	OD SCC/IGA TS	5.9, 8.3, 24.8	I690 TT	LW	LW		

Non United States
Sleeves Not In-Service

	Year	Sleeved	Vendor	Type	Reason	Length	Material	Top_Joint	Bot_Joint	Time	Exposure
MIHAMA 2 (ORIG)	82	3	MHI	Brazed	OD SCC/IGA TS	29	I600 TT	B	W		
MIHAMA 2 (ORIG)	83	14	MHI	Brazed	OD SCC/IGA TS	29	I600 TT	B	W		
MIHAMA 2 (ORIG)	84	25	MHI	Brazed	OD SCC/IGA TS	29	I600 TT	B	W		
OHI 1 (ORIG)	84	81	MHI	Brazed	ID SCC/IGA TS	29 & 11	I600 TT	B	W or B		
OHI 1 (ORIG)	85	451	MHI	Brazed	ID SCC/IGA TS	29 & 11	I600 TT	B	W or B		
OHI 1 (ORIG)	86	663	MHI	Brazed	ID SCC/IGA TS	29 & 11	I600 TT	B	W or B		
OHI 1 (ORIG)	87	781	MHI	Brazed	ID SCC/IGA TS	29 & 11	I600 TT	B	W or B		
OHI 1 (ORIG)	88	191	MHI	Brazed	ID SCC/IGA TS	29 & 11	I600 TT	B	W or B		
OHI 1 (ORIG)	89	1145	MHI	Laser Welded	OD SCC/IGA TS	5.9, 8.3, 24.8	I690 TT	LW	LW		
OHI 1 (ORIG)	90	915	MHI	Laser Welded	OD SCC/IGA TS	5.9, 8.3, 24.8	I690 TT	LW	LW		
OHI 1 (ORIG)	91	991	MHI	Laser Welded	OD SCC/IGA TS	5.9, 8.3, 24.8	I690 TT	LW	LW		
OHI 1 (ORIG)	93	721	MHI	Laser Welded	OD SCC/IGA TS	5.9, 8.3, 24.8	I690 TT	LW	LW		
TAKAHAMA 1 (ORIG)	80	2	MHI	Brazed	OD SCC/IGA TS	11 & 29	I600 TT	B	W or B		
TAKAHAMA 1 (ORIG)	81	4	MHI	Brazed	OD SCC/IGA TS	11 & 29	I600 TT	B	W or B		
TAKAHAMA 1 (ORIG)	82	32	MHI	Brazed	OD SCC/IGA TS	11 & 29	I600 TT	B	W or B		
TAKAHAMA 1 (ORIG)	84	59	MHI	Brazed	OD SCC/IGA TS	11 & 29	I600 TT	B	W or B		
TAKAHAMA 1 (ORIG)	88	6	MHI	Brazed	OD SCC/IGA TS	11 & 29	I600 TT	B	W or B		
TAKAHAMA 2 (ORIG)	84	231	MHI	Brazed	OD SCC/IGA TS	11 & 29	I600 TT	B	W or B		
TAKAHAMA 2 (ORIG)	86	340	MHI	Brazed	OD SCC/IGA TS	11 & 29	I600 TT	B	W or B		
TAKAHAMA 2 (ORIG)	87	492	MHI	Brazed	OD SCC/IGA TS	11 & 29	I600 TT	B	W or B		
TAKAHAMA 2 (ORIG)	88	1063	MHI	Brazed	OD SCC/IGA TS	11 & 29	I600 TT	B	W or B		
TAKAHAMA 2 (ORIG)	90	1202	MHI	Laser Welded	OD SCC/IGA TS	5.9, 8.3, 24.8	I690 TT	LW	LW		
TAKAHAMA 2 (ORIG)	91	700	MHI	Laser Welded	OD SCC/IGA TS	5.9, 8.3, 24.8	I690 TT	LW	LW		
TAKAHAMA 2 (ORIG)	92	682	MHI	Laser Welded	OD SCC/IGA TS	5.9, 8.3, 24.8	I690 TT	LW	LW		
		14074									
DOEL 3 (ORIG)	88	11	FRA	Nickel Plate	ID SCC/IGA TS	4	Nickel				
BUGEY 5 (ORIG)	89	76	FRA	FRA	OD SCC/IGA TS		I600 TT	HE+TIG	HE+TIG		
		87									
DOEL 3 (ORIG)	88	55	W	Laser Welded	ID SCC/IGA TS	30	I690 TT	HE+LW	HE+HR		
DOEL 4 (ORIG)	93	1738	W	HEJ	OD SCC/IGA TS	30&36	I690 TT	HE+HR	HE+HR		
DOEL 4 (ORIG)	94	11232	W	Laser Welded	OD SCC/IGA TS	12&30	I690 TT	HE+LW	HE+HR	22	
RINGHALS 2 (ORIG)	84	17	W	Brazed	OD SCC/IGA TS	30	I690 TT	HE+B	HE+B		1.7
		13042									
Total		28082									

B

FIELD EXPERIENCE WITH DEGRADED SLEEVED TUBES

Trojan

Portland General Electric discovered a number of tube support plate indications in the late 1980's. The utility installed two BWNT kinetic tube support plate sleeves in 1990 for demonstration purposes and 1111 of these sleeves in 1992. In November 1992, a tube leak caused a forced outage. The leaking tube had an installed support plate sleeve. A subsequent evaluation revealed that the joints on this sleeve did not receive proper stress relief heat treatment. The heat treatment was performed, but the heater was not in the proper axial location and the joints were not stress relieved. It is believed that high residual stress in the parent tube at the sleeve joint led to intergranular stress corrosion cracking which proceeded throughwall and caused the tube leak to occur.

