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COMBUSTION ENGINEERING, INC.

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# Prairie Island Steam Generator Tube Repair Using Leak Tight Sleeves

FINAL REPORT


Combustion Engineering, Inc.
Nuclear Power Systems
Windsor, Connecticut

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ABSTRACT

A technique is presented for repairing degraded steam generator tubes in pressurized water reactor Nuclear Steam Supply Systems (NSSS). The technique described alleviates the need for plugging steam generator tubes which have become corroded or are otherwise considered to have lost structural capability. The technique consists of installing a thermally treated Inconel 690 sleeve which spans the section of original steam generator tube which requires repair, and welding the sleeve to the tube near each end of the sleeve.

This report details analyses and testing performed to verify the adequacy of repair sleeves for installation in a nuclear steam generator tube. These verifications show tube sleeving to be an acceptable repair technique.

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# 1.0 INTRODUCTION

## 1.1 PURPOSE

The purpose of this report is to provide information sufficient to support a technical specification change allowing installation of steam generator repair sleeves in the Prairie Island plants. Although a large scale sleeving operation in the Prairie Island steam generators is not anticipated, support for reactor operation with up to two thousand sleeved tubes in each steam generator is provided. This report demonstrates that reactor operation with sleeves installed in the steam generator tubes will not increase the probability or consequence of an accident previously evaluated. Also it will not create the possibility of a new or different kind of accident and will not reduce the existing margin of safety.

Combustion Engineering (C-E) provides a leak tight sleeve which is welded to the steam generator tube near each end of the sleeve. The sleeve spans the degraded area of the parent steam generator in the tube sheet region. The steam generator tube with the welded sleeve installed meets the structural requirements of tubes which are not degraded. Design criteria for welded sleeves were prepared to ensure that all design and licensing requirements are considered. Extensive analyses and testing have been performed to demonstrate that the design criteria are met.

The effect of sleeve installation on steam generator heat removal capability and system flow rate are discussed in this report. Heat removal capability and system flow rate are considered for installation of up to two thousand sleeves in each steam generator.

After sleeves are installed and inspected, a baseline examination is performed using eddy current (ET) techniques. The ET examination serves as baseline to determine if there is sleeve degradation in later operating years. The ET examination and criteria for plugging sleeved generator tubes if there is unacceptable degradation are described in this report.

Plugs will be installed if sleeve installation is not successful or if there is unacceptable degradation of sleeves or sleeved steam generator tubes. Analyses and testing are described which demonstrate that the welded plug design which is provided by C-E is leak tight and will meet structural requirements during normal and postulated accident conditions.

## 1.2 BACKGROUND

The operation of Pressurized Water Reactor (PWR) steam generators has in some instances, resulted in localized corrosive attack on the inside (primary side) or outside (secondary side) of the steam

generator tubing. This corrosive attack results in a reduction in steam generator tube wall thickness. Steam generator tubing has been designed with considerable margin between the actual wall thickness and the wall thickness required to meet structural requirements. Thus it has not been necessary to take corrective action unless structural limits are being approached.

Historically, the corrective action taken where steam generator tube wall degradation has been severe has been to install plugs at the inlet and outlet of the steam generator tube when the reduction in wall thickness reached a calculated value referred to as a plugging criteria. Eddy current (ET) examination has been used to measure steam generator tubing degradation and the tube plugging criteria accounts for ET measurement uncertainty.

Installation of steam generator tube plugs removes the heat transfer surface of the plugged tube from service and leads to a reduction in the primary coolant flow rate available for core cooling. Installation of welded steam generator sleeves does not significantly affect the heat transfer removal capability of the tube being sleeved and a large number of sleeves can be installed without significantly affecting primary flow rate.

## 2.0 SUMMARY AND CONCLUSIONS

The sleeve design, materials, and joints were designed to the applicable ASME Boiler and Pressure Vessel Code. An extensive analysis and test program was undertaken to prove the adequacy of the welded sleeve. This program determined the effect of normal operating and postulated accident conditions on the sleeve-tube assembly, as well as the adequacy of the assembly to perform its intended function. Design criteria were established prior to performing the analysis and test program which, if met, would prove that the welded sleeve is an acceptable repair technique. Based upon the results of the analytical and test program described in this report the welded sleeve fulfills its intended function as a leak tight structural member and meets or exceeds all the established design criteria.

No detrimental effects on the sleeve-tube assembly are predicted to result from reactor system flow, coolant chemistries, or thermal and pressure conditions. Structural analyses of the sleeve-tube assembly have established its integrity under normal and accident conditions. The structural analyses have been performed on thirty-six inch long sleeves but twenty-four inch long sleeves will also be installed in Prairie Island. Discussion of why the analyses of thirty-six inch long sleeves are conservative for shorter sleeves is given in Section 8.1.

Mechanical testing has been performed to support the analyses and ASME code stress allowables have been used. Corrosion testing of typical sleeve-tube assemblies have been completed and reveal no evidence of sleeve or tube corrosion considered detrimental under anticipated service conditions.

Welding development has been performed on clean tubing and dirty tubing which has been taken from pot boiler tests and simulate operation in a steam generator. C-E successfully installed eighteen welded sleeves in a sleeve installation demonstration in Ringhals-2 steam generators in May, 1984. The sleeve installation demonstration and a demonstration showing that welded sleeves can be successfully inspected using visual examination or ultrasonic testing (UT) techniques are described in this report.

Welded plugs have been developed for sleeved steam generator tubes in the event that sleeve installation is not successful. No detrimental effects resulted from subjecting plug-sleeve-tube assemblies to pressure conditions or mechanical tests. Structural analyses of the installed plugs have demonstrated their integrity under the normal operating conditions or accident conditions.

In conclusion, steam generator tube repair by installation of welded sleeves is established as an acceptable method. Repair of sleeved steam generator tubes using welded plugs is also established as an acceptable method.

## 3.0 ACCEPTANCE CRITERIA

The objectives of installing sleeves in steam generator tubes are twofold. The sleeve must maintain structural integrity of the steam generator tube during normal, and postulated accident conditions. Additionally, the sleeve must prevent leakage in the event of a through hole in the wall of the steam generator tube. Numerous tests and analyses were performed to demonstrate the capability of the sleeves to perform these functions under normal operating and postulated service conditions. Design and operating conditions for the Prairie Island steam generators are defined as:

| | | |
|---|---|---|
| Primary Side: | 590°F (hot side) | 2235 psig (operating) |
| | 650°F (design) | 2485 psig (design) |
| Secondary Side: | 547°F | 735 psig (operating) |
| | 600°F (design) | 1085 psig (design) |

Table 3-1 provides a summary of the criteria established for sleeving in order to demonstrate the acceptability of the sleeving techniques. Justification for each of the criterion is provided. Results indicating the minimum level with which the sleeves surpassed the criteria are tabulated. The section of this report describing tests or analyses which verify the characteristics for a particular criterion is referenced in the table.

Plugs are installed in the sleeved steam generator tubes when the tubes cannot be successfully repaired with sleeves. The objective of the plugging is to prevent leakage between the primary and secondary sides of the steam generator during normal and postulated accident conditions.

Table 3-2 provides a summary of the criteria for welded plugs. The format in Table 3-2 is the same as Table 3-1.

# 4.0 DESIGN DESCRIPTI' ' OF SLEEVES, PLUGS AND INSTALLATION EQUIPMENT

## 4.1 SLEEVE DESIGN DESCRIPTION

The sleeve is shown in Figure 4-1. The sleeve is 36 inches in length and has a nominal outside diameter of [ ]. Sleeve wall thickness is [ ]. The sleeve material is thermally treated Inconel 690.

As shown in Figure 4-1 the sleeve is chamfered at the upper end to prevent hang-up with equipment which is used to install or inspect the sleeve (or steam generator tube). [ ]

The outside diameter of the sleeve was selected to provide a generous clearance between the sleeve and steam generator tube [ ] so that the sleeve slides freely through the tube during installation. There were two considerations in selecting the sleeve thickness: first, the sleeve has sufficient thickness so that the steam generator tube with the sleeve bridging the corroded section of the tube meets the structural requirements of the undamaged steam generator tube (without benefit from the tube). Second, there is a large margin in thickness over what is required structurally to allow for sleeve eddy current measurement uncertainty. The inside diameter of the sleeve is large enough so that the flow rate and heat transfer capability of the steam generator tube are not significantly affected by sleeve installation.

## 4.2 SLEEVE MATERIAL SELECTION

The tubing from which the sleeves are fabricated is procured to ASME Boiler and Pressure Vessel Code Case N-20. In addition a thermal treatment of 740°C is also specified in order to impart greater corrosion resistance and lower the residual stress level in the tube.

The primary selection criterion for the sleeve material was its corrosion resistance in primary and fault secondary PWR environments. Specific resistance to pure water and caustic stress corrosion cracking were considered.

C-E's justification for selection of this material is based on the following information:

### 4.2.1 General Corrosion and Corrosion Product Release Rates

Information published by INCO (Reference 1) indicates that the corrosion product release rate of Alloy 690 is superior to Alloy 600 in both high temperature ammoniated and borated waters. The

corrosion rate of Alloy 600 is significantly higher, especially in borated waters, with the concurrent formation of thicker oxides. The latter is a potential concern during thermal transients which could initiate crud bursts.

### 4.2.2 Stress Corrosion Cracking Resistance

Alloy 600 in a variety of thermal treatments exhibits known susceptibility to intergranular stress corrosion cracking (IGSCC) in high temperature pure water solutions. Deaerated boric acid at high temperature is relatively undisassociated and thus the resistance-susceptibility of Alloy 600 to IGSCC is comparable. Recent investigations (Reference 2) have shown that pure water IGSCC resistance of Alloy 600 can be improved via controlled thermal-mechanical processing.

Laboratory testing on Alloy 690 (References 1 and 3) tubing show it to be immune to high temperature deaerated pure $H_2O$ IGSCC in a variety of thermal-mechanical conditions. Apparently resistance to stress corrosion cracking (SCC) in Alloy 690 is the result of a compositional improvement rather than a specific microstructure thus making it more attractive for a welded sleeve design.

Tests in pure water environments with oxygen present at elevated temperatures resulted in IGSCC of 304 stainless steel, Alloy 600, and Alloy 800 within a stressed crevice region (Reference 1). Alloy 690 in a variety of metallurgical conditions exhibited complete immunity to SCC in this test program with exposure times of 48 weeks. For comparison, the former materials exhibited evidence of IGSCC corrosion after two weeks exposure.

