St. Lucie Unit 2
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L-2003-002 Attachment 5

ATTACHMENT 5

WCAP-15975-NP, Revision 0
“NDE Inspection Strategy for the Tubesheet Region in St. Lucie Unit 2”

[Non-Proprietary Version – 72 Pages]

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NDE Inspection Strategy for the Tubesheet Region in St. Lucie Unit 2

WCAP-15975-NP Rev. 0

NDE Inspection Strategy for the Tubesheet Region in St. Lucie Unit 2

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EXECUTIVE SUMMARY

Based on evaluation of testing results, analysis, and supporting references, a conservative NDE inspection extent below the secondary face of the tubesheet (TTS) has been determined to be five inches for the St. Lucie Nuclear Generating Station Unit 2 steam generators.

An engineering justification for limiting the required inspection area to the upper region of the tubesheet on the hot leg side has been developed. This engineering justification was developed for two reasons:

- Flaws below five inches in this region are unlikely to be a safety concern (which was confirmed by the work performed for this report) and,
- Existing NDE methods necessitate optimized inspection within the area of most need and relevance.

This report provides the St. Lucie 2 specific information from a project conducted for the Combustion Engineering (CE) Owners Group (1).

The inspection extent value of five inches has been derived based on a conservative assumption that a maximum number of tubes equal to [ ]$^{(c)}$ Primary Water Stress Corrosion Cracking (PWSCC) susceptibility increases markedly with increasing temperature and may be assumed to only be prevalent in steam generator tubing on the hot leg side of the tube bundle. A review of PWSCC history in CE designed units demonstrates that the assumption that less than [ ]$^{(c)}$ is a reasonable basis for specifying the inspection extent value. The inspection extent must be inspected by an adequate NDE inspection method to ensure that less than 10% of all hot leg side tubesheet joints have flaw indications within five inches of the TTS. The inspection extent assumes that all indications of tube degradation within the inspection extent will be repaired or plugged on detection.

CE explanded and WEXTEX joints compare favorably. The W* ARC (for WEXTEX) values used as a figure of merit for benchmarking the results of this effort are inspection lengths of approximately [ ]$^{(b)}$. The [ ]$^{(b)}$ value are differentiated by tubesheet flexure, which has been considered for St. Lucie 2.

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1.0 INTRODUCTION

A testing program was conducted to provide a recommended NDE inspection extent for detecting potential cracking in the tubesheet region in the St. Lucie Nuclear Generating Station Unit 2 steam generators (SGs). The evaluation provided in this report utilizes the St. Lucie 2 applicable information from a CE owners Group project recorded in Reference 1. St. Lucie Unit 2 has the Combustion Engineering designed explosively expanded (referred to as explanded) tube-to-tubesheet joints. The Westinghouse explosive tube expansion (WEXTEX) alternate repair criteria (ARC) values are used as a figure of merit for benchmarking the results of this effort. A conclusion of this work is that CE designed explanded and Westinghouse designed WEXTEX joints are quite similar. Based on an evaluation of testing and analysis results, a conservative distance for nondestructive examination (NDE) inspection of the tubes in the St. Lucie 2 SGs below the secondary face of the tubesheet, also referred to as the top of the tubesheet (TTS), has been determined to be five inches; this value is applicable without adjustment to the tubesheet holes in the St. Lucie 2 SGs #11, and #12.

Testing was performed using tubesheet mockups and the steam generator from a cancelled plant (Boston Edison) to determine the leak and burst limiting tube to tubesheet joint length needed to assure operation within generic licensing and industry developed limits.

1.1 Purpose

An engineering justification for limiting the required inspection area to the upper region of the tubesheet has been developed. This engineering justification was developed for two reasons:

- Flaws deep in this region are not a burst or significant leakage concern.
- Existing NDE methods necessitate optimized inspection within the area of most need and relevance.
- Based on testing of representative samples a defined inspection extent distance below the TTS is established. The threshold distance of five inches is based on the number of tubes in the steam generator.

Babcock & Wilcox (B&W) designed plants have discovered tube cracks within the tubesheet region leading the NRC to issue Information Notice (IN 98-27) alerting the PWR industry to the events. The B&W tube-to-tubesheet joint design is a rolled joint that has limited applicability to the CE design but highlighted the need to review inspection practices in this region.

Some Westinghouse design plants have implemented alternate repair criteria, W*, to address tube cracks in the tubesheet region. W* provides for leaving axial cracks in-service if they meet W* criteria. The inspection extent defined in this report is not intended to justify leaving stress corrosion cracks within the inspection extent in-service.

References 2 and 11 provide industry consensus requirements for inspection. Rotating probes such as the +Point probe have traditionally been used in the range of two inches above and below the TTS to inspect the expansion transition region. Several MRPC probes are qualified for detection of cracks in the tubesheet region but would add significant cost and time to outage schedules to inspect the remaining twenty plus inches of tubesheet region. In general, industry practice is to assume undetected flaws are present only if the particular flaw mechanism is detected. The case presented in this report is that the presence of undetected flaws in the tubesheet region below the threshold distance criteria are inconsequential from a tube burst and leakage standpoint. Reasonable assurance of detection of flaws in the region above a threshold distance will be provided using a qualified detection technique (e.g. +Point).

1.2 CE Design "Explansion" Joint

Beginning in 1961, Combustion Engineering pioneered the use of explosive expansion for steam generator tubesheet joints, termed "explansion". The desired design features were to provide a cost-efficient method for closing the tube to tubesheet gap over the full length with sufficient pullout strength, leak tightness and without excessive residual stress in the tube.

Figure 1.1 is a conceptual schematic of the explansion process. Figure 1.2 is a shop drawing of the charge assembly used in the explansion process and Figure 1.3 depicts a typical explosive expansion setup in the manufacturing plant. The installation processes for expansion joints were reviewed in detail to support this effort. Combustion Engineering explansion process development/review reports and qualification reports (3, 4, 5, 6) demonstrate that process controls support the position that CE explansion joints are of consistent high quality and radial force in all installed joints is within a reasonable variance. This was verified by the results from the Boston Edison (BE) SG tube pull tests. Incomplete explansions have been detected in operating units, but are a fraction of a percent of all tube joints in-service and are easily detected and the inspection length criterion would not be applied to those tubes.

A gun drill process was used for drilling the St. Lucie 2 SGs tubesheet holes. Smooth tubesheet holes, as had been the industry practice for rolled joints, are not considered essential for the explansion process. The surface finish of the tubesheet hole was required to not exceed 250 micro-inches (AA) of roughness.

W* was developed based on two radial zones to credit less tubesheet flexure for the radial zone nearest the steam generator shell. Only one radial zone was considered for the CE designed SG tube threshold distance. This is because the tubesheets in the St. Lucie 2 units experience less flexure near the stay cylinder and the shell due to the support provided by these parts of the steam generator.

1.3 WEXTEX Joint and W*

The WEXTEX joint is a full depth explosively expanded joint used in some operating Westinghouse design plants. The process for installing the WEXTEX joint is similar to that used for the CE designed joints. After the tube is placed in the tubesheet, the tube end is rolled and welded in-place. The tube is then expanded into the tubesheet hole by an explosive cord over the full length of the tubesheet.

Although the CE and WEXTEX processes are similar, there are some differences in the resulting joint. All CE joints were installed in a controlled manufacturing shop. Some Westinghouse units had WEXTEX joints installed in the field where processes can be harder to control than in a manufacturing shop. WEXTEX units were constructed utilizing low temperature mill annealed A600 tubing rather than the high temperature mill annealed tubing used in CE designed units. The WEXTEX units have experienced more PWSCC indications than the CE designed SGs. Also, it has been shown that the WEXTEX expansion may leave a small tapered region at the top of the tubesheet (refer to Figure 1.4), while there has been no evidence of any such effect in the CE explansion joints including the review of the Boston Edison steam generator pulled tubes.

The NRC has reviewed and approved the use of the W* ARC for leaving cracked tubes in-service that meet the W* criteria. The W* criteria implemented by some units utilizes two threshold distances dependent on tube radial position. These values were a useful reference for comparison to the values derived in this work.

1.4 St. Lucie 2 Design Considerations

Westinghouse designed tubesheets react to a postulated main steam line break (MSLB) event in a similar way to the CE designed tubesheets despite a significant design difference in the thickness of tubesheets. Early in the design of CE plants, it was decided to add a stay cylinder central to the tubesheet to stiffen the tubesheet and allow the use of a less thick plate. Westinghouse designed SGs do not use stay cylinders to add out of plane stiffness to the tubesheet. A difference in the tubesheet response to MSLB event between CE and Westinghouse designed units is that the maximum flexure occurs at different radial positions (i.e., circular zones).
A flexure and concomitant tubesheet hole dilation effect on joint contact was determined for the St. Lucie 2 units and is reported in Section 6 of this document.

All the St. Lucie 2 SGs have Alloy 600 high temperature mill annealed (HTMA) tubes with the same material property specifications and a wall thickness of 48 mils.

1.5 Testing Acceptance Criteria

Testing in the course of the determination of a sufficient tube engagement length in the tube to tubesheet joint satisfied two primary concerns: pullout force and leak rate. The acceptance criteria applicable to the CE design used as a basis for these test parameters are the structural integrity burst pressure for pullout load and the MSLB accident induced leak rate.

A 100% throughwall 360° extent circumferential PWSCC flaw condition was conservatively mocked up for testing by cutting tested tubes in the tubesheet specimens. These manufactured flaws are recognized to be substantially less leak tight than either axial or circumferentially oriented flaws at the same locations. Operating experience of plants with identified PWSCC flaws has shown that leakage is not a concern (21).

Pullout force as a function of joint length is determined to demonstrate that a tube severed some distance into the tubesheet (i.e. of a specific joint length) will not pullout of the tubesheet and therefore will not present a burst tube condition. Pullout force is used synonymously with blowout force as referred to in the historical records. Structural integrity per the historical approach and discussion between industry and NRC leaders is defined as the ability of a tube to withstand pressure of three times the normal operating primary to secondary differential pressure (3NODP). A 3NODP value of 4410 psid was used in this work; this value bounds the actual 3NODP value of 3810 psid for the St. Lucie 2 steam generators. The pullout load value of 2000 lbf used in testing was derived from the 3NODP value of 4410 psid acting on the area of the inside diameter of the tubesheet hole [ ][b]. The threshold value for pullout is less than the threshold length for leaks, so the threshold length for leaks determines the threshold length for inspection. Details of the pullout load testing and criteria are provided in Section 3.1.1.