McGuire 1

Duke Power Company detected top of tubesheet PWSCC indications at McGuire 1 in the mid 1980's. In 1990 the utility installed 397 BWNT kinetic tubesheet sleeves and in 1991 installed an additional 444 sleeves of this type. These tubesheet sleeves were a combination of both double kinetic welds (kinetic welds at both the upper and lower joint) and single kinetic welds (a kinetic weld at the upper joint and a roll expansion at the lower joint). In August 1993 and January 1994, McGuire 1 experienced forced tube leak outages. In both instances, the leaking tube was sleeved with a double kinetic welded sleeve. An extensive review of the sleeve installation and qualification process indicated that the parent tube failed due to ID initiated circumferential cracking at the sleeve joint caused by high residual stress. The high residual stress was attributed to the sleeve being installed in a tube locked at the first support plate elevation. The locked tube condition was not originally tested in the sleeve qualification program. The residual stresses on the single kinetic welded sleeve are calculated to be lower than on the double kinetic welded sleeve. The experience at McGuire 1 supports this evaluation. However, in order to preclude the possibility of any additional tube leak outages, Duke Power Company has plugged all the tubes at its units that contain either single or double kinetic welded sleeves.

Kewaunee

Wisconsin Public Service Corporation began detecting secondary side tubesheet indications at Kewaunee in the mid 1980's. Several hundred tubes were plugged and in 1988 the utility began a preventive sleeving campaign. In 1988 a total of 1940 Westinghouse Hybrid Expansion Joint (HEJ) sleeves were installed. In 1989 another 1698 HEJ sleeves were installed and in 1991 an additional 690 HEJ sleeves were installed. In 1992 the utility also installed 16 ABB CE welded peripheral sleeves.

During the 1994 refueling outage, sleeve inspections were performed. A total of 77 indications were reported. A majority of these indications were located at the lower hardroll transition in the upper joint and most were circumferential in nature. After some discussion on the merits of leaving the tubes with these indications in service, it was decided to plug the tubes with indications located above or within the hardroll lower transition. During the 1995 refueling outage over 700 parent tube indications were detected. Three sleeve/tube joint samples were removed for examination and root cause determination. The examination results confirmed that the parent tubes were cracked in the lower hard roll transition. The cracks were on the inside diameter of the parent tube caused by PWSCC. The indications were 360 degrees ranging from 5% to 92% throughwall with multiple ligaments. The results of the examination correlated well with the field calls from the Plus Point probe. Two of the three samples were destructively examined and over 10,000 pounds of force was required to pull apart the joint.

During the 1996/1997 outage over 1350 new parent tube indications were detected. Seven sleeve-tube upper joints were removed from service for further laboratory testing. Due to the significant number of new parent tube indications, sleeve joint repairs were necessary to return the plant to operation. The welded repair of the upper HEJ and re-sleeving are discussed below.

Laser Welded Repair of HEJ Sleeves

Due to the significant number of parent tube indications detected during the 1996/1997 outage, a method was required to repair the sleeve joint in order to keep tubes in service and return the plant to operation. The first repair technique attempt was to place a laser weld in the center of the existing hardroll joint, see Figure B-1. This repair method had a very low success rate. Of approximately 650 welds attempted only 198 were determined to be acceptable following UT and eddy current inspection. The cause of the weld failure was two-fold. First, due to the confined geometry of the hardroll, there was not a vent path for hot weld gases and contaminants volitized during the welding to escape. This resulted in a significant number of blowholes forming on the weld inner diameter. Therefore, as allowed by the welding procedure, subsequent re-weld passes were made. This then resulted in hot weld cracks forming on the inner