### 4.2.3 Coordinated Phosphate Chemistry

An extensive laboratory test program utilizing high temperature pot and model boiler facilities was performed by C-E in the early 1970's. The results of these heat transfer tests indicated that phosphate chemicals concentrated in areas of steam blanketing and produced thinning of the Alloy 600 heat transfer tubing. This phenomena was observed over a wide range of sodium to phosphate ratios with and without feedtrain corrosion product additions. The corrosion product in all cases consisted of a green nickel-rich phosphate compound containing lesser amounts of iron and chromium. In this program Alloy 800 and 304 stainless steel tubing were also tested and determined to be more resistant to phosphate wastage. A general correlation between corrosion rate and the nickel content of the transfer tube alloy was observed.

Although the corrosion resistance of Alloy 690 in coordinated phosphate solutions has not been extensively tested at C-E, based on the observed correlation between corrosion rate and nickel concentrations, its performance should be better than Alloy 600.

## 4.2.4 Faulted Phosphate Chemistry Control

If condenser leakage occurs it is possible to alter the sodium to phosphate ratio of the coordinated phosphate solution such that caustic conditions result in the boiler water. Under these conditions, caustic induced SCC may occur. While none of the presently used heat transfer tubing alloys are totally resistant to this form of corrosion attack, mill annealed Alloy 690 shows equivalent resistance to mill annealed Alloy 600 in concentrated solutions (Reference 3). Thermally treated Alloy 690 exhibited notable improvement in this stress corrosion test as compared with mill annealed Alloy 690 and a slight improvement as compared with thermally treated Alloy 600.

Similarly, acid forming impurities species introduced as the result of condenser leakage may concentrate in low flow regions to aggressive levels. Chlorides have been shown to readily produce SCC of austenitic stainless steels and iron base allows, e.g. Alloy 800 under these conditions. Immunity to chloride induced SCC was a primary criteria for the switch to nickel-base (Alloy 600) tubing for nuclear steam generating units. Laboratory tests indicate that Alloy 690 also exhibits immunity to chloride induced SCC probably due to its intermediate nickel concentrations (Reference 1).

Recent information obtained via cooperative test programs with the Electric Power Research Institute has identified acid sulfur species as aggressive impurities leading to accelerated corrosion of Alloy 600 steam generator tubing. The modes of attack observed with different sulfur species and concentrations consist of wastage, intergranular attack (IGA) and IGSCC. The latter produced primary to secondary leakage of Alloy 600 tubing representative of all commercial heat treatments, i.e. mill annealed, sensitized, thermally treated. The environment consisted of volatile chemistry control faulted with acidified ($H_2SO_4$) fresh water impurities. Alloy 690 (mill annealed) tubing exposed to this environment for longer test periods did not exhibit through-wall IGSCC.

## 4.3 SLEEVE-TUBE ASSEMBLY

The installed sleeve is shown in Figure 4-2. Since the sleeve is 36 inches long, the upper end of the sleeve is about 15 inches above the top of the tubesheet and about 31 inches below the first tube support plate. [

]

The weld and welding operators have been qualified for making upper and lower welds and the weld qualification documents are given in Appendix A. Since the upper weld is repaired by making a second weld which is centered two inches below the first weld and is made using the same welding parameters, a qualification document for repair is not required.

## 4.4 PLUG DESIGN DESCRIPTION

## 4.5 WELDED PLUG ASSEMBLY

The weld and weld operator qualification document for installing plugs in sleeved steam generator tubes is given in Appendix A.

## 4.6 SLEEVE INSTALLATION EQUIPMENT

The equipment used for remote installation of sleeves in a steam generator is made up of the following basic systems. These systems are:

1. Remote Controlled Manipulator

8. Nondestructive Examination Equipment

These systems, when used together, allow installation of the sleeves without entering the steam generator. In this way, personnel exposure to radiation is held to a minimum.

### 4.6.1 Remote Controlled Manipulator

The remote controlled manipulator serves as a transport vehicle for inspection or repair equipment inside a steam generator primary head.

The manipulator consists of two major components; the manipulator leg and manipulator arm. The manipulator leg is installed between the tube sheet and bottom of the primary head and provides axial movement of the arm. The manipulator arm is divided into the head arm, probe arm and a swivel arm. Each arm is moved independently with electric motors with encoder position control. The swivel arm

allows motion for tool alignment in both square pitch and triangular pitch tube arrays. Computer control of the manipulator allows the operator to move sleeving tools from outside the manway and accurately position them against the tube sheet.

4.6.2 Manipulator Elevator

4.6.3 Tube Brushing-Cleaning Equipment

4.6.4 Tube Size Rolling Equipment

4.6.5 Sleeve Installation Equipment

4.6.6 Sleeve Expansion Equipment

4.6.7 Sleeve Welding Equipment

4.6.8 Nondestructive Examination

Three types of nondestructive examination equipment are used during the sleeving process. They are as follows: eddy current testing (ET) equipment, ultrasonic testing (UT) equipment and visual equipment.

A dual cross wound probe and bobbin probe using the multifrequency eddy current method will be used to do a base line inspection of the installed sleeve for future reference. The ET fixture with conduit is used on the manipulator arm to position the probe. Eddy current testing using a bobbin probe may also be used to determine the inside diameter of the tube to be sleeved and the sleeve expansion size.

Ultrasonic testing using an immersion technique with demineralized water as a couplant is used to inspect the upper tube to sleeve weld. A one-quarter inch diameter focusing transducer is positioned in the weld area by the elevator and is rotated with an electric motor to scan the weld. The pulse echo tester has the ability to interface with an on line data reduction computer to produce a display/hardcopy during radial and axial scanning.

Visual inspection of the upper and lower tube to sleeve weld is accomplished with the use of a boroscope mounted on the manipulator arm.

4.7 PLUG INSTALLATION EQUIPMENT

The equipment used for remote installation of plugs in a sleeve steam generator tube is made up of the following systems:

1. Remote Controlled Manipulator

5. Nondestructive Examination Equipment

4.7.1 Remote Control Manipulator

See Section 4.6.1 for a description of the Remote Control Manipulator.

4.7.2 Sleeve Size Rolling Equipment

4.7.3 Plug Installation Equipment

4.7.4 Plug Welding Equipment

4.7.5 Nondestructive Examination

Visual inspection of the plug weld is accomplished with the use of a boroscope mounted on the manipulator arm.

## 4.8 ALARA CONSIDERATIONS

The steam generator repair operation is designed to minimize personnel exposure during installation of sleeves or plugs. The manipulator is installed from the manway without entering the steam generator. It is operated remotely from a control station outside the containment building. The positioning accuracy of the manipulator is such that it can be remotely positioned without having to install templates in the steam generator.

[ ]

Air, water and electrical supply lines for the tooling are designed and maintained so that they do not become entangled during operation. This minimizes personnel exposure outside the steam generator. Except for the welding power source and programmer all equipment is operated from outside the containment. The power source and programmer is stationed about a hundred feet from the steam generator in a low radiation area.

In summary, the steam generator operation is designed to minimize personnel exposure and is in full compliance with ALARA standards.

## 4.9 REFERENCES TO SECTION 4.0

(1) Sedricks, A. J., Schultz, J. W., and Cordovi, M. A., "Inconel Alloy 690 - A New Corrosion Resistant Material", Japan Society of Corrosion Engineering, 28, 2 (1979).

(2) Airey, G. P., "Optimization of Metallurgical Variables to Improve the Stress Corrosion Resistance of Inconel 600", Electric Power Research Institute Research Program RP1708-1 (1982).

(3) Airey, G. P., Vaia, A. R., and Aspden, R. G., "A Stress Corrosion Cracking Evaluation of Inconel 690 for Steam Generator Tubing Applications", Nuclear Technology, 55, (November, 1981) 436.

## 5.0 SLEEVE EXAMINATION PROGRAM

[ ]

### 5.1 ULTRASONIC INSPECTION

#### 5.1.1 Summary and Conclusions

An ultrasonic examination is used to confirm fusion of the sleeve to the tube after welding. This test consists of introducing a sound wave with a frequency of [ ] into the welded region. This sound wave is rotated 360 degrees around the tube, the fixture is then raised approximately [ ] inches and scanned again. A minimum of three scans are performed and if one or more of these scans show fusion for the whole 360 degrees, the weld is considered acceptable. The beam that is used is capable of easily detecting a [ ] inch diameter flat bottomed hole.

#### 5.1.2 Ultrasonic Evaluation

Ultrasonic techniques are employed to confirm the presence of sleeve-tube weld fusion. The evaluations were made of Inconel 690 alloy sleeves with nominal dimensions of [ ] inch outside diameter, and minimum [ ] inch wall. The Inconel 600 alloy steam generator tubes are 0.875 inch outside diameter X 0.050 inch wall. Weld position is approximately [ ] inches from the top of the sleeve.

Ultrasonic energy at [ ] is emitted from a transducer through a contained water column in the vicinity of the weld. After passing into the sleeve at its entry point, the sound continues to travel

until it arrives at a separation in material or to the opposite side of the material. The transducer is designed so that when traveling through the total thickness of sleeve, weld and tube, the energy is focused at the sleeve outer diameter wall, with a spot size of approximately [ ]

When sound enters the sleeve some of the sound energy is reflected at the sleeve I.D. and the reflection is referred to as the interface signal. The transmitted sound passes through a weld with proper fusion and is sometimes, but not always reflected back to the transmitter from the tube backwall; i.e., the tube O.D. Should no fusion exist at a given point, the sound energy will be reflected at the sleeve backwall, i.e. the sleeve O.D. A weld area is considered to have proper fusion where an interface signal exists without the presence of sleeve backwall reflection. A good weld is shown in Figure 5-1 where the tube backwall signal is also present. No fusion is shown in Figure 5-2 where the display in the cathode ray tube (CRT) shows the interface signal followed by a sleeve backwall signal. Sometimes when there is lack of fusion the interface signal is followed by multiple sleeve backwall signals.

The weld examination begins when the transducer is inserted into the sleeve/tube assembly to a position such that the transducer is aligned with the weld. The transducer is then rotated 360 degrees at this elevation and the degree of fusion is determined by observing the ultrasonic instrument's CRT, or by other readouts. Additional scans at other elevations can be performed to evaluate the complete weld area.