Leak rate as a function of joint length was determined in order to demonstrate that an assumed number of 100% throughwall tube flaws would not exceed the leak rate criterion. The leak rate criterion was derived from an MSLB accident induced leak rate limit of 0.5 gpm per steam generator, which is bounding based on the traditional limiting condition for operation (LCO) limit for event initiation. The Standard Review Plan (22) specifies that the LCO leakage limit would result in one-fifth of the 10CFR100 dose limit. [ ][c].

No tubes have been pulled to confirm PWSCC but the explansion is a full depth joint that makes ODSCC unlikely. [ ][c].

To provide allowance for leakage from other defect types, particularly in operational assessment calculations, the contribution of leakage from tubesheet region flaws was conservatively limited to [ ][c]. Operational assessment calculations include assumptions for undetected flaw populations and determine acceptable plant run-time based in part on acceptable EOC leakage. The joint length leak rate (determined by testing) multiplied by the number of tubes assumed to be defective that results in a leak rate less than or equal to the leak rate criteria of [ ][c] is the threshold length for leaks. Details of the leak rate test methods and criteria are provided in Section 3.1.2.

1.6 Overview of Approach

A parametric approach was used for testing the pressure, temperature, and explansion contact force effects to consider the key contributions to joint integrity. Two types of tests were conducted: pullout load and leak rate. Both test types were conducted on two test beds applicable to the St. Lucie 2 units:

- The Boston Edison canceled plant as-built steam generator
- Single tube to tubesheet joint mockups (collars)

The test beds are described in the Section 3.3 of this report.

This work had several major steps:

1. Develop a preliminary test plan for pullout and leak rate testing.
2. Develop acceptance criteria for pullout and leak rate.
3. Pull and Leak test Boston Edison SG tube joints as a benchmark to as-built plants.
4. Pull and Leak test single tube to tubesheet joint mockups (collars) at various pressures and temperatures.
5. Verify that mockup collars are representative of BE SG (i.e., as operating SGs).
6. Determine the effect of tubesheet hole dilation under MSLB conditions.
7. Calculate inspection lengths (threshold length for inspection) from the test results.

Other considerations that factored into the uncertainties in the development of threshold length were:

- Joint contact force at the explansion transition
- Joint contact force changes during a MSLB
- NDE axial position uncertainty

NDE probe axial position uncertainty is not explicitly addressed in this report. However, it is considered to be covered within the conservatisms applied in the results reported in this report. The uncertainty is judged to be a minor effect and may be handled in the same way that utilities consider position uncertainty in the current tubesheet region inspection scope.
A reduction in joint contact force at the expansion transition is addressed in the W* topical report (10). [

]$^{(b)}$

Visual inspection of several sectioned specimens indicates that a taper is not present in the CE explansion joint. A taper of several tenths of an inch would be visually observable but no taper was observed in the single tube mockup specimens examined by microscope or by visual exam of the Boston Edison tubes. This supports the information provided in Reference 4 indicating that CE explansion joints do not have a taper effect.

The metal disintegration machining (MDM) process of cutting the artificial flaws used in the pull and leak testing provides conservatism in that the tube material pulled away from the tubesheet wall such that all measured joint lengths are considered conservative by several tenths of an inch.

Under MSLB conditions, the differential pressure across the tubesheet causes tubesheet flexure and dilation of the tubesheet hole. Dilation of the hole reduces the contact force in the region of dilation. The other side of the tubesheet actually compresses, but it is not in the range of interest. Reduced contact in the joint may increase existing leakage and reduces the resistance to pullout. [

]$^{(b)}$ A compensating effect occurs as primary to secondary pressure increases. Increasing differential pressure induces axial and hoop stresses on the tube ID. The hoop stress due to internal pressure is nominally twice the axial stress in magnitude resulting in a diametric expansion of the tube approximately one mil at MSLB differential pressure. This tends to mitigate the effect of the tubesheet hole opening at and near the tubesheet surface.

Tubesheet hole surface roughness was addressed in the fabrication of tubesheet mockups and visual inspection of the roughness in the Boston Edison steam generator and several single tube mockups. Smoothness beyond the roughness specification criteria of 250 micro-inches was identified in early process development reports (3, 4, 5) as not desirable for explanded joints . Tubesheet mockup holes were fabricated by drilling to represent the CE design applicable to St. Lucie 2. The drilled holes are referred to as rough bore holes in some parts of this report representing the gun drill process. In addition, the expected variability in tubesheet hole roughness in operating SGs is best characterized by the Boston Edison steam generator results. NDE measurements for each test were recorded for comparison.

Leak rate testing was conducted using a very small capacity positive displacement pump, high accuracy pressure gauge, recording equipment, and associated tubing. Pump strokes were counted measuring nominally 0.6 milliliters per pump stroke, over a defined test period of approximately forty minutes, providing a minimum detectable leak rate of approximately $5x10^{-6}$ gpm per tube. If no strokes were recorded, one stroke was assumed. In most cases, the test logs indicate that seepage was observable at the tube to tubesheet interface even though no pump stroke occurred. Leakage from the manufactured flaws in tests would not experience as large a pressure drop across the flaw as would be expected in any SCC flaw in the tubesheet region. The test leak rate reported accounts only for the joint length pressure drop and not the pressure drop across the flaw. This can be a significant conservatism depending on the flaw size and location.

Details of the results are provided in Section 4.0 of this report. Evaluation of the results is provided in Section 8.0.

1.7 Conservatisms in Results

A number of conservatisms have been employed which ensure that the results reported are reasonable for safe operation. The conservatisms are also addressed in more detail in the other sections of this report but are listed here to highlight the combined effect on results.

Conservatisms used in this work are:

- A 360°, 100% throughwall circumferential cut represents a limiting flaw form for pullout and leak testing.
- Use of an MDM tool to cut the flaw results in a large width flaw providing little or no flow resistance compared to SCC.
- Tube draw-back due to MDM cutting heat up and contraction of the tube is not credited in the measured joint length. There was no evidence that MDM cutting resulted in solidification at the tube-tubesheet interface.

- Only partial credit is taken for the increase in tube-to-tubesheet contact force due differential thermal expansion between the tube and tubesheet.
- The 3NOPD value used (4410 psid) exceeds the St. Lucie 2 actual 3NOPD value (3810 psid) by 15.7% (600 psid).
- Only partial credit is taken for the increase in tube-to-tubesheet contact force due to the internal pressure in the tube during NOP.
- Tubes used in single tube mockup tests have material properties at the upper end of the yield specification at 54 ksi per CMTR (18). The higher yield strength tubing would result in a lower tube-tubesheet contact from the explansion process. This can have a significant effect on pullout force and leak rate (8).
- No credit is taken for corrosion of the tubesheet in the tubesheet joint.
- Choked flow effects under MSLB conditions are not considered.
- [

  ]$^{(c)}$

1.8 Quality Assurance

This work was completed under the requirements of the Westinghouse Quality Assurance Program (9). QA documentation for the Boston Edison steam generator is no longer available from Westinghouse information archives, but is reasonably assumed to meet all requirements regarding tube material specifications and the tube joint installation process.

1.9 Other Considerations

Corrosion of the carbon steel tubesheet probably occurs even with the minute amount of air and moisture trapped in the tubesheet joint after explansion. Corrosion would tend to increase the friction between the tube and tubesheet impeding both pullout and leakage. Operating steam generators would have more corrosion in the joint than the mockups fabricated for this work. No explicit credit is taken for corrosion in the tubesheet joint. However, corrosion of the joint may explain some of the variability in results in the single tube mockup leak rate tests. In particular, leak rates tended to decrease as more tests were done on a given mockup indicating an increasing flow resistance over time after the initial test. Red rust (iron oxide) was observed at the top of the single tube mockup in some tests that were run later in the testing program.