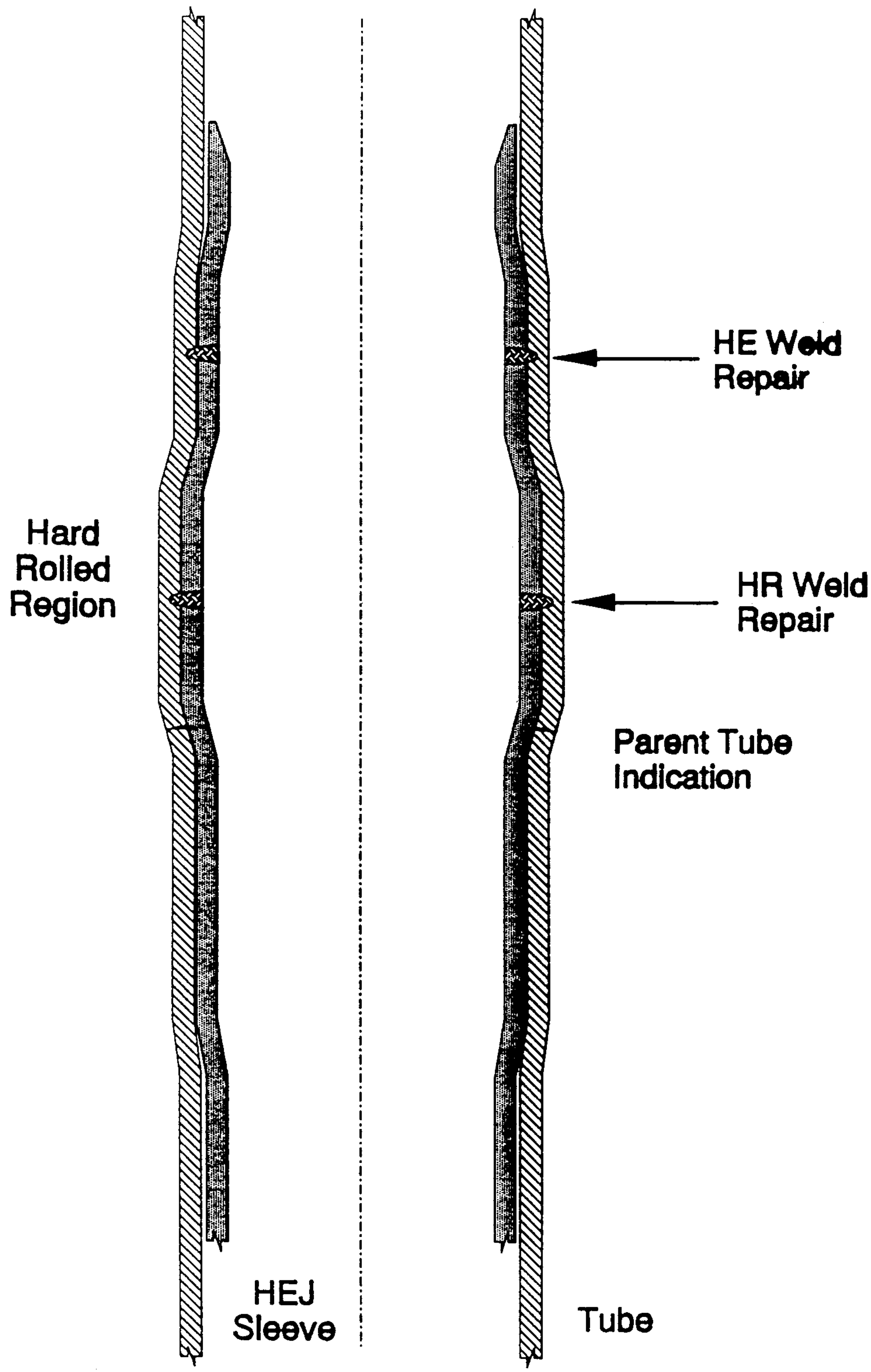


Figure B-1
Location of Welds in HEJ Sleeved Tubes

diameter of the weld due to too much heat input. All welds with hot cracks or blowholes were either plugged or re-sleeved.

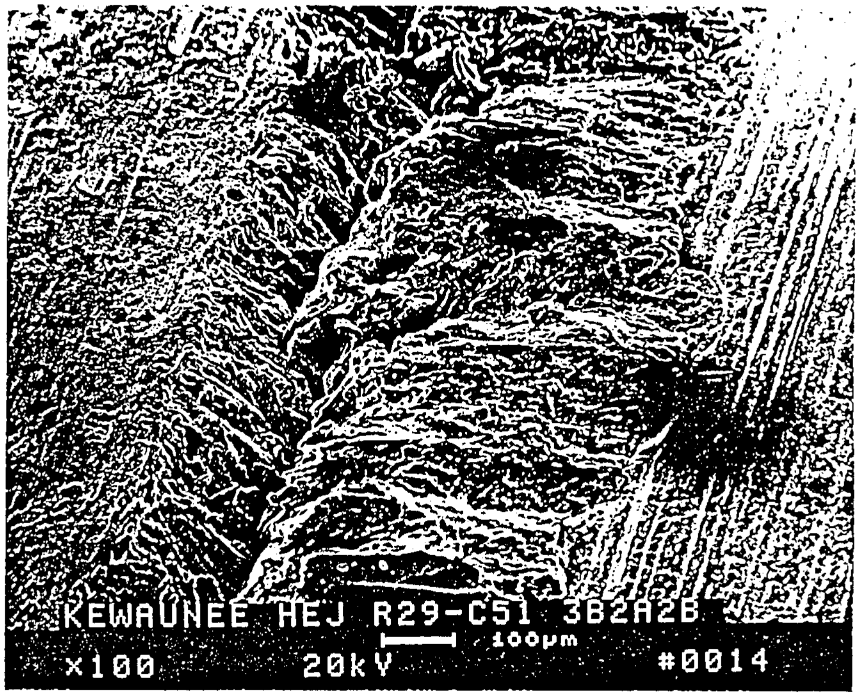
The second attempt to repair sleeves with laser welding was to re-locate the weld to the upper hydraulic expansion (HE) location, also shown in Figure B-1. Approximately 1250 welds were made in the upper HE location with an initial weld acceptance rate of over 80% following the UT and ECT examination. The sequence for weld repair was typical of new sleeve installation, i.e., welding, UT, re-welding if needed, post-weld heat treatment (PWHT) and then a baseline ECT.

In preparation for plans to startup, the secondary side of the steam generators were filled with water and a number of the repaired tubes with He welds were noted to be dripping water during a visual inspection of the primary tubesheet. A video probe was run up a number of the tubes and the leaks were re-examined with both ECT and UT. The ECT showed no change, but the re-UT inspection showed a significant number of the welds had “debonded” after the post weld heat treatment.

Six laser welded HEJs with a variety of weld conditions were removed for laboratory testing. The testing confirmed two items. First, the presence of small (below detection) hot weld cracks at the sleeve / tube / weld interface due to contaminants present during the weld pool cooling. Second, during the post weld heat treatment there were uneven forces applied over the hydraulic expansion weld which caused a mechanical shearing of the weld. The welds in the hardroll location were not affected by the uneven stress distribution and did not fail during the post weld heat treatment. Figure B-2 shows the small triple point cracks and Figure B-3 shows the shear fracturing that occurred during the post weld heat treatment.