In this manner, the weld integrity can be assured and lack of fusion, with an area equivalent to a [ ] diameter flat bottom hole or a slot with a width of [ ], can reliably be detected. In actual test specimens, a lack of fusion had been reliably detected as shown in Figure 9-2.

### 5.1.3 Test Equipment

Test equipment for welded sleeve inspection consists of the following components:

[ ]

5.1.4 Defect Samples

Qualification of the ultrasonic inspection system was made through a variety of pedigree defect samples, as well as welds with good fusion across the entire area. Weld samples are typical of conditions to be present in the steam generator. The calibration samples are described as follows:

5.1.5 Detailed Results

The computer output for each calibration sample is included in this report. The information contained on each chart consists of the following:

1. Rotation (degrees). This is the angular position of the transducer measured in degrees. The zero degree point for the transducer is arbitrarily selected, locked into place and is consistent for all following scans. This enables circumferential location of any lack of fusion area indicated on the print out.

2. Elevation (inches or centimeters). The elevation or vertical position of the transducer within the sleeve is given in both inches and centimeters. This information enables approximation of the weld height and location of any lack of fusion areas.

3. Scan limits. The upper and lower scan limits for the weld are shown by the unprinted section of the scan limit figure.

4. Data on the top of each chart relates to information concerning the inspected tube, steam generator and time, as well as weld signal amplitude threshold values for recording. There are two sleeve-tube areas that can be monitored by electronic gating circuits. One gate measures the level of the signal from the tube outer surface and the other gate monitors the sleeve-tube interface. A tube outer surface signal above the threshold value and/or no sleeve signal above the threshold value can indicate fusion.

   Gate 1, the tube backwall monitor, is positioned so that its leading edge aligns with the leading edge of the tube backwall signal.

   Gate 2, the sleeve backwall monitor, is positioned so its leading edge follows the interface signal and terminates before the tube backwall signal.

   The computer software allows versatility with regard to monitoring the weld integrity by selection of the gates to be used, as well as the setting of the threshold limits. The normal inspection is performed by monitoring only the sleeve-tube signal (Gate 2) without regard to the tube backwall signals (Gate 1).

In reviewing the computer readouts for the two calibration samples used, the following analysis is offered:

It can be seen that each of the artificial flaws used for these qualification examinations can be detected, while the good fusion areas of the weld presented no indicated areas of lack of fusion.

## 5.2 EDDY CURRENT INSPECTION

The objective of this examination is to establish baseline data on the primary pressure boundary of the sleeve-tube assembly. The

examination was developed to detect 40 percent ASME sized flaws in the parent tube and/or sleeve in any region of the sleeve-tube assembly with a single pass of an eddy current coil.

5.2.1 Summary and Conclusions

An eddy current test has been qualified for the inspection of installed welded sleeves to detect flaws in the pressure boundary. Eddy currents circulating in the sleeve and steam generator tube are interrupted by the presence of flaws in the material with a resultant change in test coil impedance. This impedance change is processed and displayed on the test instrument to indicate the presence of a flaw.

The pressure boundary is considered to be the sleeve up to and including the upper weld joint and the steam generator tube above the weld. Consequently, there are three distinct regions relative to the inspection methods: 1) The sleeve below the weld, 2) the steam generator tube behind the top section of the sleeve (above the weld) and 3) the steam generator tube above the sleeve.

Using specialized probes and multifrequency eddy current techniques, it has been demonstrated that a [ ] is detectable anywhere in the sleeve or tube, including the weld region. [ ] The test results are recorded on magnetic tape and strip chart recordings. Other than the probes, the inspection equipment is the same as used for a conventional eddy current test of steam generator tubing. Additional laboratory testing of accelerated corrosion samples has shown that this method can detect IGSCC in the parent tube.

5.2.2 Multi-Frequency Eddy Current Equipment Requirements

The equipment required to perform this examination include the following:

[ ]

5.2.3 Defect Samples

A variety of simulated defect samples were fabricated to represent different possible flaw locations in the sleeve or steam generator tube. The basis for the qualification was to demonstrate detectability of a [

] at any location in the pressure boundary. Several samples were required to simulate the potential signal interference from the sleeve end, sleeve bulge and weld. The sample matrix included:

[ ]

5.2.4 Results and Conclusions

[ ]

[ ] multi-frequency eddy current techniques are employed to further enhance the signal to noise ratio. A total of four separate test frequencies and two

mixing channels are employed simultaneously. By combining the signals from two frequencies, the residual noise signals from the bulge, etc., can be virtually eliminated. For this particular application, a combination [ ] is used to inspect the sleeve. In Figures 5-11 through 5-15, the eddy current test signals for various qualification samples are shown, both the single and multi-frequency results are shown, however, in general, the [ ] will be used as the basis of analysis.

The low frequency required to examine the steam generator tube through the sleeve and the total wall thickness of the sleeve-tube assembly result in insufficient phase shift of the defect signals from the steam generator tube defect calibration standard to allow evaluation of steam generator tube wall degradation indications by relating signal phase angle to the depth of penetration. Consequently, detection is possible, but accurate sizing generally is not possible.

Sleeve wall degradation indications can be evaluated for depth of penetration and origin by plotting the phase angle of [ ] data to graphs relating signal phase angle to depth of penetration. The smallest sleeve wall degradation demonstrated to be detectable with this examination technique was a single [ ] from the O.D. of the sleeve.

## 5.3 VISUAL INSPECTION

### 5.3.1 Summary and Conclusions

Visual examinations are performed on the upper and lower sleeve to tube welds to determine their integrity and acceptance. The welds are examined using a fiber optic or boroscope examination system. The lighting is supplied either as an integral part of the visual examination system or as a supplemental system. Each examination is recorded on video tape for optional later viewing and to provide a permanent record of each weld's condition.

The inspections are performed to ascertain the mechanical and structural condition of each weld. Critical conditions which are checked include weld width and completeness and the absence of visibly noticeable indications such as cracks, pits, blow holes, burn through, etc.

### 5.3.2 Lower Weld Evaluation

The lower weld of the sleeve-tube assembly is inspected using a boroscope examination system. The boroscope is positioned under the lower weld and the lighting is adjusted to obtain the optimal viewing conditions. Rotating the boroscope around the weld and tilting it when necessary, provides complete coverage of the

examination area. A videotape recording is made of the entire examinations.

Prior to the inspection, the system's accuracy is ascertained by observing a 1/32" black line on an 18% neutral gray card placed on the surface to be examined or a location similar to the inspection area. Proper use of this system provides image resolution on the order of 0.001 inch.

Weld acceptance is based on the absence of any cracks or other visible imperfections which would be detrimental to the integrity of the weld. During the examination, an area containing a noticable indication is inspected more closely. This is done by varying the light intensity, distance from the lens to the indication, and/or the angle used during the viewing.

5.3.3 Upper Weld Examination

A visual examination is made of the upper sleeve to tube weld using a boroscope inspection system. This system utilizes a right-angle lens and a tool which can deliver the lens up to the weld as well as to provide 360° rotational capabilities.

To perform the inspection, the optics system is inserted into the sleeve/tube assembly such that the lens is located at the upper weld. After checking for visual clarity and adjusting the lighting to reduce unwanted glare, the lens is rotated 360°. The lens may then be raised or lowered and the process repeated to ensure complete weld coverage. The entire examination is video-taped for a permanent record.

Prior to the inspection, the system's adequacy is checked by observing a 1/32" black line on an 18% neutral gray card placed in a location similar to the area to be inspected. Additionally, to obtain an aspect for size and to check the in-tube lighting, a welded sleeve-type sample with a .020" diameter through hole is placed over the lens.

The weld acceptance is based on the absence of cracks or other visible imperfections which would be detrimental to the integrity of the weld. Detrimental imperfections include blow holes, burn through, weld mismatch, etc. During the examination, any area which contains noticable imperfections is examined more closely by varying the light intensity and/or the position of the lens with respect to the indication.

5.3.4 Test Equipment

The test equipment necessary to visually inspect the upper and lower sleeve to tube welds consists of the following:

1. Boroscope visual examination system with an integral lighting system, lenses and a delivery and rotational tool for inspecting the upper and lower welds.

2. 18% neutral gray card with a 1/32" black line.

3. Welded sleeve-tube sample with a .020 inch diameter through drilled hole.

4. Video camera and recording equipment.

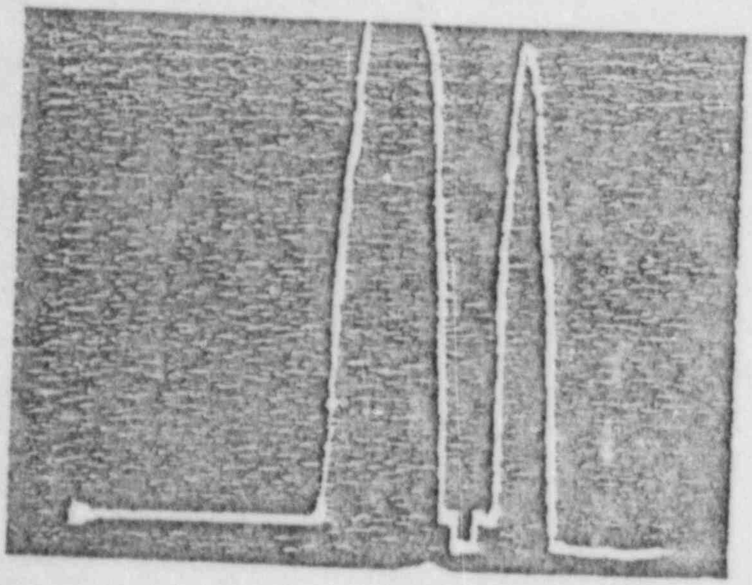
5.3.5 <u>Defect Standards</u>

Various methods are used to determine system adequacy and to aid in determining weld acceptability.

1. System adequacy, including lighting intensity and camera system clarity, is verified by resolving a 1/32" black line on an 18% neutral gray card.

2. Size aspect for upper weld inspections is obtained by viewing a welded sleeve-tube sample which has a .020 inch through drilled hole.