Figure 1.1
Explansion Process Schematic

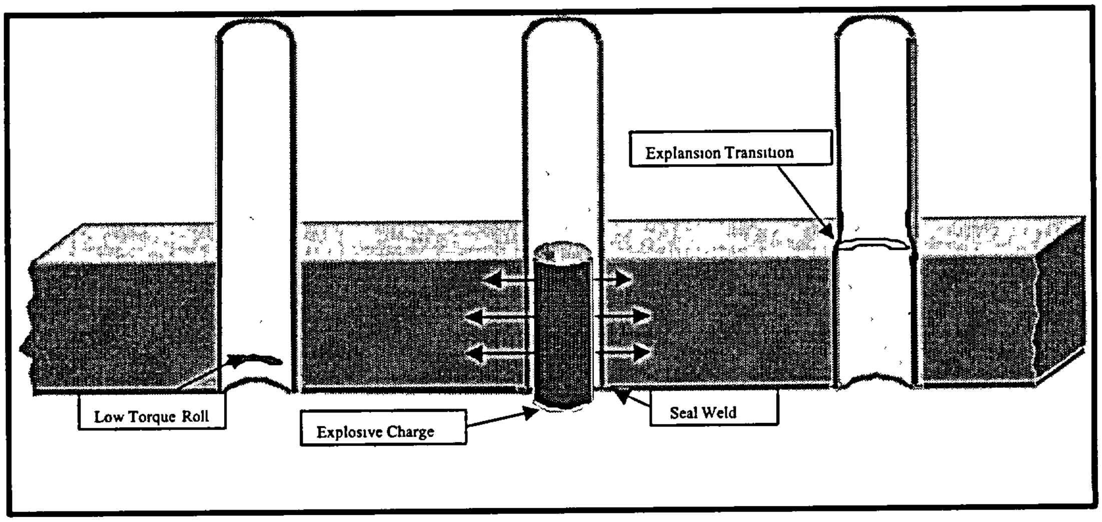


Figure 1.2
Charge Assembly Shop Drawing

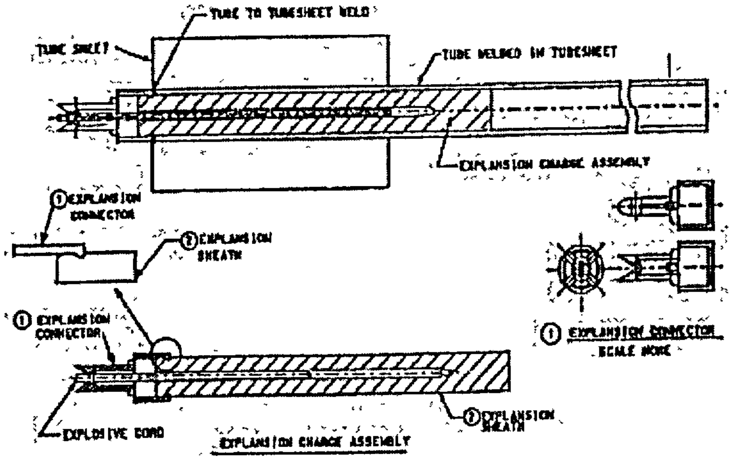


Figure 1.3
Depiction of Explansion During SG Manufacturing

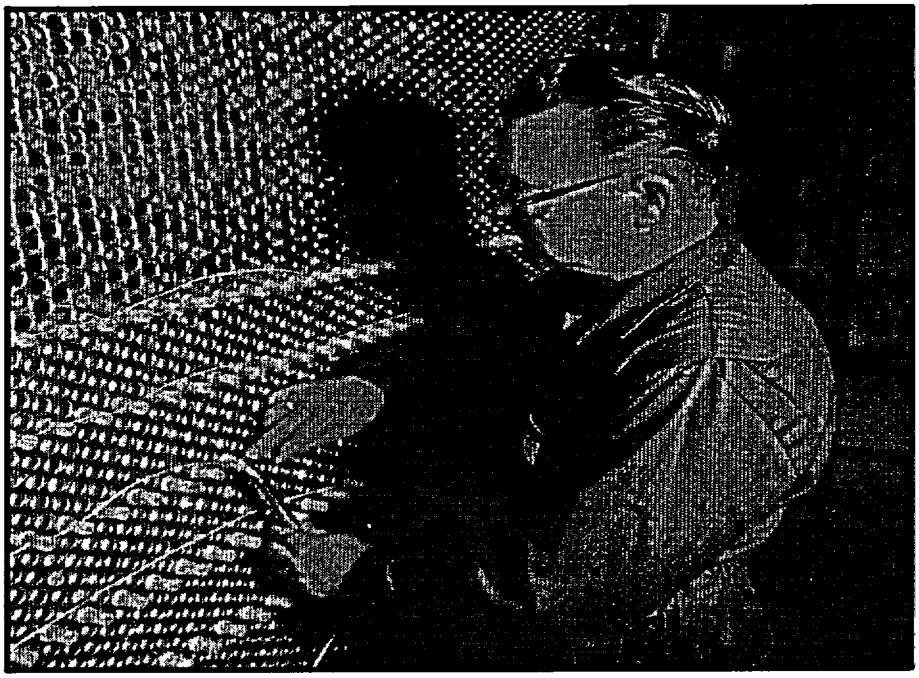
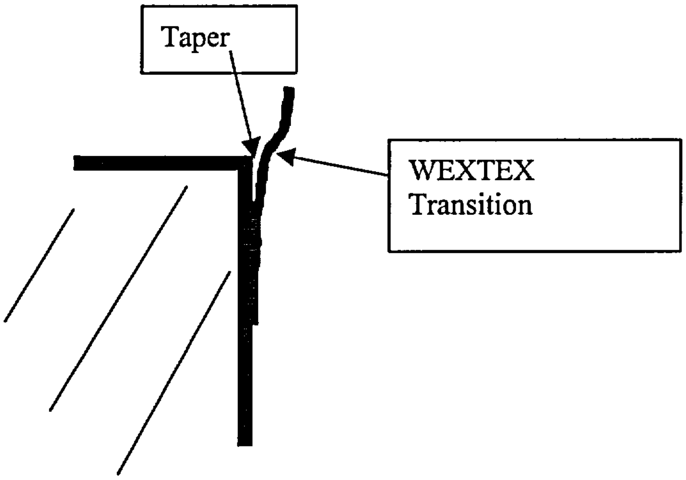


Figure 1.4
WEXTEX Joint Expansion Taper Concept



2.0 DEFINITIONS

ARC – Alternate repair criteria are approvals by NRC to utilize specific criteria for repair decisions based on detection of flaws.

Single tube mockup - Tubesheet mockups were fabricated from tubesheet bar stock material SA-508, Class 3. The machined bar stock in which a tube was explosively expanded was referred to in this project as a collar.

EOC – End of the operating cycle

Joint – The tube and tubesheet contact surface area created by the explansion process.

Leakage criteria – [

]$^{(c)}$

LCO – Technical specifications limiting condition for operation.

MSLB – The design basis event known as main steam line break.

NODP – Normal operating differential pressure. RCS pressure minus secondary side SG pressure at normal full power operating conditions.

3NODP = 4410 psid. Three times the NODP is the governing performance criterion for tube integrity, bounding for the St. Lucie 2 SGs for this evaluation.

Pullout force - The force required to overcome the joint static and sliding friction such that tube movement within the tubesheet may occur.

Pullout force criterion - The load value of 2000 lbf derived from a 3NODP value of 4410 psid acting on the area of the inside diameter of the tubesheet hole (assuming 0.760 inch diameter based on 0.758 inch with a manufacturing tolerance of 0.002 inches).

POD – Probability of detection based on the ability of an NDE technique to indicate the presence of a flaw.

Rough Bore – The machined surface on the inside diameter of each rough bore single tube mockup was drilled on a lathe to a surface roughness not greater than 250 micro-inches (AA) to mockup the gun-drilled tubesheet hole surface.

Taper – The theoretically incomplete contact near the top of the joint just below the explansion transition. [
]$^{(b)}$

Tube Engagement length – The tube to tubesheet joint length below the TTS that provides a sufficient contact force to preclude pull out at 3NODP and leakage at MSLB pressures.

TTS – Top of the tubesheet

3.0 TECHNICAL APPROACH SUMMARY

This is a summary of the approach used for collecting and evaluating the data from which the recommendations are derived. Detailed test apparatus, test procedures, technique description, and data tables are provided in the references.

As part of the test design, it was decided that a parametric approach would be used to identify the contributions of the three components of joint force due to explansion, temperature and pressure.

All materials were procured and methods/procedures were executed under Combustion Engineering Nuclear Power (CENP) quality requirements.

All Alloy 600 tubing used for the mockups was selected to be in the upper range of the 35 to 55 ksi yield strength to bound tubing installed in operating steam generators. All tubes were from the same heat of material and had yield strength of 54 ksi. Use of tubing at the upper end of the yield strength ranges provides conservatism in joint contact force (8). As the Boston Edison tubing information was not available for review it was assumed to be nominally in the mid-range and attendant larger variability in properties, i.e., throughout the range of the CE procurement specification.

3.1 Test Methods and Acceptance Criteria

Acceptable joint length was determined by testing for two categories of concern: pullout load and leak rate. Pullout load and leak rate testing data were compared to industry accepted criteria (11).

The tube to tubesheet joint length needed to ensure that both pullout (burst) and leakage criteria are met are provided in this report. The length needed to ensure both criteria are met is dominated in all cases by the threshold length defined by the leakage criterion.

3.1.1 Pullout Load Tests Methods and Criteria

Pullout testing was conducted in laboratory facilities in Chattanooga, Tennessee and in Windsor, Connecticut using calibrated load cells (16, 17). Pullout testing is reported in Section 4 as the force required to move the tube in the tubesheet hole against the sliding friction. Data is reported in units of pounds-force (lbf.).

Figure 3.1 is a schematic representation of the load cell used for the pull tests. Figure 3.2 is a photograph of the load cell apparatus used in the tests conducted in Windsor. Figure 3.3 illustrates the data logging and process control equipment used in the Windsor tests. Chattanooga load cell equipment was essentially the same.

The pull test results were directed toward establishing the threshold length below which a completely severed tube would not be ejected from the tubesheet. Mockups with varying engaged lengths of tubing were tested in accordance with Procedure 00-TP-FSW-001, Rev. 01. The engaged lengths for rough hole mockups were 2, 2.5, 3, 3.5 and 4 inches.

The equipment for the pull tests in the Chattanooga and Windsor laboratories were similar and both were calibrated to accepted standards. For the tests performed in Chattanooga, a mechanical gripper secured the upper end of the tube to the load cell. A tight fitting mandrel inside the tube prevented the gripper from deforming the tube at the gripper location and a bracket secured the mockups to the piston that applied the load. For the tests performed in Windsor, a retention plate with a threaded hole was used to secure the upper end of the tube to the load cell and a similar plate was used to secure the single tube mockup to the crosshead. Threaded plugs that had a means of allowing water to enter and exit the tube were welded to the upper end of the tube and to the lower end of the single tube mockup. The threaded portion of the plugs were screwed into the threaded hole of the two retention plates. When a pressurized test was conducted, the tube was filled and pressurized with water through holes that were drilled in the plug. X-Y plotters were used to record load versus crosshead displacement.

After the specimen was secure in the test machine, loads were applied at a fixed crosshead displacement rate in the Windsor tests and at a manually adjusted load in the Chattanooga tests until the severed tube was pulled from the tubesheet. The load at which first slippage of the tube in the tubesheet occurred and the maximum load during the test were noted and recorded. A plot of load versus crosshead displacement was also obtained for each mockup tested. In the Chattanooga tests, the slope of the ascending load vs. time curve varied as the rate at which the hydraulic pump pressure regulator screw was adjusted. This was done manually and intentionally slowly so as not to miss the data readings. Once the tube began to move, the pressure regulator was not adjusted any more, unless the tube stopped moving. In most cases, the maximum force was achieved after the tubes had moved some distance.

The pressurized specimens had welded plugs of the same type as the high temperature leak rate specimens. During the pull tests, these specimens had an internal pressure of 2575 psi + 100 –0 psi to determine if internal pressure would affect the loads required to displace the specimens from the tubesheets.

An accumulator with a 3000 psig rating and a three gallon capacity or a positive displacement pump were used to maintain pressure during tests.