Re-Sleeving Repair of HEJ Sleeves

A number of HEJs were also repaired by resleeving the tube. This was a multiple step process illustrated in Figures B-4 and B-5. First, the lower section of the existing HEJ sleeve was TIG relaxed, and the HEJ sleeve was whip cut below the upper joint and the lower section of the sleeve was removed. Once the lower sleeve section was removed, the upper sleeve joint was expanded to allow passage of a new sleeve. A number of expansion processes were tested and the most successful was a kinetic expansion. After the expansion , the lower section of the parent tube was cut within the tubesheet to relieve the residual and far field stresses. After the tube preparation steps, a new longer re-sleeve was installed and welded into place using normal sleeve installation techniques. For the 1997 repair campaign, 39 inch ABB CE TIG welded sleeves were used. During the initial performance demonstration on 25 tubes, the weld acceptance rate was lower than expected. This was due to additional deposits left on the tube inner diameter surface by the kinetic expansion step which had prevented the use of the normal tube cleaning process. The vendor developed additional tube cleaning steps and was able to successfully clean the tubes. The re-sleeving is a multi-step process



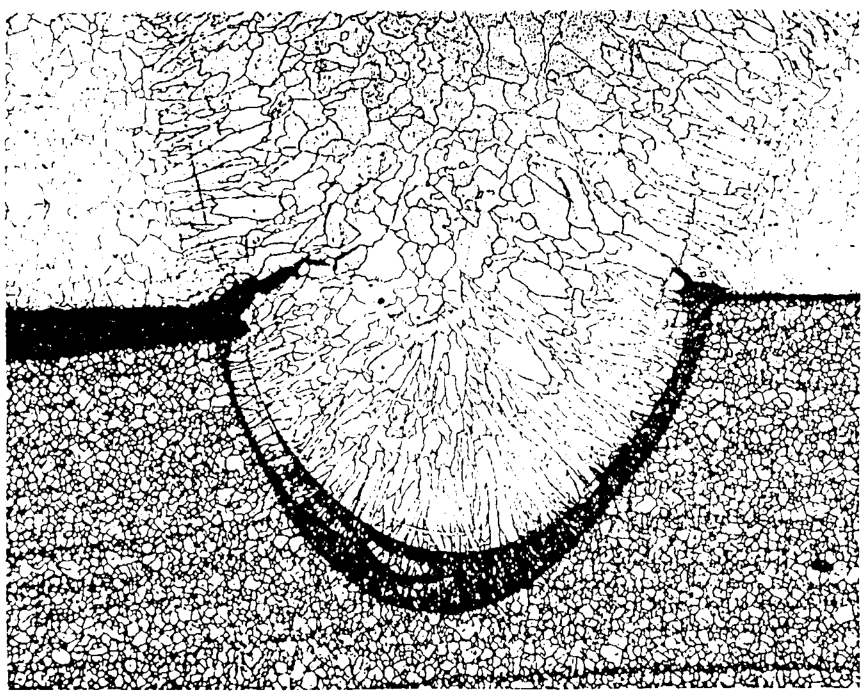


Figure B-2
Triple Point Cracks

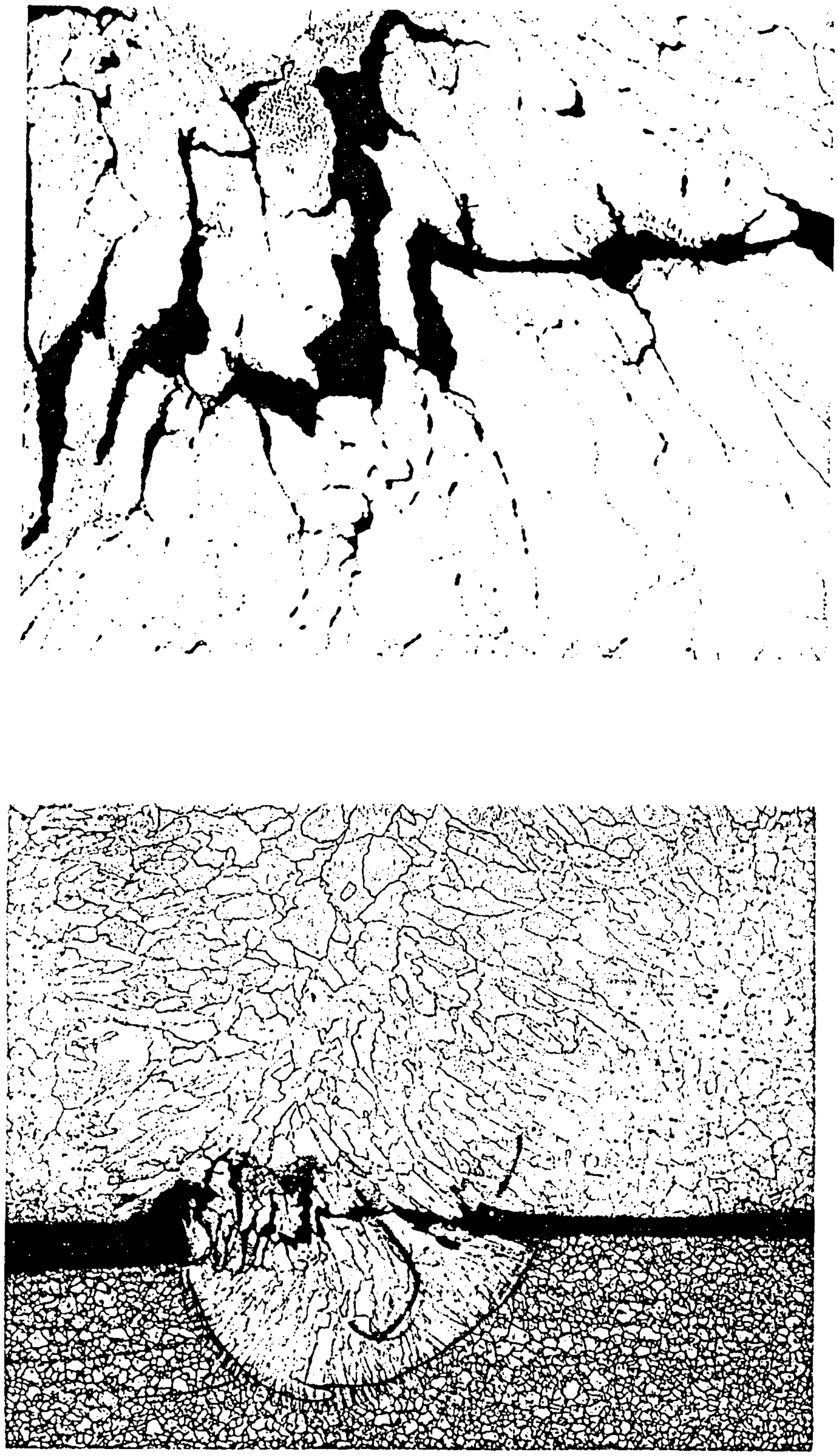


Figure B-3
Shear Fractures

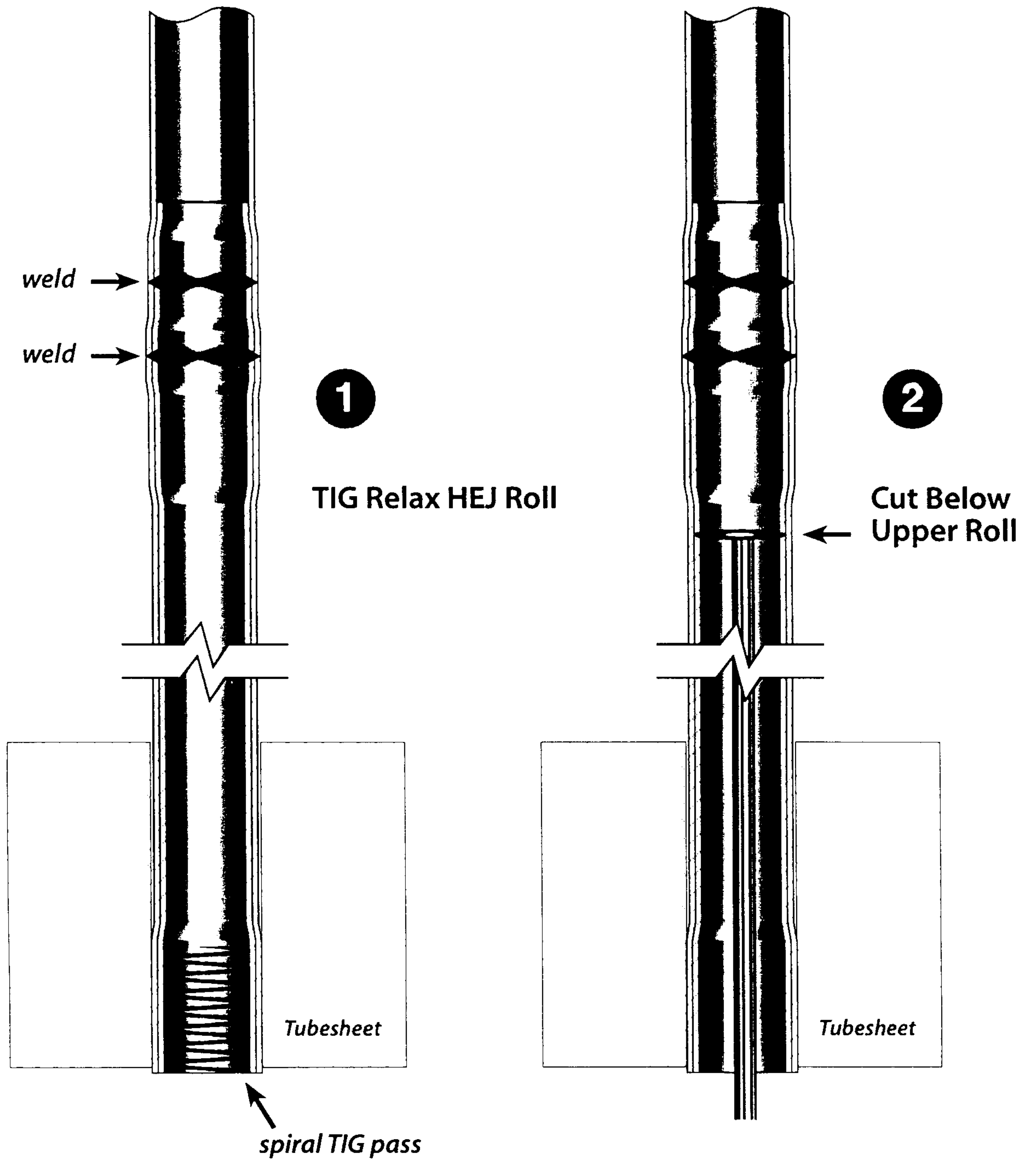


Figure B-4
Sleeve Removal, New Sleeve Installation

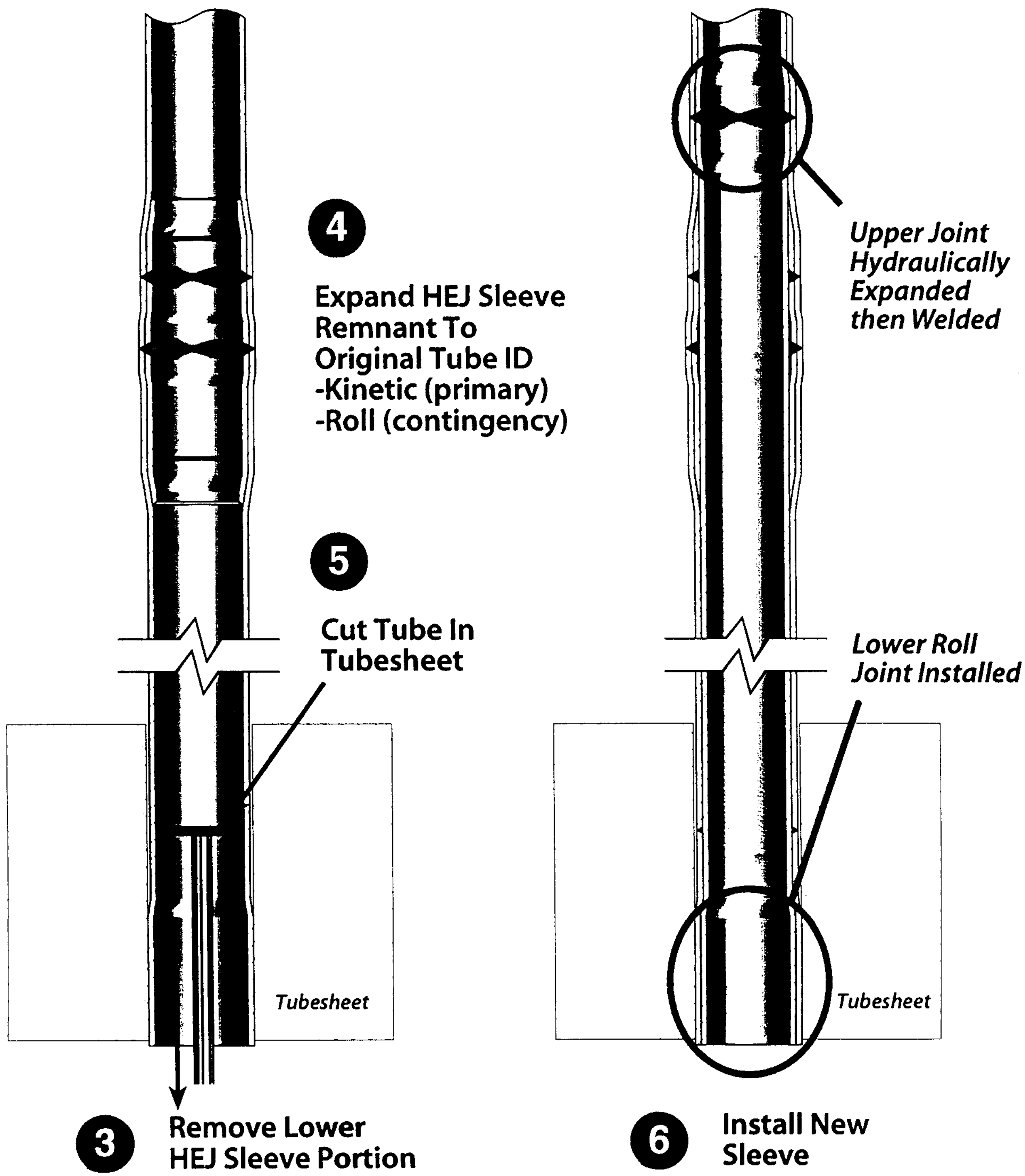


Figure B-5
Sleeve Removal, New Sleeve Installation (cont.)

which requires close attention to detail at every step. The final re-sleeving process had a high acceptance rate.

Point Beach 2

Wisconsin Electric Power Company began detecting secondary side tubesheet indications in the late 1970's. A few tubes were plugged and in 1983 the utility installed 3001 Westinghouse HEJ sleeves. Eighty-seven HEJ sleeves were installed in 1987, 509 in 1988, and 298 in 1989. During the 1994 refueling outage the sleeved tubes were inspected and 221 indications were detected. These indications were similar to those seen at Kewaunee. The indications are on the parent tube predominately at the hard roll lower transition. The majority of these indications are circumferential in nature. The tubes with these indications were plugged during the outage.

Cook 1

Unit 1 at the Donald C. Cook station underwent a major sleeving campaign in the fall of 1992 to repair tube indications in the hot leg tubesheet region, the majority of which were at the top-of-tubesheet. A total of 1840 Westinghouse HEJ sleeves were installed in the four steam generators. As a result of parent tube indications found at Kewaunee and other plants with similar HEJ sleeves, inspections were conducted in the sleeves portion of all Cook 1 HEJ sleeves tubes in 1995 using a CECCO 5 probe. During this inspection no parent tubes indications in the vicinity of the sleeve were found. One HEJ sleeved tube was removed from service due to a defect at another location in the tube.