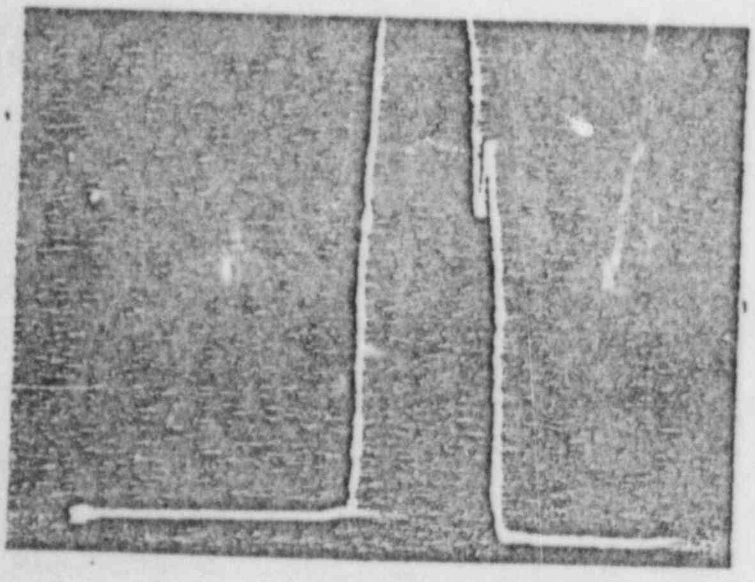
3. Sleeve-tube upper and lower welds were made with both acceptable welds and intentional weld malformities. These welds were photographed and are used as aids to examiner.



UT TRACE SHOWING ACCEPTABLE WELD

FIGURE 5-1

The interface signal (left) and tube back wall signal are shown.



UT TRACE SHOWING WELD WITH LACK OF FUSION

FIGURE 5-2

Lack of fusion is indicated by multiple sleeve backwall signals following the interface signal.

# COMBUSTION > ENGINEERING SLEEVE WELD INSPECTION REPORT

INSP DATE: 21AUG84
TUBE NO: HOLE STD
FILE NAME: 210841.010

TIME: 17:19:20
ST GEN NO: STAND

THRESH % OF FSH: 20
SITE: WINDSOR
SCAN 0 TO 360 DEG

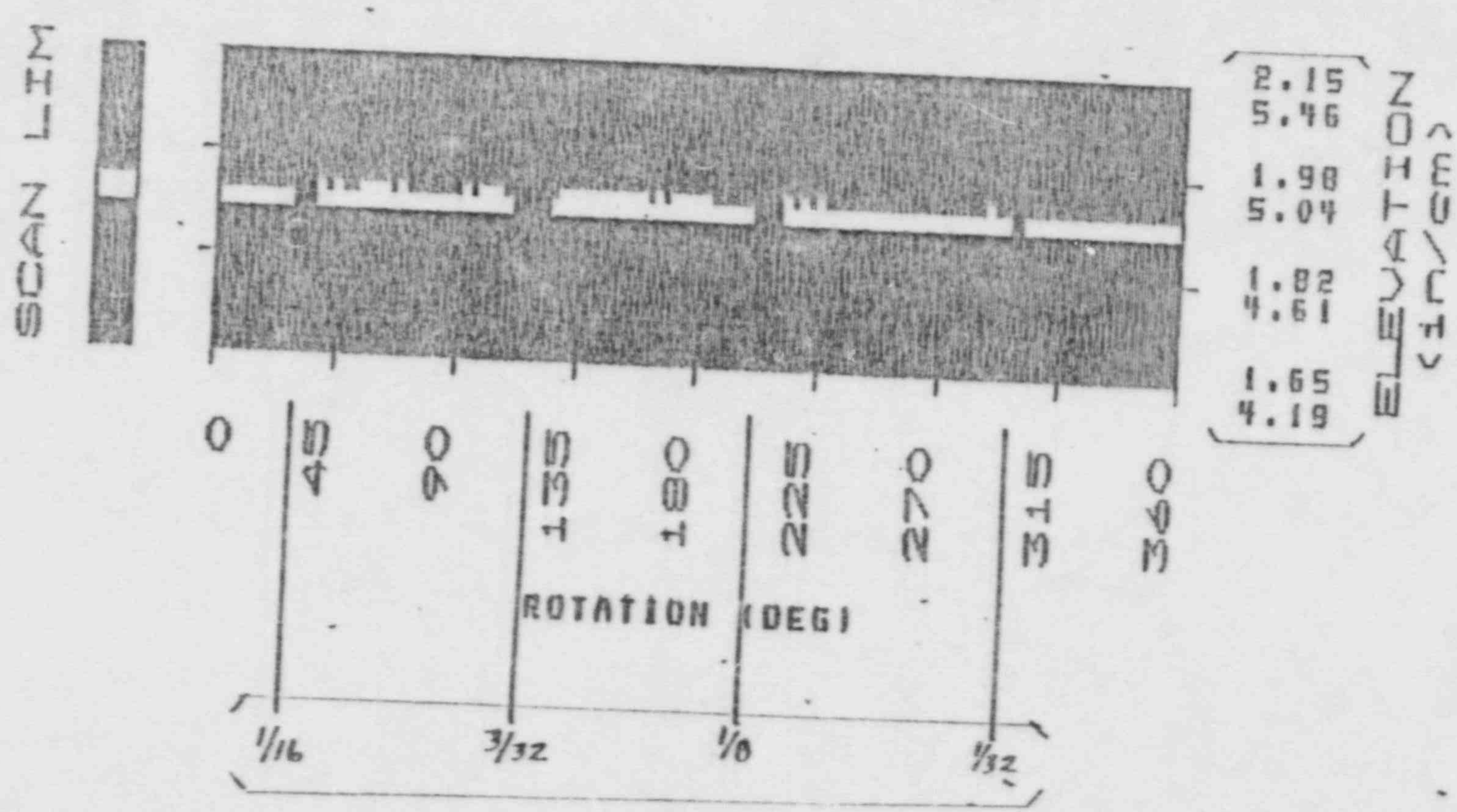



Figure 5-4
Flat Bottom Drilled Hole Standards

# COMBUSTION > ENGINEERING SLEEVE WELD INSPECTION REPORT

INSP DATE: 21AUG84 TIME: 16:39:41 THRESH % OF FSH: 20

TUBE NO: CE3 ST GEN NO: ,STD SITE: WINDSOR

FILE NAME: 210841.016 SCAN 0 TO 360 DEG

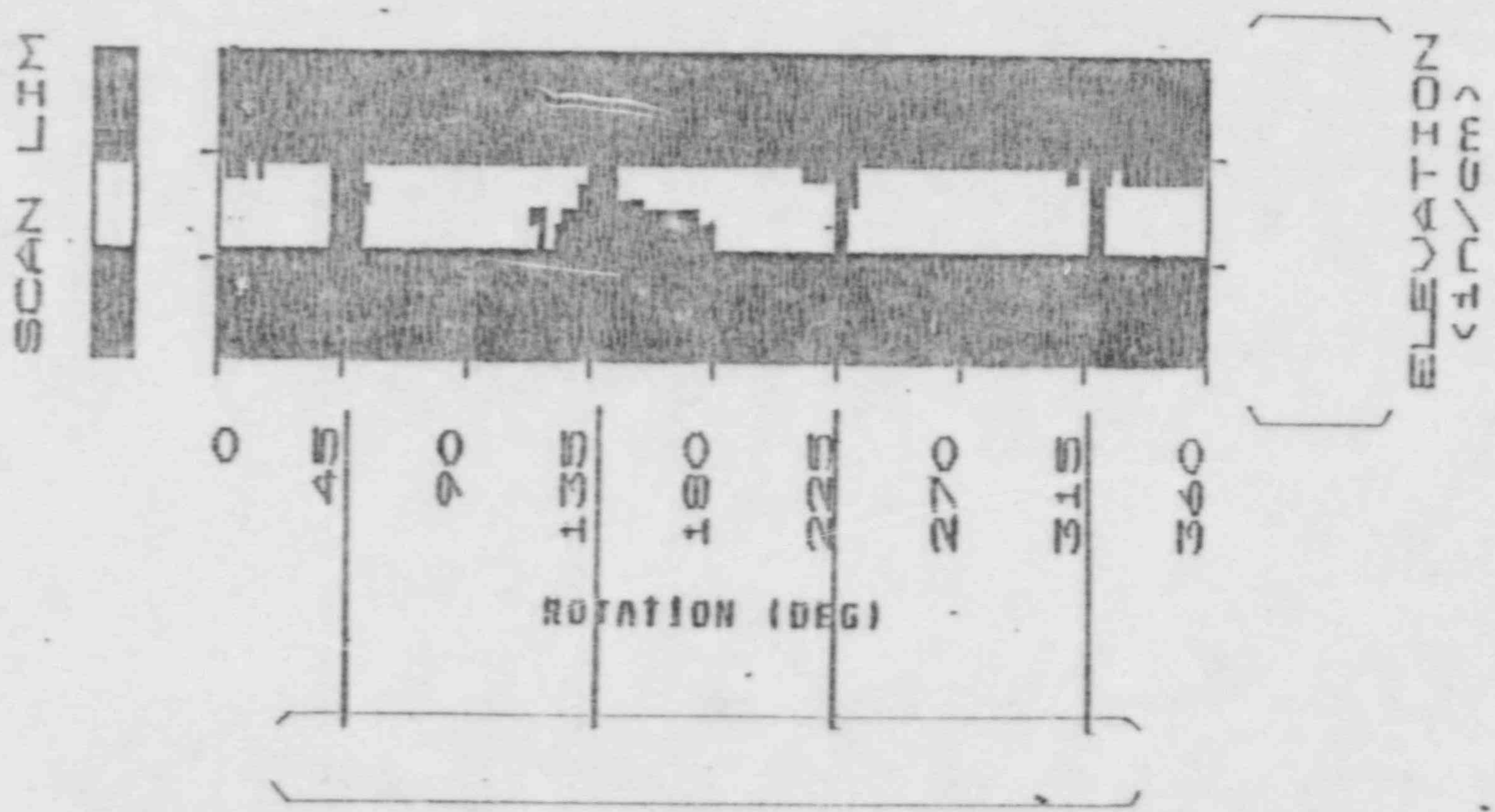



Figure 5-6

Milled Slot Standard

# COMBUSTION > ENGINEERING SLEEVE WELD INSPFCTION REPORT

| | | |
|---|---|---|
| INSP DATE: 22AUG84 | TIME: 09:30:03 | THRESH % OF FSH: 20 |
| TUBE NO: C3 LOWER | ST GEN NO: MOCK UP | SITE: WINDSOR |
| FILE NAME: 220841.003 | | SCAN 360 TO 0 DEG |