For the hydrostatic test approach, a nitrogen gas bottle was used to apply pressure to the accumulator. A system to collect the leakage from the mockup was used to insure that the amount of spillage onto the test machine was minimized. The mockups were pressurized to the specified pressure before starting the test and the pressure was maintained until approximately one-half inch of tubing remained in the mockup, at which time pressure was reduced to 0 psig. The data acquisition system monitored mockup pressure throughout the test.

The pullout load criterion is based on 3NODP. The 3NODP value used (4410 psid) bounds the actual St. Lucie 2 value (3810 psid) based on NODP of 1270 psid. The criteria for this evaluation is based on:

NODP	1470 psid
3NODP	4410 psid

Pullout is based on the tube burst criteria of 3NODP because it was conservatively assumed for this work (consistent with W*) that the tube is completely severed and can move axially up under a pressure load. If the severed tube can exit the tubesheet, system effects and off-site dose consequences would be the same as a postulated guillotine tube burst. The 3NODP criterion is consistent with NEI 97-06 requirements (11) and is conservative relative to the criterion of 1.4 times the MSLB differential pressure (including accounting for the dilation of the tubesheet holes). Because the MSLB is the most probable event that would cause a tube to be at risk for pullout and because the MSLB criterion is a fixed value whereas 3NODP increases margin as steam generator pressure degrades over the operating life of the plant due to plugging, etc., the 3NODP criterion is considered as very conservative for use in this test program.

The pull force is dependent upon the contact force, contact area, coefficient of friction, and in general, the tribology. Pullout at 3NODP for these tests is recorded as a function of joint length and tube surface roughness. The force (F) required on a 0.75" nominal diameter tube equivalent to 4410 psid is:

$$\text{Tube area} = \pi\ (0.758''\ /\ 2)^2 = 0.451\ \text{in.}^2$$

$$F = 4410\ \text{lbf/in}^2 * 0.451\ \text{in.}^2 \cong 2000\ \text{lbf.}\ (1989\ \text{lbf. rounded up})$$

Pullout force was applied using two different load cell processes. The Chattanooga load cell applied a manually adjustable constant load process. The Windsor load cell was applied in a constant displacement rate process. The test plan called for two single tube mockup specimens to be tested in Chattanooga as a cross-reference between the Chattanooga and Windsor load cell tests to show that the test setups would provide comparable results. The difference in processes results in some variability in the results as indicated by the two rough bore single tube mockup specimens (specimens 20 and 21) tested in Chattanooga and the remainder of the rough bore single tube mockup specimens tested in Windsor.

Pullout testing was conducted after leak rate testing on the majority of the specimens. A few specimens had pull tests without leak tests. Measurements were taken on the Boston Edison SG before and after leak testing from a fixed reference point to determine tube movement. Table 3-1 illustrates that the joint was not measurably disturbed at the leak test pressure (i.e. MSLB pressure).

3.1.2 Leak Rate Tests Methods and Criteria

Leak rate is a function of differential pressure. Empirical data is necessary for understanding the leak rate as a function of joint length but the Poiseuille equation (12) provides an expression that approximates the fundamental relationship between the length of the tubesheet joint and leak rate:

$$dP = \frac{64}{R_e}\frac{L}{D}\frac{\rho v^2}{2g_c}$$

Where:

R_e = Reynolds number
D = in this case, the diameter difference between the tube and tubesheet
ρ = fluid density
g_c = gravitational constant
L = joint length
v = fluid velocity or flow rate
dP = differential pressure at MSLB

For the leak rate tests conducted in this project, all of the terms in the equation are essentially constant except the joint length and flow rate. Therefore, it can be stated that the flow rate varies inversely as the square root of the joint length. This relationship indicates that flow rate should reduce quickly over a very short joint length and then flatten out over longer joint lengths. This set of tests did not attempt to establish experimentally or analytically the knee of the curve or a usable formulation to cover all joint lengths. [

]$^{(c)}$ This relationship is conservative with respect to expected flow conditions in the event of a MSLB. During a MSLB event the maximum differential pressure (the flow forcing function) will occur when the steam generator pressure is approaching atmospheric pressure. Any primary coolant leaking from tubesheet joints into atmospheric pressure will undoubtedly flash to steam and create a choked flow condition. The choked flow condition is not considered in this project but is an additional conservatism in the development of the threshold joint length. The purpose of these tests was to determine a sufficient joint length that satisfied the criteria and provided a cost-effective NDE inspection length.

The leak rate criterion is based on the generic allowable leakage technical specification limiting condition for operation of 0.5 gpm per steam generator. Operational assessment calculations include assumptions for undetected flaw populations and determine acceptable plant run-time based in part on acceptable EOC leakage. [

]$^{(c)}$

Each tube has two joints – the hot leg and the cold leg sides. PWSCC is a temperature driven cracking mechanism and hot-leg joints will be the predominant number of tube joints affected over time. On this basis, only the hot-leg joints are considered in the development of threshold length for inspection. Leak rate is considered cumulatively for all tube joint leaks in the steam generator. Therefore, the test results provided on a single joint basis are multiplied by the number of tubes assumed to be leaking. [

]$^{(c)}$ This approach is very conservative as explained in Section 1.5.

Leak rate testing was used to determine the joint length (i.e. the threshold length for leakage) for acceptable leakage at MSLB conditions from through-wall defects located within the tubesheet region. This phase of the program used the tube-tubesheet joint mockups and cut tubes in the scrapped Boston Edison steam generator. A test procedure (13), was developed and used for both types of tests.

Figure 3.4 is a schematic diagram of the leak rate test system. The testing system consisted of:

- An air operated positive displacement pump (Haskel model MS110),
- A calibrated pressure gauge (0 to 10,000 psi),
- A calibrated pressure transducer (0 to 7,500 psi range),
- Data acquisition system (including DATAQ signal conditioner/processor and a computer),
- A reservoir of demineralized water, a high pressure hose with a mechanical plug/seal, and
- Ancillary tubing and valves

It was not necessary to adjust leak rates for accident conditions. Appendix D of the EPRI Steam Generator In Situ Guidelines (26) calls for a correction to account for the difference in material properties at room and operating temperature. The factors that can influence leak rate testing results gathered at room temperature conditions listed in Reference 26 were: (1) increased crack opening due to material property differences with temperature, (2) ligament tearing, and (3) thermal hydraulic effects of leakage at accident conditions (i.e. phase changing and flashing). The flaws in this program were 360°, 100% throughwall MDM cuts without ligaments; thus the first two reasons for an adjustment do not apply. As a conservatism, this program did not take credit for the reduced leak rates that would result from the choked flow exiting the tube-tubesheet annulus, thus the third reason for not needing an adjustment is accepted as an assumption.

Leak rate testing was conducted using a very small capacity positive displacement pump, high accuracy pressure gauge, recording equipment, and associated tubing. Pump strokes were counted measuring nominally 0.6 milliliters per pump stroke. Before any testing, the pump capacity was experimentally measured to increase the accuracy of the leak rate measurements. The identified capacity of the pump was independently characterized (13, Section 4.2). The test times were specified by the Leak Test Matrix and Test Conditions document (14). The test conditions specified that leakage be measured for 40 minutes or 20 to 30 pump strokes, whichever came first. The test time was designed to reach the criterion for leakage based on 25% of the tube joints leaking for about 20 minutes. For conservatism, this was further increased to 40 minutes. For the pump test, the pump discharge was collected for 20 to 40 strokes, was weighed on a calibrated Mettler balance and the weight divided by the number of strokes as indicated by the data acquisition system to determine volume per stroke. This process was repeated 10 times and the ten measurements were averaged. The average pump capacity was calculated as 0.619 ml (1.64×10^{-4} gal) per stroke. For a 40 minute test period this provides a minimum detectable leak rate of:

$$1.64 \times 10^{-4} \text{ gal} / 40 \text{ min.} = 4.1 \times 10^{-6} \text{ gpm}$$

This amount is equivalent to less than a drop of water per minute. For reference, 150 gallons per day equals about 0.1 gpm or a factor of 24,000 higher than the minimum detectable leak rate from these tests for a single tube.

The single tube mockups (collars) were tested in the upright (vertical) position. During the testing, each tube specimen was sealed with a mechanical plug at the bottom of the simulated tubesheet and a vented mechanical fitting at the upper end. Water was pumped into the tubes from the bottom until water began to exit the upper vent valve. Once this occurred, the vent was closed. Any standing water on the secondary face of the single tube mockups was removed and the test was initiated by adjusting the pump to obtain the desired target pressure which was specified as 2575 + 100 – 0 psi (14). The target test pressure was maintained by adjusting the pump air regulator as required to insure that the mean test pressure was consistent with the target pressure.

Multiple test periods were conducted on each specimen, with at least 3 test periods being required. The cumulative exposure of each testing during this phase of testing was limited to two hours. Between each test period, the specimens were depressurized.

After the basic test program was completed, three specimens were retested as specified in Reference 15. These specimens were pressurized to simulated normal operating DP (1275 + 100 – 0 psi) followed by pressurization to 2575 +100 – 0 psi. The hold time at each pressure was 40 minutes after which the specimen was depressurized. This test sequence was repeated three times for each specimen.

Figure 3.5 illustrates one case of visible leakage from a specimen under pressure.

The twelve leak rate tests in the Boston Edison steam generator were conducted in the same manner as the single tube mockup tests. The only exception was one tube that was pressurized for 41.6 minutes at a median test pressure of 2594 psi. This tube (R119L83) was then pressurized to about the same pressure (2592 psi) for 81.3 minutes to see if the leak rate varied with this test sequence.

3.1.3 In Situ Pressure Testing for Supplementary "Pullout" and Leak Rate

Supplementary testing was also conducted in Windsor using standard In Situ Pressure Test equipment capable of 7,000 psi maximum pressure.

The supplementary testing was conducted to test a hypothesis that the pressure effect contribution to joint force was not correctly characterized in the load cell testing. The maximum pressure capability of 7,000 psi is equivalent to an axial force of 3,519 lbf, which is about 1.5 times the pullout force criterion. As this testing was done after the originally planned testing, only a few remaining tubesheet collar specimens were available. Figure 3.6 shows the test apparatus. As illustrated in the Figure 3.6 hydraulic pressure was applied into the lower end of the test rig and subsequent to venting was capped at the top of the tube specimen. A clip gauge was used to detect any tube movement relative to the top surface of the single tube mockup (TTS).