A follow-up inspection was conducted in the spring of 1997 on all in-service HEJ sleeved tubes. Each sleeve was inspected full length using a Plus Point Probe. A total of 108 parent tube indications were found in the upper sleeve joint. The indications were both axially and circumferentially oriented and were similar to indications found in HEJ sleeves installed at other sites. The repair criteria applied to the indications required that tubes with indications in the upper joint above the lower hydraulic transition be removed from service. Forty-one tubes were plugged using this criteria. Tubes with indications below the lower hydraulic transition in the upper joint were allowed to remain in service. An additional four tubes were removed from service due to indications in other locations of the sleeved tube.

Zion 1 and 2

Commonwealth Edison began detecting secondary side tubesheet indications in 1982 at Zion 1. By the late 1980's both Zion 1 and Zion 2 were also experiencing PWSCC at the roll transition zones. In 1986, 127 ABB CE TIG welded sleeves were installed in Zion 1 and in 1988, 47 Westinghouse HEJ sleeves were installed in the same unit. Since 1989, 1542 additional ABB CE TIG welded sleeves have been installed in Zion 1 and 640 in Zion 2.

As a result of the weld zone indications found at Prairie Island using the Plus Point probe, ABB CE revised the sleeving process to visually verify the tube cleaning step. Zion has evaluated previously installed sleeves using the Plus Point probe. Zion 1 plugged 43 previously installed TIG welded sleeves due to weld zone indications and 10 HEJ sleeves due to cracking at the upper expansion joint. In 1996, Zion 2 plugged 86 previously installed TIG welded sleeves. Seventy-five of the sleeves were plugged due to weld zone indications and eleven were plugged due to lower edge weld defects.

Doel 4

The Doel 4 plant in Belgium is owned and operated by Electrabel. The utility began detecting top of tubesheet indications in 1991. The utility pulled several tubes and confirmed secondary side circumferential stress corrosion cracking. Due to an increase in the number of indications at the end of the operating cycle in 1993, the utility installed 1738 Westinghouse HEJ sleeves. During the next operating cycle, a primary to secondary leak occurred and reached the technical specification limit at the end of the cycle. A hydrostatic test was performed on the steam generators and the utility identified several leaking sleeved tubes. The utility pulled a sleeved tube with a confirmed leak and removed one additional sleeved tube which had no indication of cracking by NDE. The subsequent examination revealed primary side initiated circumferential cracks in the parent tubes at the upper transition of the hydraulic expansion of both tubes. An extensive evaluation of the installation and qualification process indicated that the cracks in the parent tube were due to high residual stress, high operating temperature, and susceptible parent tube material. Doel 4 operated at a hot leg temperature of 626°F (330°C) for 5 cycles and lowered the hot leg temperature to 619°F (326°C) in 1990. After the identification of circumferential cracking, an extensive repair campaign was undertaken. The HEJ sleeves were repaired by hydraulically expanding the sleeve above the existing HEJ joint, performing a laser weld, and followed by a stress relief heat treatment. In addition, 11,232 Westinghouse Laser Welded and stress relieved sleeves were installed in the remaining unsleeved tubes. This included 11,083 elevated 12 inch tubesheet sleeves and 149 tubesheet sleeves which were 30 inches in length. Doel 4 has drilled hole tube support plates made from 405 stainless steel and it was presumed that the tubes were not locked at the first support plate. The utility viewed the sleeves as a short term fix as it planned to replace the steam generators at Doel 4 in 1996.

In June of 1995, both the laser welded and repaired HEJ sleeves were inspected with CECCO-3 and Plus-Point probes, and ten samples (six repaired HEJs and four LWSs) were pulled for laboratory examination and testing. The following observations were made from the pulled tube examination (see Figure B-6):