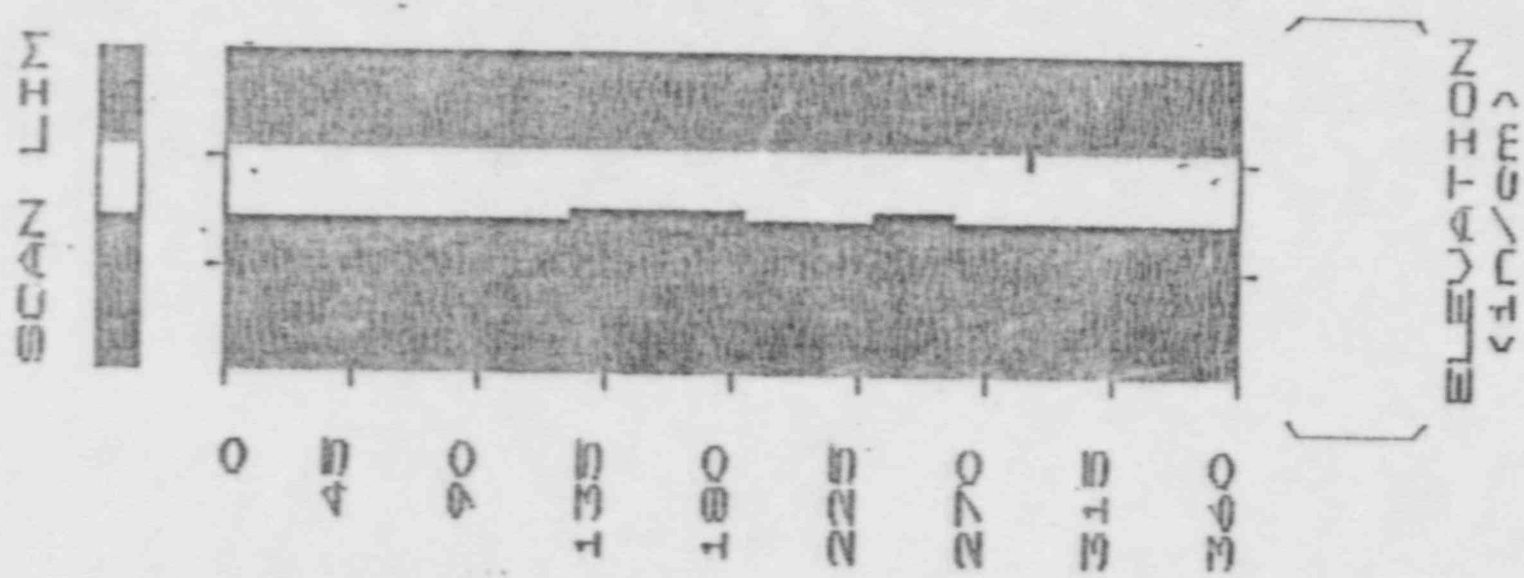



Figure 5-7

Acceptable Weld

# COMBUSTION > ENGINEERING SLEEVE WELD INSPECTION REPORT

| | | |
|---|---|---|
| INSP DATE: 21AUG84 | TIME: 10:45:58 | THRESH % OF FSH: 20 |
| TUBE NO: D3 UPPER | ST GEN NO: MOCK UP | SITE: WINDSOR |
| FILE NAME: 210841.023 | | SCAN 360 TO 0 DEG |

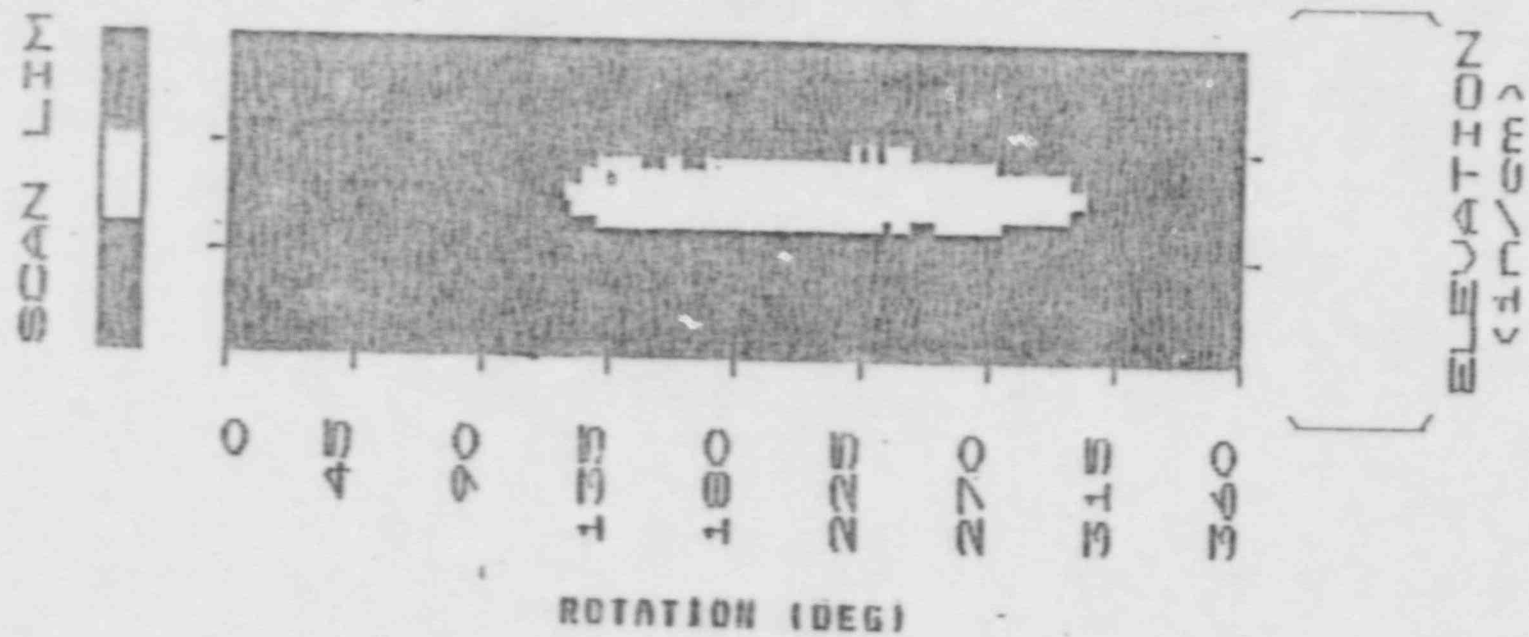



Figure 5-8

Weld with Lack of Fusion

# COMBUSTION > ENGINEERING SLEEVE WELD INSPECTION REPORT

INSP DATE: 21AUG84 TIME: 10:50:51 THRESH % OF FSH: 20

TUBE NO: D3 LOWER ST GEN NO: MOCK UP SITE: WINDSOR

FILE NAME: 210841.024 SCAN 0 TO 360 DEG

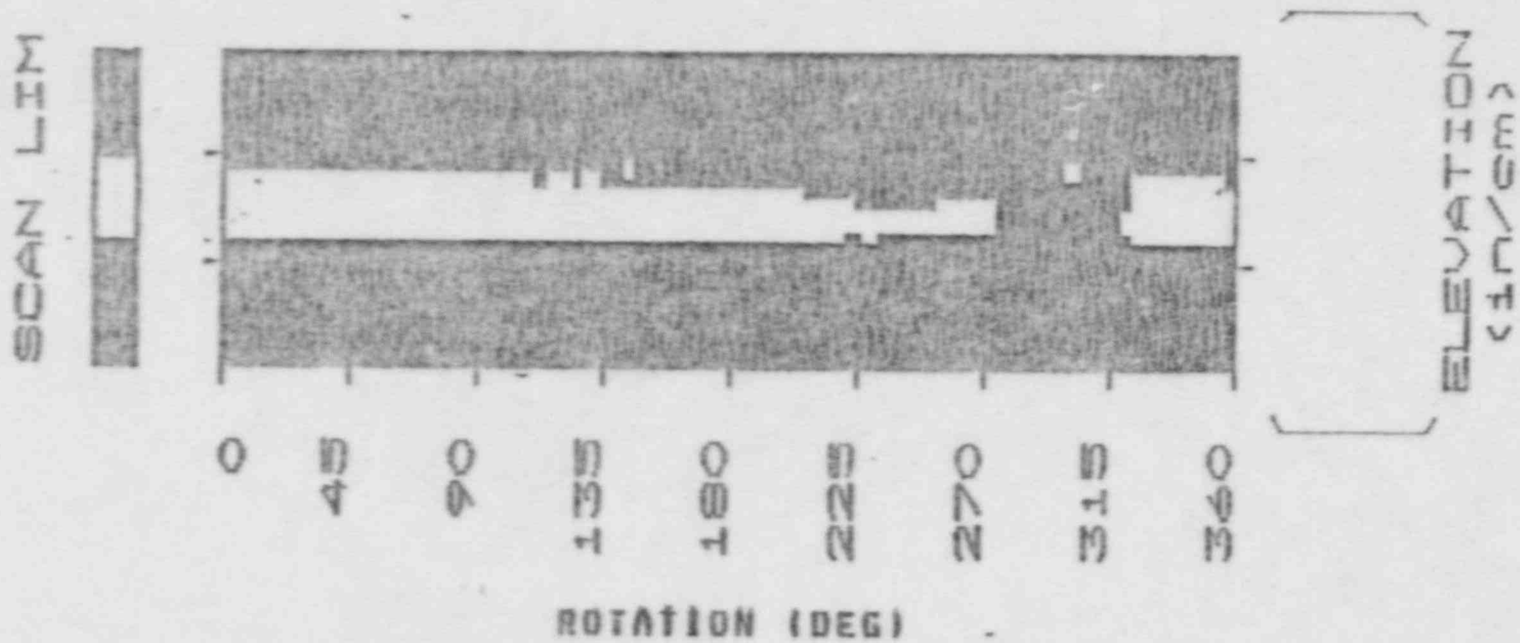
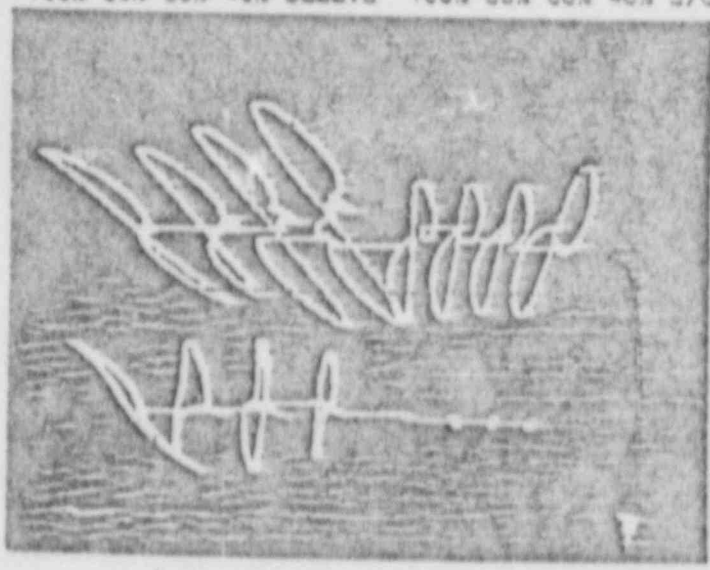