3.1.4 Tubesheet Deflection Analysis Method

A Finite Element Model (FEM) analysis was used to calculate the effect of the tubesheet deflection (flexure) on the contact load between the tube and tubesheet. Tubesheet hole dilation effects were calculated using a single tube model and tubesheet stresses for the Design Differential pressure from the San Onofre Unit 2 Design Report (19) which bounds the St. Lucie Unit 2 condition. The FEM analysis provided a direct output of the tube-to-tubesheet interface loads, which represent a reduction of the contact loads from the tube explansion. The reduction in the interface loads varies from a maximum at the TTS to approximately zero at the mid-surface. This variation was included in the combination with the explansion loads.

The tube pullout tests were used to establish the residual contact load from the tube explansion. The pullout tests for the tubesheet collars at room temperature with and without internal pressure were used. The average load was determined by normalizing the load to a one-inch engagement length and averaging the total data.

The contact load was calculated from the pullout load and the coefficient of friction. [

]$^{(c)}$. The calculated contact load was uniformly applied over the full tubesheet thickness.

The net contact load results from subtracting the tubesheet flexure load from the explansion load. The net loads were calculated as a function of depth into the tubesheet and compared with the maximum pullout load for 3 times Normal Operating pressure. The 3NODP represents the governing criteria for tube/tubesheet joint integrity. The tubesheet depth limit occurs when the net contact load exceeds the maximum pullout load.

3.2 Elevated Temperature Tests

3.2.1 Pullout Tests - Single Tube Mockups

There were five elevated temperature pull tests to determine if temperature had an effect on the loads required to move the tubes in the tubesheets. The ambient temperature test procedure was used for the elevated temperature tests. Equipment for these tests was the same as for the ambient temperature tests but included thermocouples and digital thermometers to control test chamber air temperature and monitor mockup temperature. A thermocouple (Figure 3.7) in contact with the secondary face of the mockups recorded mockup temperatures. A BEMCO™ test chamber (see Figure 3.8) was used to heat each specimen. The specified temperature for these tests was 585°F + 0 -5°F. The test chamber was at this temperature for at least 30 minutes and the mockup thermocouple indicated a similar temperature before initiating the tests.

The elevated temperature mockups had threaded welded plugs on each end to permit application of the loads. The test chamber dimensions did not permit the arrangement used for the ambient temperature tests to be used. The loads were applied by a constant displacement of 0.2 inch per minute for these tests also.

3.2.2 Leak Rate Tests - Single Tube Mockups

Four elevated temperature leak rate tests were conducted at a temperature of a CE design bounding normal operating temperature of 585°F on single tube mockups to evaluate temperature effects on the leak rates of tubes with flaws within the tubesheet.

As for the ambient temperature tests, stainless steel plugs were welded into the upper and lower ends of the specimens. The plugs were designed to permit water to enter the specimen lower end and high pressure tubing through the upper end was connected to a valve to vent pressure during the test. A coil of high pressure tubing was used as a preheater for the ambient temperature water from the pump. The preheater and the specimen were inserted into the BEMCO test chamber that was used to heat specimen and water to the specified test temperature.

A thermocouple was attached with a hose clamp directly to the surface of each of the tubes in the mockups. A second thermocouple monitored the air temperature in the test chamber and controlled test chamber temperature. Each specimen was maintained at the specified temperature of 585°F + 0 - 5°F for at least 30 minutes before leak rate testing commenced.

The procedure for the leak rate testing was the same as for the ambient temperature testing. The target pressure for each test was 2575 +100 –0 psi. The specimen hold time for each test period was 40 minutes or 20 to 30 strokes, which ever came first, and at least three test periods were conducted for each specimen.

3.3 Test Beds and Specimens Description

Two types of tests were conducted: pullout load and leak rate. Both test types were conducted in the test beds:

- The Boston Edison canceled plant as-built steam generator
- Tube to tubesheet joint mockups (single tube mockups)

A description of test specimens used in each test bed is provided in the sections below.

In each test bed, the steam generator tubes were cut at measured distances below the "top of the tubesheet." All tests were conducted as a function of joint length that is nominally the length of the tube from the TTS to the cut surface.

After trials with other methods, MDM cutting was selected as the method for cutting the tube specimens at specified joint lengths. MDM provided a relatively clean cut without leaving residual material in the cut area that would impede the motion of the tube from the cut surface in testing. The precision of cutter head placement was not critical as the joint length was subsequently measured and results recorded according to as-cut joint length. Draw-back of the tube wall at the MDM cut was observed resulting in a reduction of the joint contact length from the as-measured value. No cut residual material that would increase the flow resistance of the test specimen joint or the tube-to-tubesheet surface friction was observed.

3.3.1 Boston Edison Steam Generator

The Boston Edison steam generator was fabricated for the Boston Edison NSSS contract that was subsequently canceled. The lower portion of one of the steam generators was maintained as a test bed. As such, the tube to tubesheet joints represent a set of as-built conditions typifying Combustion Engineering manufacturing processes. The tubesheet material is typical of operating units, the tube holes are also typical in terms of size, tolerances and surface finish of a rough bore (gun-drilled) finish in terms of the surface finish test conditions considered in this work. The tube material is typical of production material installed in the St. Lucie 2 steam generators. The Boston Edison tube material, provided by Noranda, is 0.042 inch average wall thickness and should have the normal variations in tube wall thickness and yield strengths that would be expected in operating units. The explosive expansion process was also obviously typical of the techniques employed for CE steam generators. Since all of the properties that might affect leak rates are typical of steam generator installations, the leak rates themselves should also be most representative of leak rates in the St. Lucie 2 steam generators.

Figure 3.9 shows the condition of the region of the steam generator on the cold leg side at the flow distribution plate prior to any cleanup being performed. The first step in the top side cleanup process was to grind down the tubes to the level of the flow distribution plate. Then the flow distribution plate was cut out in a rectangular pattern, see Figure 3.10. Next, the tubes were cut off at an elevation approximately 6 inches from the top surface of the tubesheet. Some of these tubes were removed easily; others were pulled out when the flow distribution plate was jacked out. Figure 3.11 is a photograph of the load test cell used to determine the pull-out force necessary to remove the tubes as a function of the tubesheet joint length.

All BE SG tubes that are leak tested were also pull tested as described above. Table 3-2 provides the planned test matrix for the BE SG tests. The test plan was subsequently truncated eliminating some of the planned tests that were determined to be unnecessary. The actual tests performed are listed in Appendix B.

3.3.2 Single Tube Mockups

3.3.2.1 Tubesheet and Tubing Specifications

The single tube mockups consist of an 8" thick tubesheet 1.625" OD containing a single 0.75" OD tube. Approximately 6" of tube length extends out from the secondary face of the tubesheet (23).

The single tube specimen specification is shown on Figure 3.12. The tubesheet material is SA-508, Class 3 and the tubing is Nickel Alloy 600. Two tubing wall thicknesses were tested: 0.048" and 0.042". The tubing material properties were at the high end of the standard CE specification for yield strength (18). The standard yield strength specification for CE design steam generator tubes is 35 - 55 ksi. The single tube specimens are all from the same heat of material with yield strength of 54 ksi. The tubes were explanded into the simulated tubesheets (collars) using the standard Combustion Engineering method. Figure 3.13 provides a picture of the setup before explansion.

3.3.2.2 Drilled Tubesheet Hole

Tubesheet drilling of all but a few steam generators manufactured by CE for CE designed units was done by a "gun-drill" process utilizing a cutter on the end of a rotating tube. Chips from the cutting process spiraled back from the cutting area via the flutes in the cutting tool and were carried away by cutting fluid injected into the cutting area. Cutting procedures on tool feed (cutting) rate and tool replacement frequency provided the specified tube hole surface smoothness and hole straightness. Excessive cutting rate causes tool wandering and scoring of the surface as the chip expulsion rate approaches capacity. Surface roughness was specified in manufacturing drawings as less than 250 micro-inches (AA). Records of measurement techniques and typical as-built roughness are no longer available but the Boston Edison steam generator tube joints provide a bench-mark representation. Explansion process development documents indicate that surface smoothness better than the specification was not necessary or desirable. It was recognized through testing in the process development that surface roughness provided anchor points in the tubesheet joints and ensured good resistance to pullout.

3.3.2.3 Test Matrix Overview

The test plan for single tube (collar) testing is shown in the Single Tube Test Matrix, Table 3-4 below. Not all tests in the plan were completed. Appendix C provides the as-tested data.