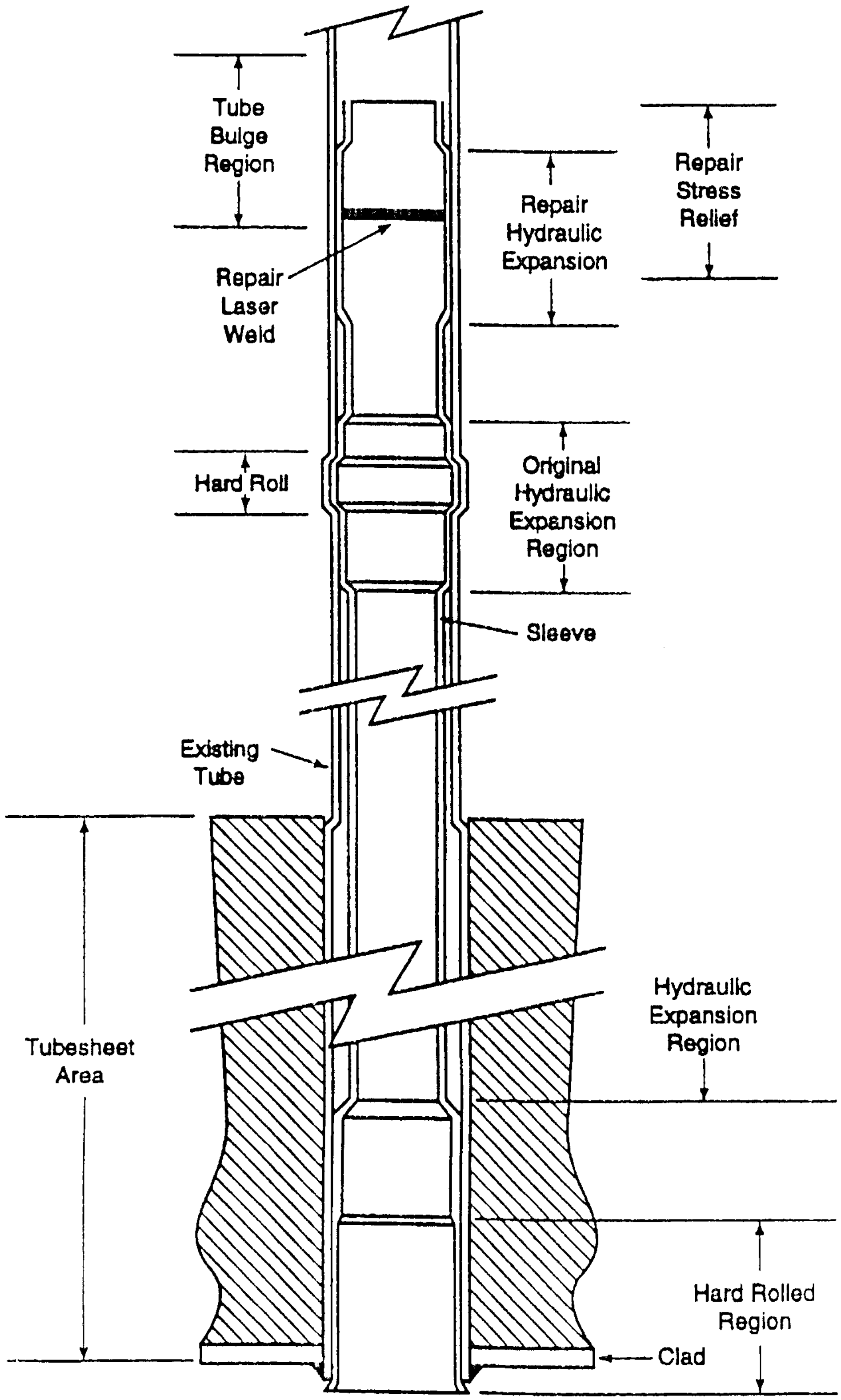


Figure B-6
Doel 4 HEJ Sleeve Repair

- A bulging, or outward expansion of the parent tube, was discovered in the region just above the welded joint. The degree of bulging ranged between 0.1 mm to 0.7 mm for the ten pulled sleeved tube samples. Bulges in the range of 0.4 to 0.7 mm were seen in the HEJ sleeves, and bulges in the range of 0.1 to 0.25 mm were seen on the laser welded sleeves. The bulging was caused by the stress relief treatment of the weld. Two stress relief cycles were performed using an oscillating heater to obtain coverage on the upper hydraulic expansion as well as the laser weld. The stress relief cycles were performed consecutively without allowing the joints to cool to room temperature. Based on the observation of bulging, it is now concluded that tubing was locked at support plates when the repairs were performed.

- Weld defects, either hot weld cracks or porosity, were detected in many of the repaired HEJs and some of the laser welded sleeves. The weld defects were from original installation, not service induced defects. The hot weld cracks were in the Alloy 690 sleeve material and could have been caused by too high of a heat input, air ingress, or contaminants during the welding process. The porosity in the repaired HEJs could have been caused by trapped contaminants or residual moisture since it was not possible to clean or thoroughly dry the surface between the sleeve and the parent tube prior to making the repair weld.

- Wastage of both the sleeve (Alloy 690) and parent tube (Alloy 600 LTMA) was observed in the trapped crevice region between the original upper HEJ joint and the repair joint. Three of the six repaired HEJ samples that were removed due to NDE indications in this area showed volumetric wastage. The throughwall extent of the wastage was approximately 25% for the sleeve and 10% for the parent tube. In addition, one of the sleeves had some shallow cracking. The cause of the wastage is believed to be a very high concentration of boric acid entrapped in the crevice region. However, initial tests in a 25% boric acid environment at 662°F (350°C) for three and one half weeks were unable to create an equivalent wastage attack. Additional exposures in more concentrated environments is in progress to duplicate this wastage attack.

The utility elected during that outage to plug all of the repaired HEJ tubes since the current NDE techniques would not be able to perform an adequate inspection of the region above the weld because of a reduced length of sleeve extending above the joint (hop off distance), and wastage attack on the Alloy 690 sleeve. The utility also had doped steam tests performed to determine relative comparisons of laser welded sleeves to HEJ sleeves and roll transition specimens.

Tihange 2 and 3

Electrabel began to detect top-of-tubesheet indications at Tihange 3 in 1991 (both ID and OD circumferential cracks at the roll transition). In September 1995, twenty tubes were repaired by the ABB CE “PLUSS” Sleeve. This Alloy 800 sleeve had a upper joint made of three hydraulic expansions without deformation of the 3/4 inch parent tube ("zero expansion"). The sleeving procedure was qualified by ABB CE , except for the corrosion tests, which were performed by Laborelec in 10% NaOH. The procedure was similar to the Doel 4 qualification program. The tests were stopped after three times the reference lifetime of the roll transition mock-ups (made from the same heat of tube), in order to simulate the three remaining cycles before steam generator replacement scheduled for 1998. The test results were satisfactory for the expected three remaining cycles of operation.

The twenty tubes sleeved in 1995 were inspected in December 1996 after one cycle of operation. One potential indication was observed at the sleeved tube and was pulled. The destructive examination showed no degradation in the sleeve or parent tube. During this outage, 104 additional ABB CE "PLUSS" Sleeves were installed.

In June, 1997, nine ABB CE "PLUSS" Sleeves were installed in Tihange 2. The upper joint of these sleeves were made with six hydraulic expansions without deformation of the 7/8 inch parent tube. The corrosion tests performed by Laborelec showed that these sleeves should resist PWSCC for at least ten cycles of operation.

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