Figure 5-9

WELD WITH LACK OF FUSION
(SECOND SAMPLE)

100% 80% 60% 40% SLEEVE 100% 80% 60% 40% S/G TUBE

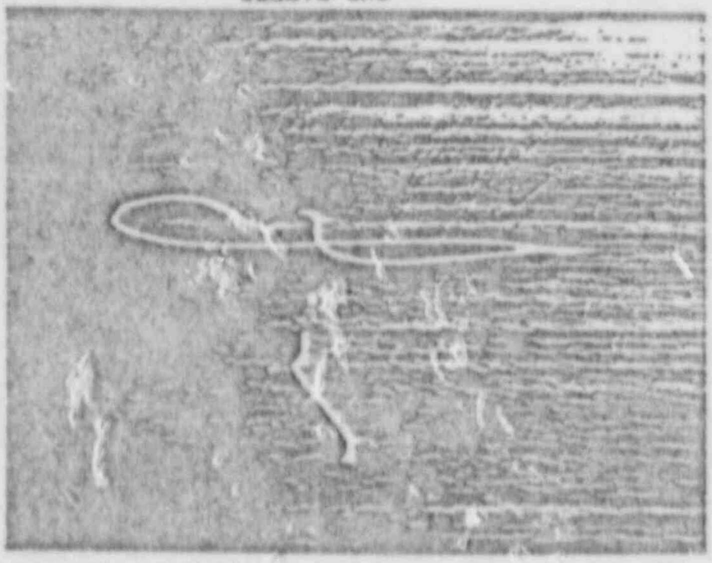


100% 80% 60% 40% SLEEVE. 100% 80% 60% 40% S/G TUBE

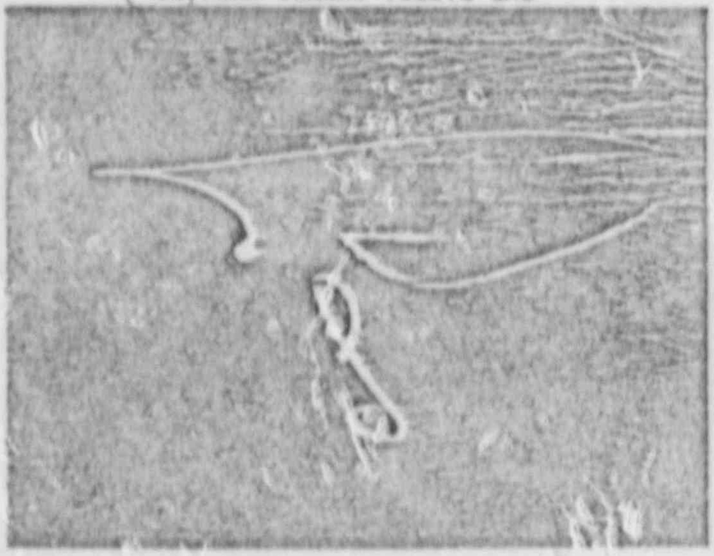
EDDY CURRENT TEST SIGNALS - SLEEVE AND TUBE FLAWS

FIGURE 5-11

SLEEVE END



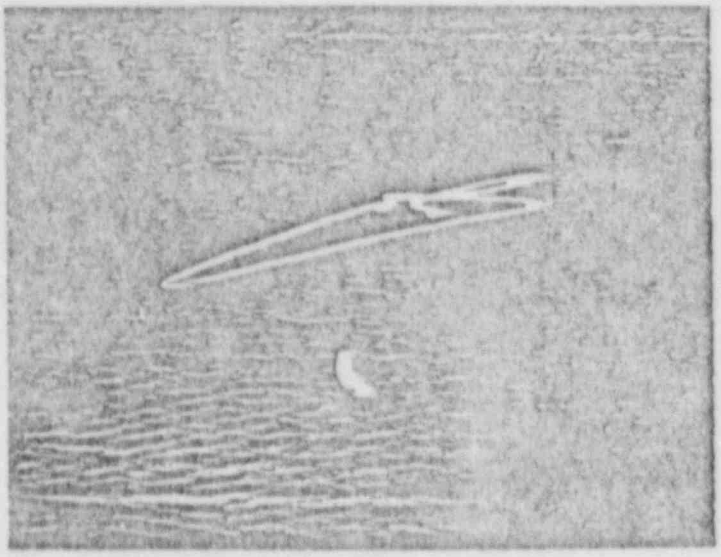
[40%] FLAW BEHIND SLEEVE END



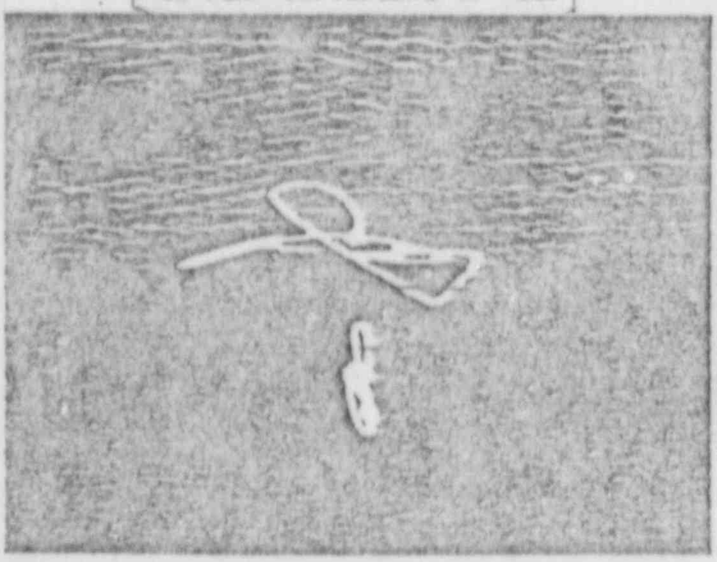
TUBE INSPECTION CURRENT TEST SIGNALS - SLEEVE END WITHOUT AND WITH A TUBE FLAW

FIGURE 5-12

SLEEVE EXPANSION and WELD

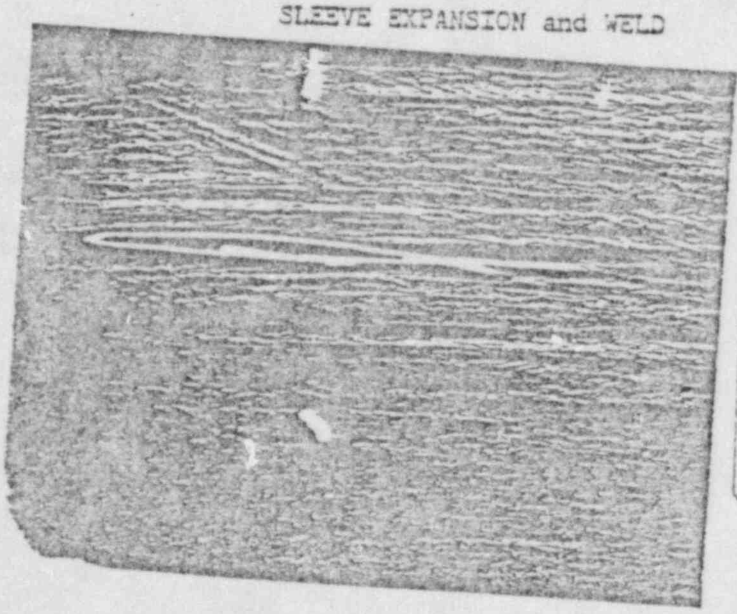


[40% FLAW CENTERLINE OF WELD]



TUBE INSPECTION EDDY CURRENT TEST SIGNALS - EXPANSION AND WELD WITHOUT AND WITH A TUBE FLAW

FIGURE 5-13

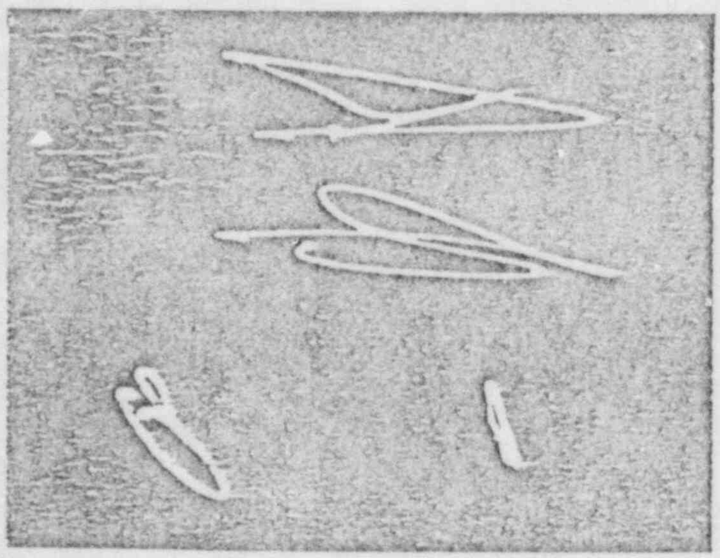




SLEEVE INSPECTION EDDY CURRENT TEST SIGNALS - SLEEVE FLAWS, EXPANSION AND WELD

FIGURE 5-14

40% FLAW TRANSITION OF EXPANSION

40% FLAW TRANSITION OF EXPANSION



50/150 KHz Mix 400/800 KHz Mix

SLEEVE INSPECTION EDDY CURRENT TEST SIGNALS - SLEEVE FLAWS AT EXPANSION TRANSITION

FIGURE 5-16

## 6.0 SLEEVE-TUBE CORROSION TEST PROGRAM

C-E has conducted a number of bench and autoclave tests to evaluate the corrosion resistance of the welded sleeve joint. Of particular interest is the effect of the mechanical expansion/weld residual stresses and the condition of the weld and weld heat affected zone. Various tests have or are presently being conducted under accelerated conditions to assess the sleeve-tube joint performance under potential nominal and fault environmental conditions. An outline of these tests is shown in Table 6-1. [ ]

## 6.1 SUMMARY AND CONCLUSIONS

[ ]

## 6.2 TEST DESCRIPTION AND RESULTS

### 6.2.1 Modified Huey Tests

[ ]

[ ]

6.3 REFERENCES FOR SECTION 6.0


1. I. L. W. Wilson and R. G. Aspden, "Caustic Stress Corrosion Cracking of Iron-Nickel-Chromium Alloys." Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys, NACE, Houston, Texas, pp 1189-1204, 1977.