Table 3-1
Boston Edison Steam Generator
Axial Tube Position Measurements Before And After Testing

Tube Number	Crevice Depth (inches)	Reference Length Before Leak Testing (inches)	Reference Length After Leak Testing (inches)	Change in Reference Length (inches)
R128L82	3	28 3/8	28 3/8	0
R131L83	3	28 5/8	28 5/8	0
R107L83	4	27 9/16	27 9/16	0
R115L83	4	27 7/8	27 7/8	0
R117L83	4	27 31/32	27 31/32	0
R119L83	4	27 31/32	27 31/32	0
R127L83	4	28 1/4	28 1/4	0
R109L83	5	27 13/16	27 13/16	0
R111L83	5	27 11/16	27 11/16	0
R113L83	5	27 7/8	27 7/8	0
R123L83	5	28 1/8	28 1/8	0
R125L83	5	28 5/16	28 5/16	0

Table 3-2
Boston Edison SG Test Plan

Row	Line	Nominal Joint Length (in.)	Leak Test	Pull Test
112	82	2	Y	Y
114	82	2	Y	Y
129	83	3	N	Y
131	83	3	Y	Y
130	82	3	N	Y
128	82	3	Y	Y
126	82	3	N	Y
124	82	3	N	Y
122	82	3	N	Y
107	81	3	N	Y
107	83	4	Y	Y
115	83	4	Y	Y
117	83	4	Y	Y
119	83	4	Y	Y
127	83	4	Y	Y
108	82	4	N	Y
110	82	4	N	Y
123	83	5	Y	Y
125	83	5	Y	Y
109	83	5	Y	Y
111	83	5	Y	Y
113	83	5	Y	Y

Table 3-3
Single Tube Test Plan

Spec. No.	Tube Wall	Joint Length (in.)	Pressure	Temp.	Leak Test	Pull Test	Comment
1	0.048"						Explansion Test Sample
2	0.048"	2	MSLB	Ambient	N	Y	
3	0.048"	2	MSLB	Ambient	N	Y	
4	0.048"	2.5	MSLB	Ambient	N	Y	
5	0.048"						Explansion Test Sample
6	0.048"	2.5	MSLB	Ambient	N	Y	
7	0.048"	3	MSLB	Ambient	Y	Y	
8	0.048"	3	MSLB	Ambient	Y	Y	
9	0.048"	3.5	MSLB	Ambient	Y	Y	
10	0.048"	3.5	MSLB	Ambient	Y	Y	
11	0.048"	4	MSLB	Ambient	Y	Y	
12	0.048"	4	MSLB	Ambient	Y	Y	
13	0.048"	2	Atm.	NOT	N	Y	
14	0.048"	2	Atm.	NOT	N	Y	
15	0.048"	3	Atm.	NOT	N	Y	
16	0.048"	3	Atm.	NOT	N	Y	
17	0.048"	4	Atm.	NOT	N	Y	
18	0.048"	4	Atm.	NOT	N	Y	
20	0.042"	2	Atm.	Ambient	N	Y	
21	0.042"	3	Atm.	Ambient	N	Y	