2. A. J. Sedriks, S. Floreen, and A. R. McIlree, "The Effect of Nickel Content on the Stress Corrosion Resistance of Fe-Cr-Ni in an Elevated Temperature Caustic Environment". Corrosion, Vol. 32, No. 4, pp 157-158, April 1976.

3. F. W. Pement, I. L. W. Wilson and R. G. Aspden, "Stress Corrosion Cracking Studies of High Nickel Austentic Alloys in Several High Temperature Aqueous Solutions." Materials Performance, Vol. 19, pp 43-49, April 1980.

4. P. Berge and J. R. Donati, "Materials Requirements for Pressurized Water Reactor Steam Generator Tubing." Nuclear Technology, Vol. 55, pp 88-104, October 1981.

5. G. P. Airey, A. R. Vaia and R. G. Aspden, "A Stress Corrosion Cracking Evaluation of Inconel 690 for Steam Generator Tubing Applications." Nuclear Technology, Vol. 55, pp 436-448, November 1981.

6. J. R. Crum and R. C. Scarberry, "Corrosion Testing of Inconel Alloy 690 for PWR Steam Generators." Journal of Materials for Energy Systems, Vol. 4, No. 3, pp 125-130, December 1982.

# 7.0 MECHANICAL TESTS OF SLEEVED AND PLUGGED STEAM GENERATOR TUBES

## 7.1 SUMMARY AND CONCLUSIONS

Mechanical tests were performed on mockup steam generator tubes containing sleeves and plugs to provide qualified test data describing the basic properties of the completed assemblies. [ ]

[ ]

The welded plugs have sufficient load capacity to perform their function during normal and postulated accident conditions. The axial load required to loosen the plug from the sleeve-tube assembly is approximately four times greater than the design load.

## 7.2 CONDITIONS TESTED

[ ]

[ ]

## 7.3 WELDED SLEEVE TEST PARAMETERS AND RESULTS

### 7.3.1 Axial Pull Tests

[ ]

8.0 STRUCTURAL ANALYSIS OF SLEEVE-TUBE ASSEMBLY

It is the purpose of this analysis to establish the structural adequacy of the sleeve-tube assembly. The methodology used is in accordance with the ASME Boiler and Pressure Vessel Code, Section III. The work was performed in a manner in accordance with 10CFR50 Appendix B. Also, it is constructed such that all U.S. Regulatory requirements are met.

8.1 SUMMARY AND CONCLUSIONS

Based on the analytical evaluation contained in this section and the technical test data contained in Section 7.0, it is concluded that the welded tube sleeve, described in this document, meets all the requirements stipulated in Section 8.0 with substantial additional margins.

8.1.1 Design Sizing

In accordance with ASME Code practice, the design requirements for tubing is covered by the specification for the steam generator "vessel". The appropriate formula for calculating the minimum required tube or sleeve thickness is found in Paragraph NB-3224.1, tentative pressure thickness for cylindrical shells. The following calculation uses this formula.

$$t = \frac{PR}{S_m - 0.5P}$$

Where

t = Min required wall thick (in.)

P = Design Tubesheet differential pressure (ksi)

R = Inside Radius (in)

$S_m$ = Design Stress Intensity (S.I.) (per Ref. 8.2)

t = [ ]

t = [ ]

8.1.2 Detailed Analysis Summary

When properly installed and welded within specified tolerances, the sleeve and its two primary welds possess considerable margin against pull-out for all conceivable loading which can be postulated.

Depending on the degree of tube/support lock-up, axial loads in the sleeve do not exceed[ ] When considering the favorable results from the cyclic loading tests[ ]fatigue problems are not anticipated.

In Section 8.2, a comparison is made between calculated failure modes and test data discussed in Section 7.0 of this report. The agreement between calculated and test data was good. Safety factors were determined for hypothetical pipe break accidents, and a minimum factor of safety of[ ]was determined. The normal operations factor of safety was[ ]based on the full power restrained thermal expansion loading. Pushout at the lower sleeve/tube stub joint is the critical consideration (see Section 8.4.6).

The axial sleeve loads calculated in Section 8.4 are used as boundary conditions and the basis for assumptions used in the Section 8.6 and 8.7 fatigue evaluations.

An NRC Regulatory Guide 1.121 evaluation was performed in Section 8.3 to determine a sleeved tube plugging limit. A[ ]allowable degradation limit was determined. This is possible because the Reg. Guide specifically uses normal operating parameters, such as operating differential pressure, rather than tubesheet design differential pressure.

Considerations of susceptibility to flow induced vibration was discussed in Section 8.5. Based on C-E experience and test data, it was determined that a sleeved tube is no more susceptible to vibration than a normal tube.

Fatigue of both the upper and lower joints was considered in Section 8.6. The geometry was shown to meet all ASME Code allowable stress intensities including local primary and range of primary plus secondary stress. A tabulation of the results is presented in Table 8-1. The maximum local primary stress intensity was[ ]ksi across the sleeve at the lower weld joint, as compared with the allowable of [ ]ksi. The maximum range of primary plus secondary stress was [ ]ksi across the sleeve at the lower joint, near the weld, as compared with the allowable of[ ]ksi. The maximum fatigue usage factor was[0.49]at the same location. This high usage factor was due in part to consistantly conservative assumptions made in the calculation.

Sleeve evaluation was performed for 36 inch sleeves in the central tube bundle and 24 inch near bundle periphery. The thermal mismatch between the sleeve and tube which affects axial loads occurs over a short distance between the top of the tube sheet and the upper weld. The relative severity of the axial loads which are developed are a function of that distance divided by the overall distance between the upper and lower welds.

A sleeved tube plug was successfully evaluated in Section 8.7 in case it should ever be needed (see Table 8-1 and Appendix 8C).

## 8.2 LOADINGS CONSIDERED

In this section a number of potential failure modes are examined to determine the relative safety margins for selected events. Failure loads are calculated based on minimum dimensions and compared with mechanical testing results from Section 7.0. Both calculated and measured loads are compared with the maximum postulated loads.

### 8.2.1 Upper Tube Weld Pullout Load

Assuming the parent tube is totally severed, the minimum load required to shear the upper tube weld is calculated. The force required to pull the expanded sleeve through the unexpanded tube is conservatively neglected.

In the event of a main steam line break (MSLB) accident the secondary pressure would drop during a short time interval. The primary pressure would rise briefly then follow the drop in secondary pressure. It will be conservatively assumed that full primary pressure remains when the secondary pressure reaches zero. Postulating a main steam line break (MSLB) accident, the maximum available load would be:

### 8.2.2 Lower Stub Weld Pushout Load

Assuming the parent tube is totally severed, the minimum load required to rupture the lower stub weld is calculated. It is interesting to note that for this geometry, based on the test results, the weld did not fail in pure shear.

The weld lip seemed to "roll over" as is illustrated in Figure 8.2 such that the weld failed primarily in tension.

Weld area = weld throat · circumference

[ ]

From References 8.1 and 8.2, the minimum tensile strength is 80.0 ksi. Therefore, a predicted "pushout" load on the sleeve might be calculated:

[ ]

Postulating a loss of primary coolant accident (LOCA) during hot standby conditions (0% power), the maximum available load would be:

[ ]

8.2.3 Weld Fatigue

Since the factors of safety are quite high for loadings due to primary stress, the mechanism of greatest interest is the fatigue failure mode due to variable axial loading of the sleeve during normal operation.

In Section 8.6, fatigue evaluations of both the upper and lower welds, which join the sleeve to the tube will be made. It is first necessary to determine the effects, which tube lock-up within the tubesheet and tube support plates have on the axial loads in the sleeve during normal operation. This subject is addressed in Section 8.4.

## 8.3 REGULATORY GUIDE 1.121 EVALUATION FOR ALLOWABLE SLEEVE WALL DEGRADATION

R.G. 1.121 (Reference 8.3) requires that a minimum acceptable tube (or sleeve) wall thickness be established to provide a basis for removing a tube from service. For partial thru-wall attack from any source, the requirements fall into two categories, (a) normal operation safety margins, and (b) considerations related to postulated pipe rupture accidents.

8.3.1 Normal Operation Safety Margins

It is the general intent of these requirements to maintain the same factors of safety in evaluating degraded tubes as those which were contained in the original construction code, ASME Boiler and Pressure Vessel Code, Section III (Reference 8.1).

For Inconel Alloy 600 and 690 tube or sleeve material the controlling safety margin is:

"Tubes with part thru-wall cracks, wastage, or combinations of these should have a factor of safety against failure by bursting under normal operating conditions of not less than 3 at any tube location".

8.8 REFERENCES FOR SECTION 8.0


8.1 ASME Boiler and Pressure Vessel Code, Section III for Nuclear Power Plant Components.

8.2 ASME Boiler and Pressure Vessel Code Case N-20, "SB-163 Nickel-Chromium-Iron Tubing (Alloys 600 and 690) at a Specified Minimum Yield Strength of 40.0 KSI".

8.3 U.S. NRC Regulatory Guide 1.121, "Bases for Plugging Degraded PWR Steam Generator Tubes".

8.4 RFQ from Swedish State Power Board, BIV1-L8n/Gn-6331, dated January 4, 1984, to C-E Power Systems, for Ringhals 2 Steam Generator Demonstration Sleeving.

8.5 Letter, E. L. Watzl (NSP) to R. B. Granstrand (CE), dated July 20, 1984, "Prairie Island Geometric and Operating Parameters".