Figure 3.1
Load Cell Test Rig Schematic

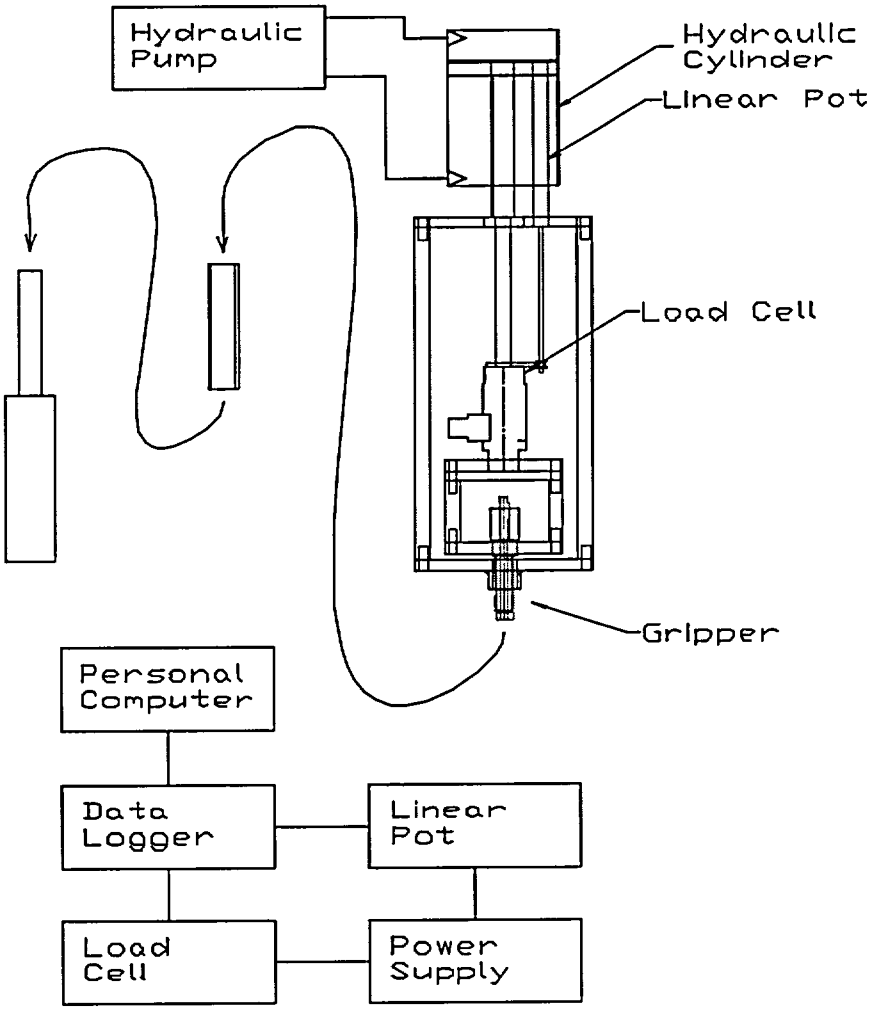


Figure 3.2
Windsor Load Cell Test Rig

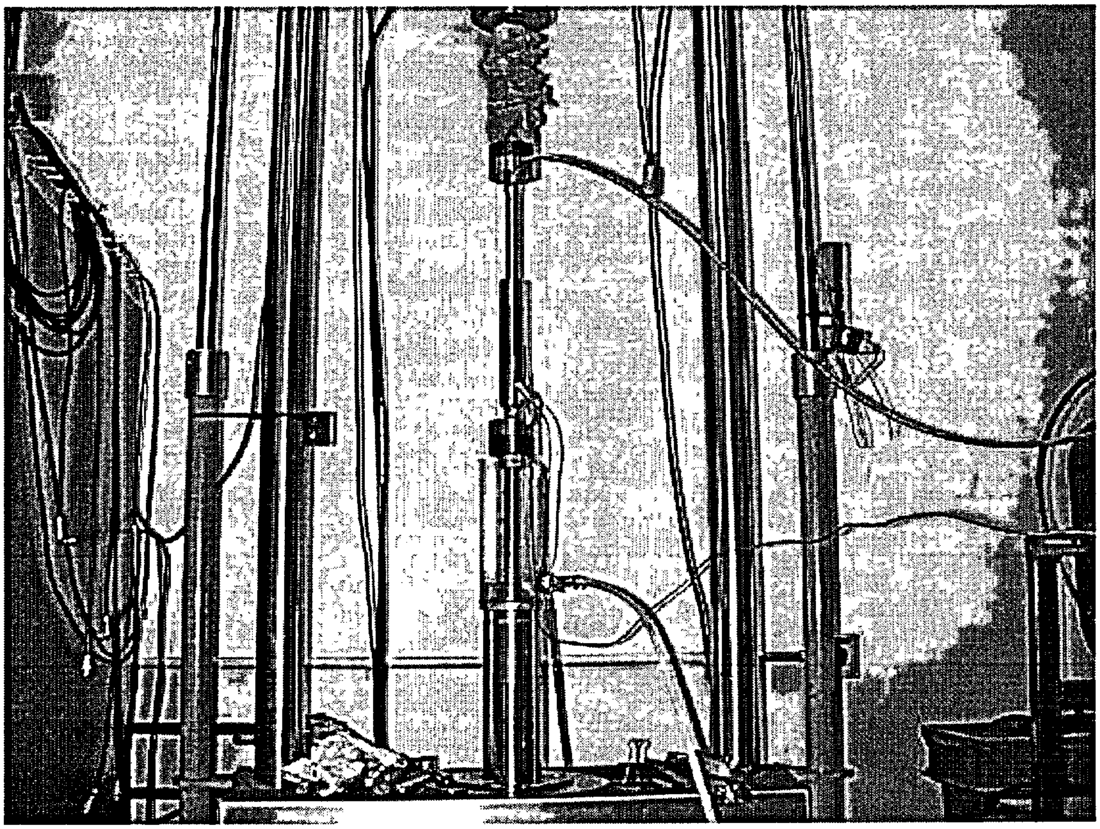


Figure 3.3
Windsor Load Cell Test Controls and Data Plotter

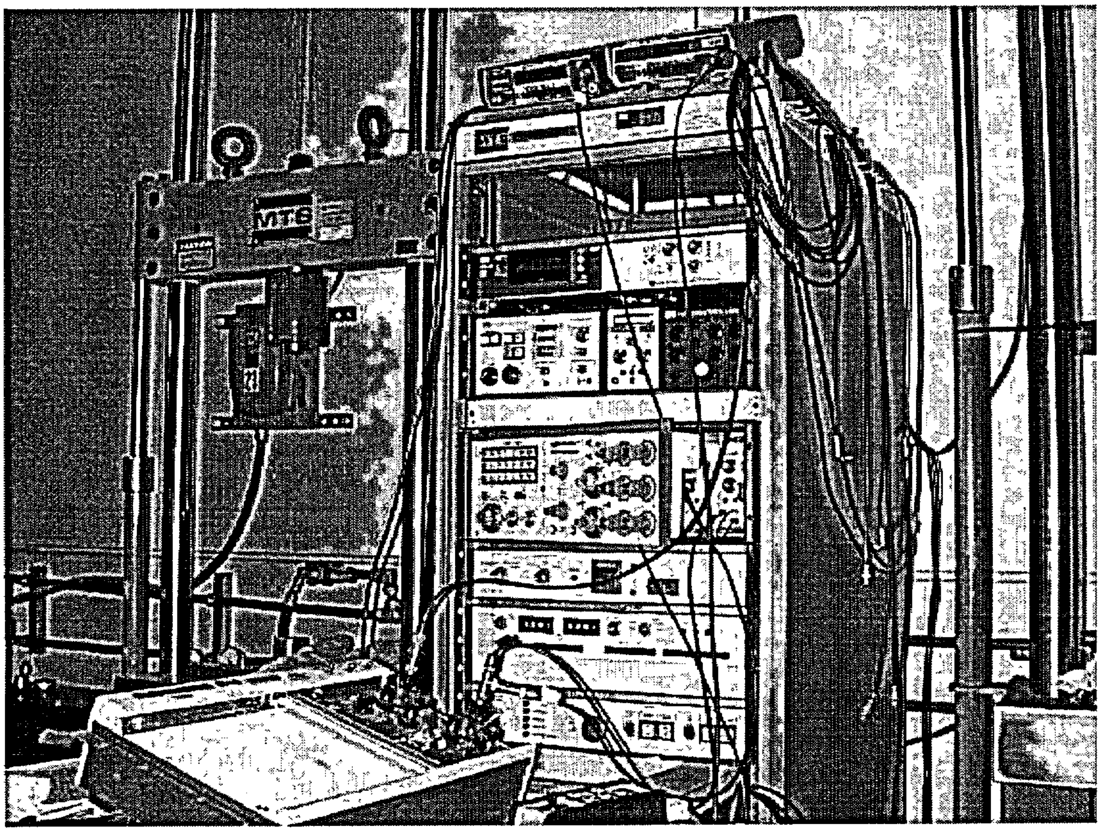


Figure 3.4
Leak Rate Test Rig Schematic

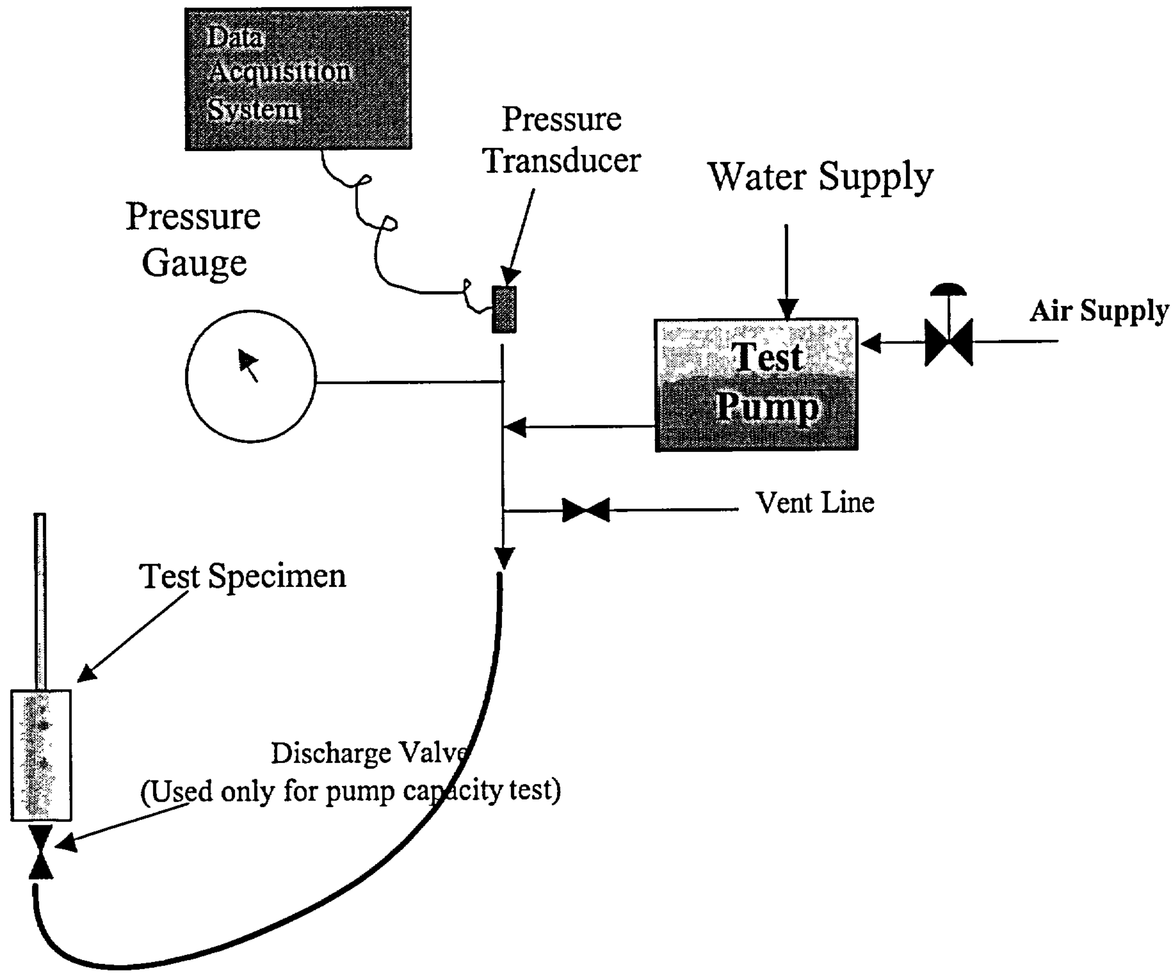


Figure 3.5
Leak Rate Test

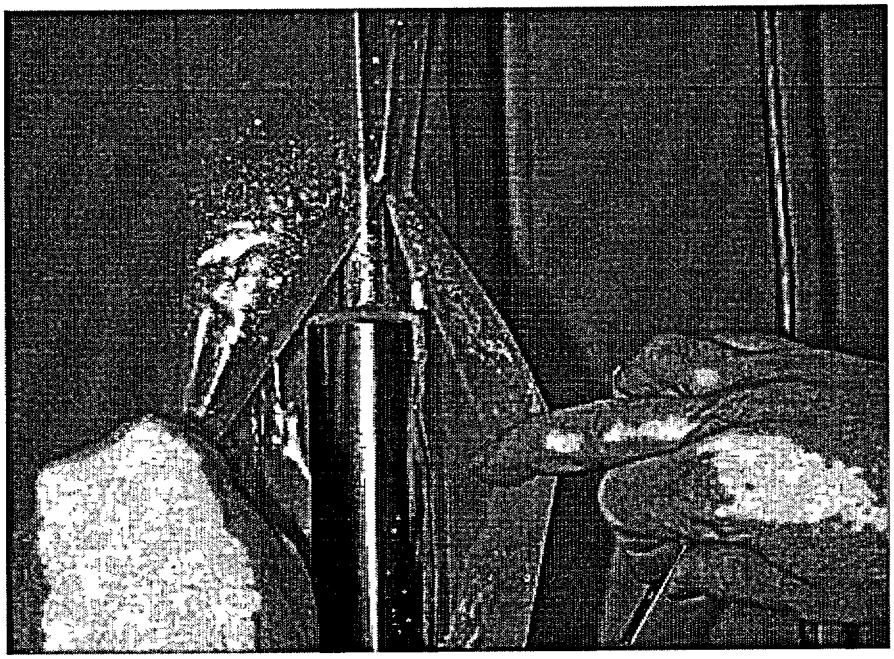


Figure 3.6
Windsor ISPT Test Rig

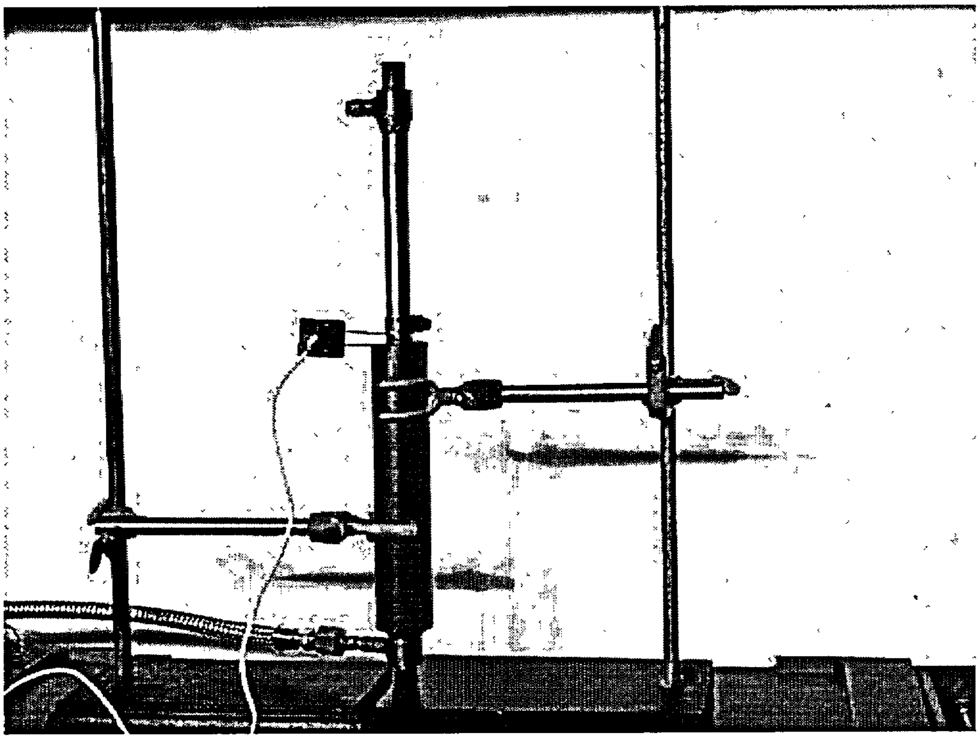


Figure 3.7
Elevated Temperature Test Single Tube
Prior to Inserting into the BEMCO Test Chamber