8.6 SSPB Specification for Replacement Steam Generator for Ringhals 2 Nuclear Power Plant, dated January 1984.

8.7 International Nickel Co. Booklet, "Inconel 690".

8.8 Nuclear Systems Materials Handbook, Volume 1 "Design Data", Part I, Group 4, Section 3 - Inconel Alloy 600.

8.9 "Vibration in Nuclear Heat Exchangers Due to Liquid and Two-Phase Flow", By W. J. Heilker and R. Q. Vincent, Journal of Engineering for Power, Volume 103, Pages 358-366, April 1981.

8.10 "ANSYS", Engineering Analysis System, User's Manual, by John A. Swanson.

8.11 EPRI NP-1479, "Effect of Out-of-Plane Denting Loads on the Structural Integrity of Steam Generator Internals, Contractor: C-E, August 1980.

8.12 "Primary/Secondary Boundary Components Steady State Stress Evaluation", Prepared by Raymond Paul Wedler, Westing Electric Corp., April 1965.

COMBUSTION > ENGINEERING SLEEVE WE'.D INSPECTION REPORT

INSP DATE: 30AUG84 TIME: 17:07:12 THRESH % OF FSH: 20

TUBE NO: R8 C32 ST GEN NO: MOCK UP SITE: RINGHALS

FILE NAME: 300841.029 SCAN 0 TO 360 DEG

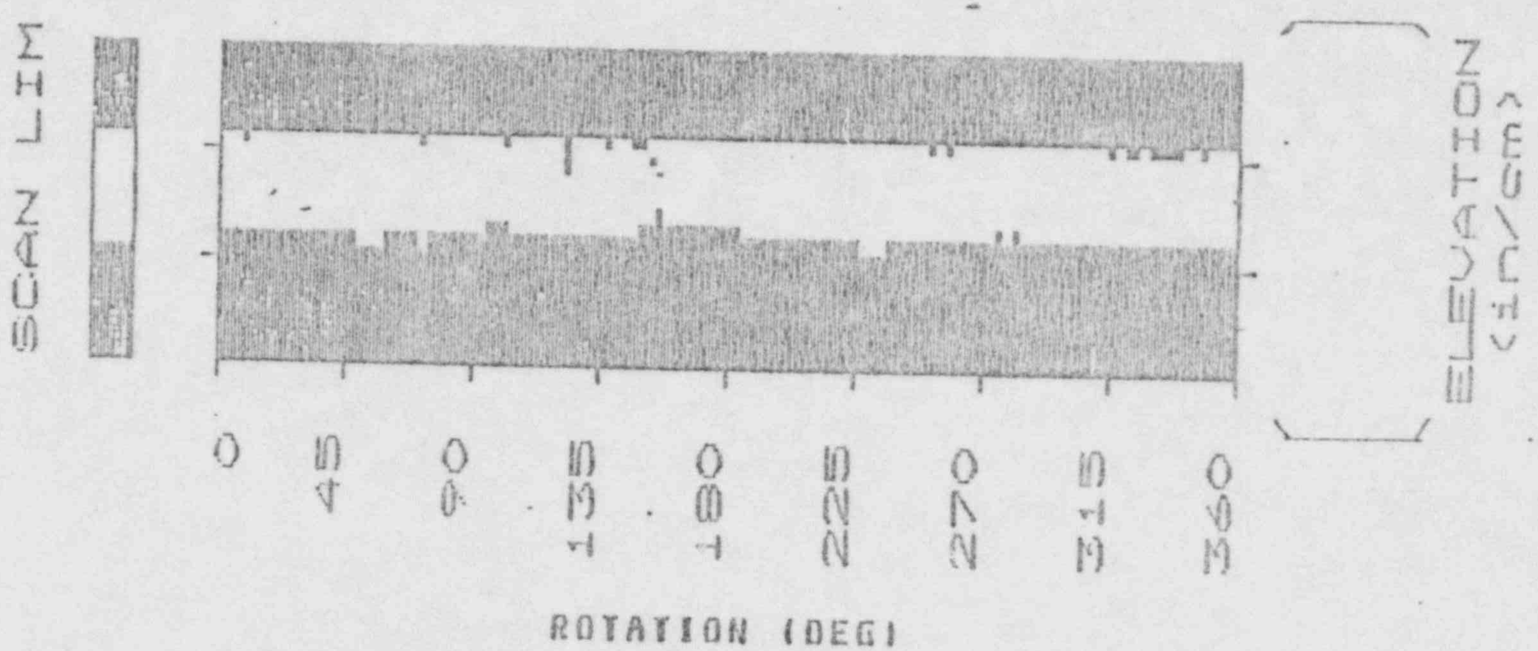



FIGURE 9-1

RINGHALS 2 - DEMONSTRATION

TYPICAL GOOD WELD

COMBUSTION > ENGINEERING SLEEVE WELD INSPECTION REPORT

INSP DATE: 30AUG84 | TIME: 13:15:04 | THRESH % OF FSH: 20

TUBE NO: R21 C50 | ST GEN NO: MOCK UP | SITE: RINGHALS

FILE NAME: 300841.023 | SCAN 0 TO 360 DEG

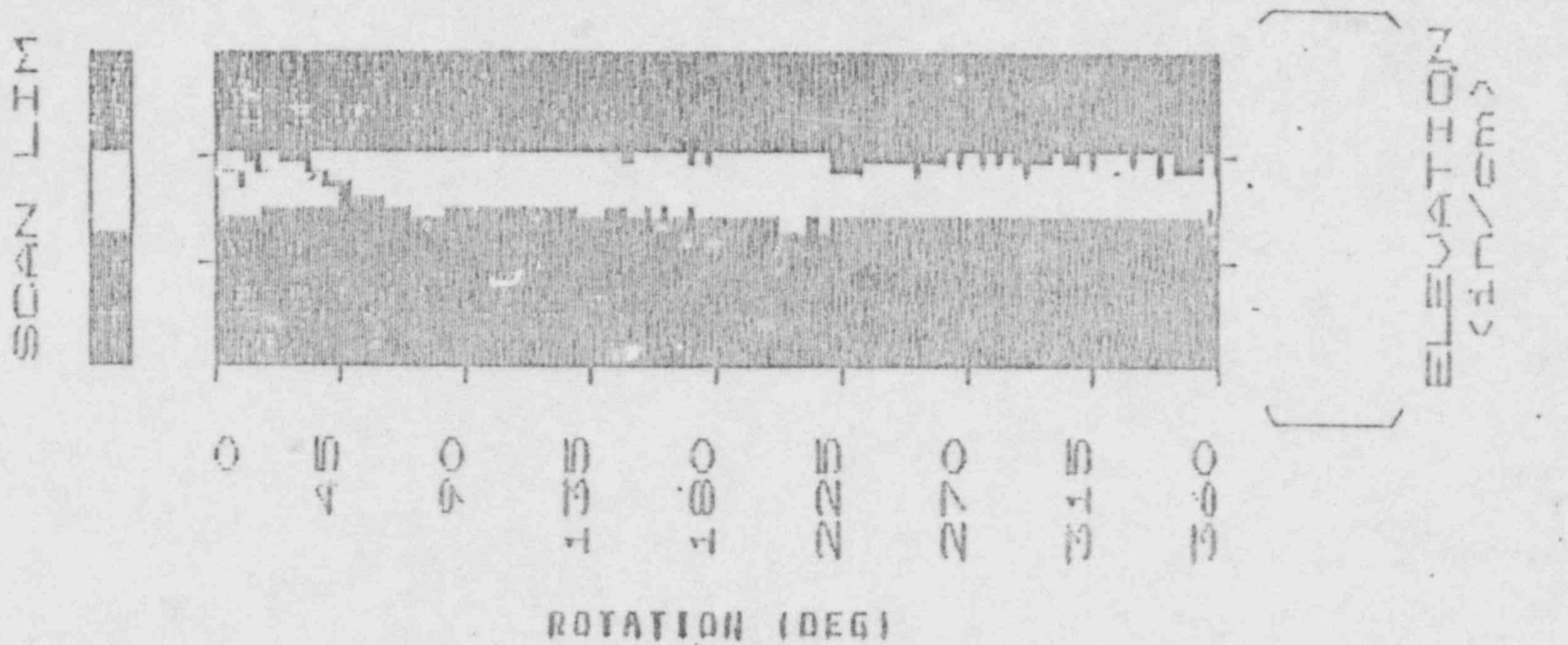



FIGURE 9-2

RINGHALS 2 - DEMONSTRATION WELD WITH LACK OF FUSION ACROSS THE WELD

## 10.0 EFFECT OF SLEEVING ON OPERATION

An analysis was performed to determine the effect of installing welded sleeves in the steam generators. It was assumed that two thousand sleeves would be installed in each steam generator. Since it is not known how many 36" long and how many 24" long sleeves will be installed; it was conservatively assumed that all sleeves were 36" long. Using the pump characteristic curve and the system resistance curve, the flow rate change was determined for increased flow resistance associated with installing the sleeves. The change in total flow rate was only [ ] and should not have a significant effect on reactor operation.

[ ]

# APPENDIX A TO REPORT NO

# PROCESS AND WELD OPERATOR QUALIFICATIONS

# FOR TUBE SLEEVE AND PLUGGING

# SLEEVED TUBES

## APPENDIX A

### A.1 SLEEVE WELDING AND SLEEVE WELDER QUALIFICATION

Sleeve welding is qualified using an approved test procedure (Reference 1). Plug welding in sleeved tubes is qualified using an approved test procedure (Reference 2). The sleeving test procedure is in compliance with applicable sections of the ASME Code even though it does not directly apply to sleeves, and the plugging procedure is in compliance with Section XI of the latest edition of the ASME Code. Sleeve and plug welders are qualified using test records in accordance with applicable sections of the Code.

The test procedures specify the requirements for performing the welds, the conditions (or changes) which require requalification, the method for examining the welded test assemblies and the requirements for qualifying the welding operators. Sleeve and plug welding are qualified by performing six consecutive welds of each type which meet specified design requirements. Welders are qualified by performing two consecutive successful welds of each type.

A.2 REFERENCES TO APPENDIX A

1. Welded Steam Generator Tube Sleeve Semi-Automatic Gas Tungsten Arc Detached Welding Procedure Qualification, Test Procedure 00000-MCM-050, Rev. 00, April 14, 1984

2. Engineering Requirements for Plugging Sleeve Tubes in Westinghouse Series 44 and 51 Steam Generators, NCE Engineering Procedure EP-627SG-104 Rev. 0, April 19, 1984