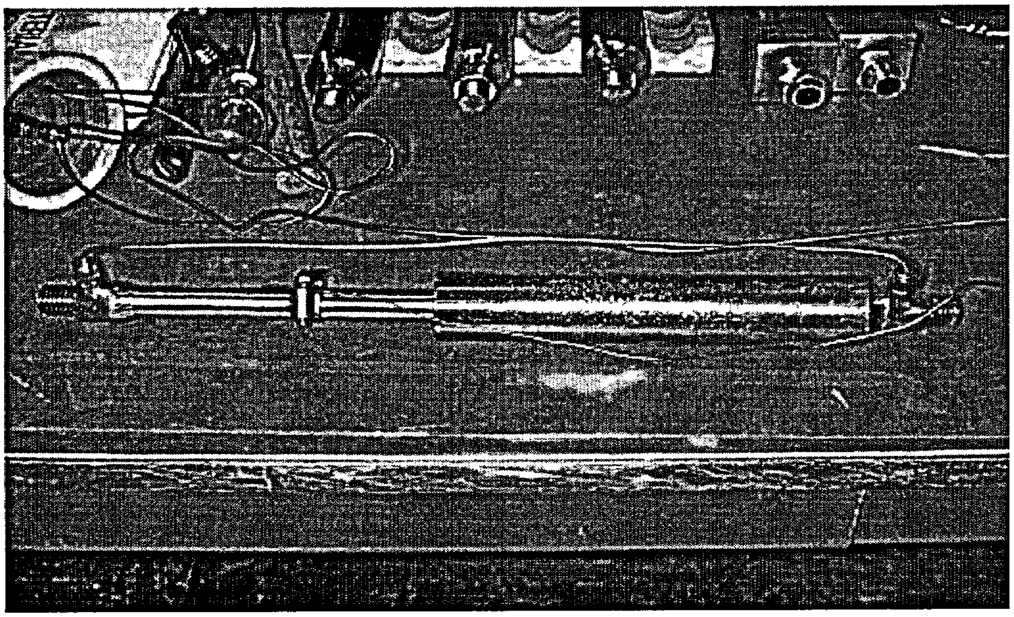


Figure 3.8
BEMCO Elevated Temperature Test Chamber

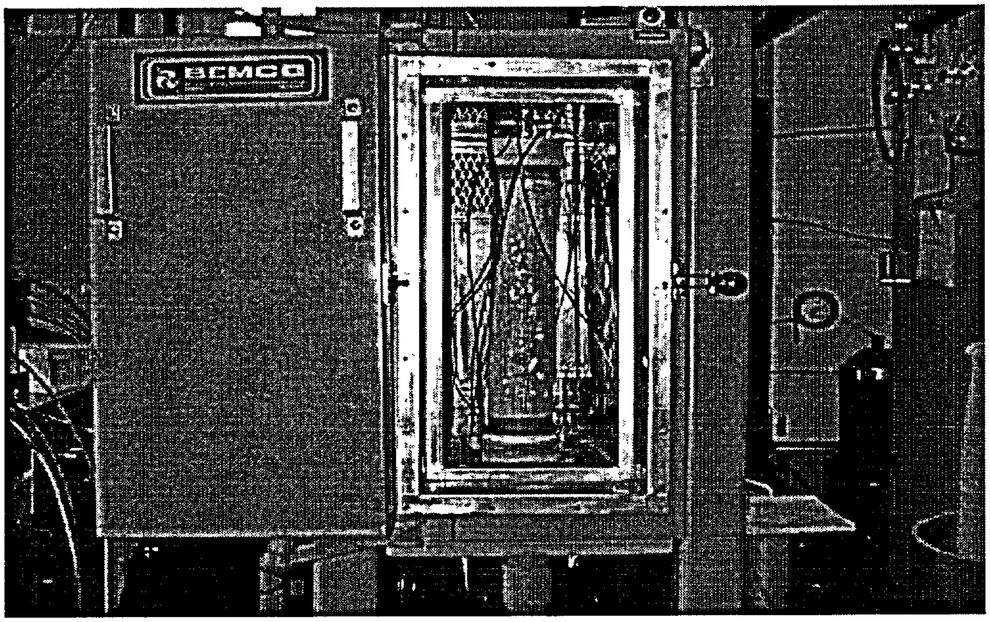


Figure 3.9
Boston Edison Scrapped Steam Generator

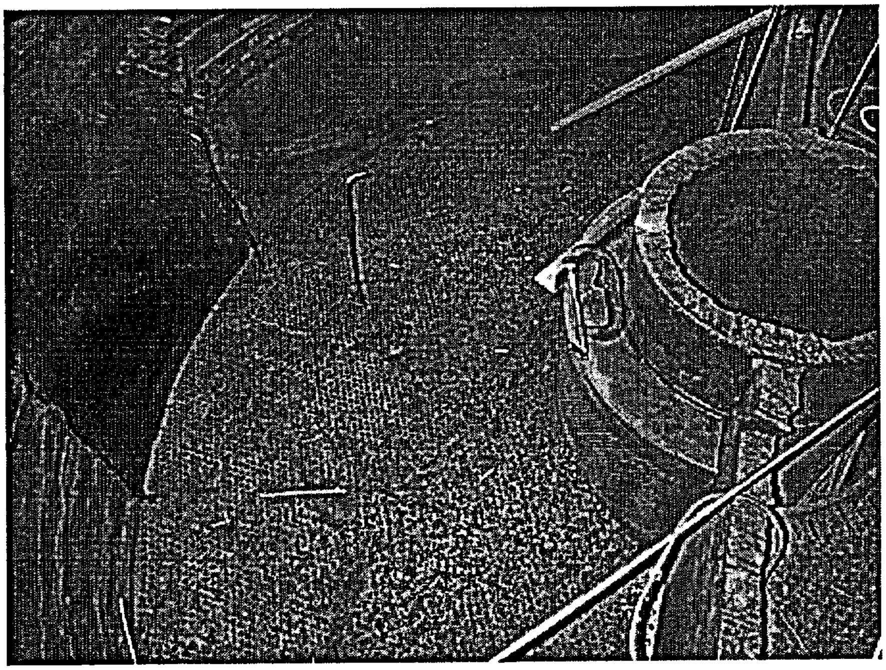


Figure 3.10
Boston Edison Steam Generator, Flow Distribution
Plate Cut Out

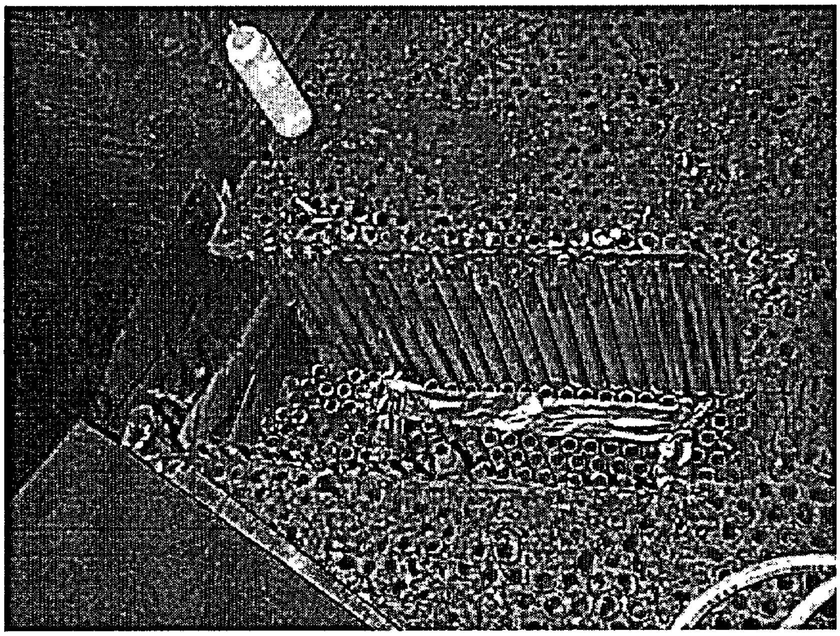


Figure 3.11
Load Cell Test Rig Tube Pull Fixture

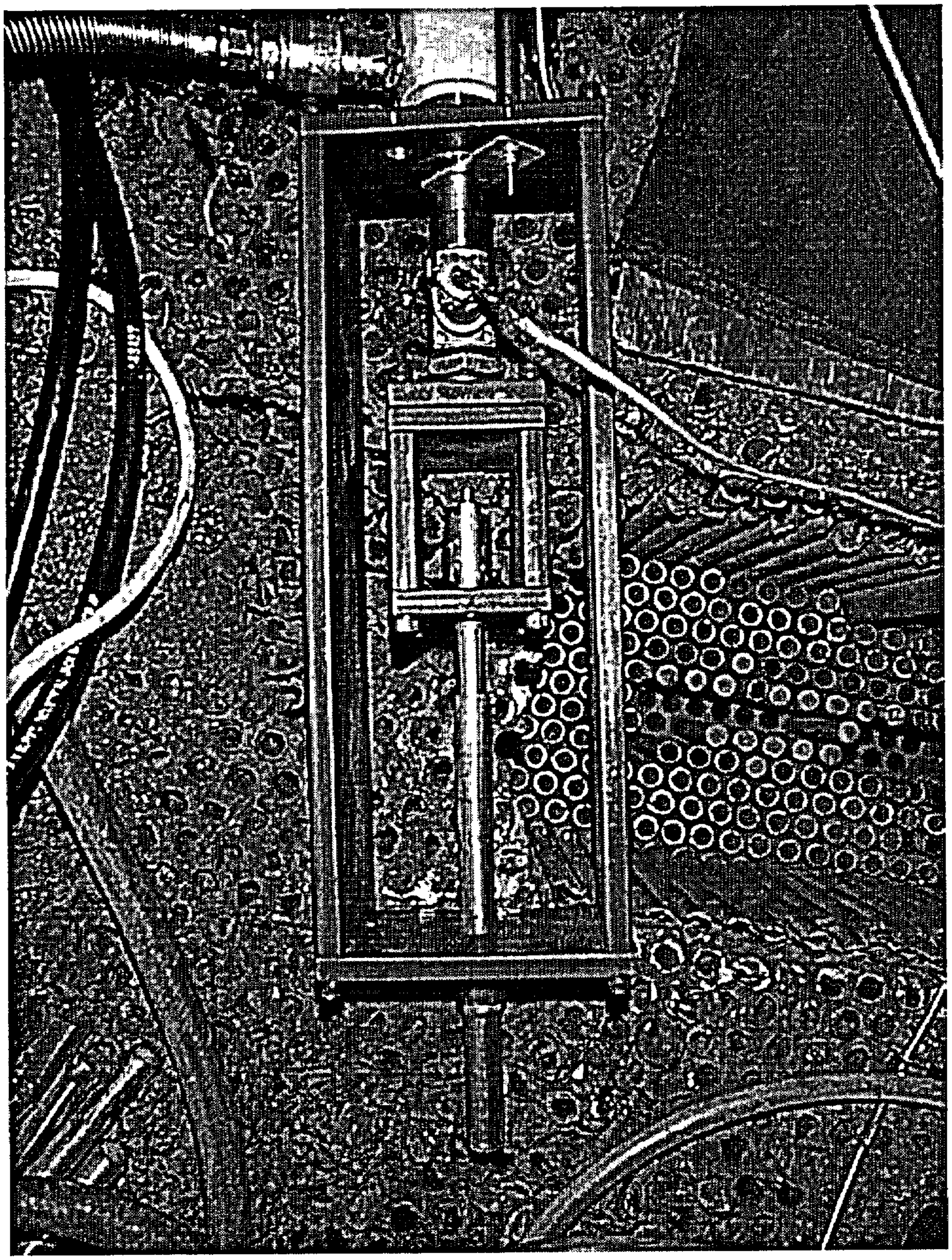


Figure 3.12
Single Tube Mockups

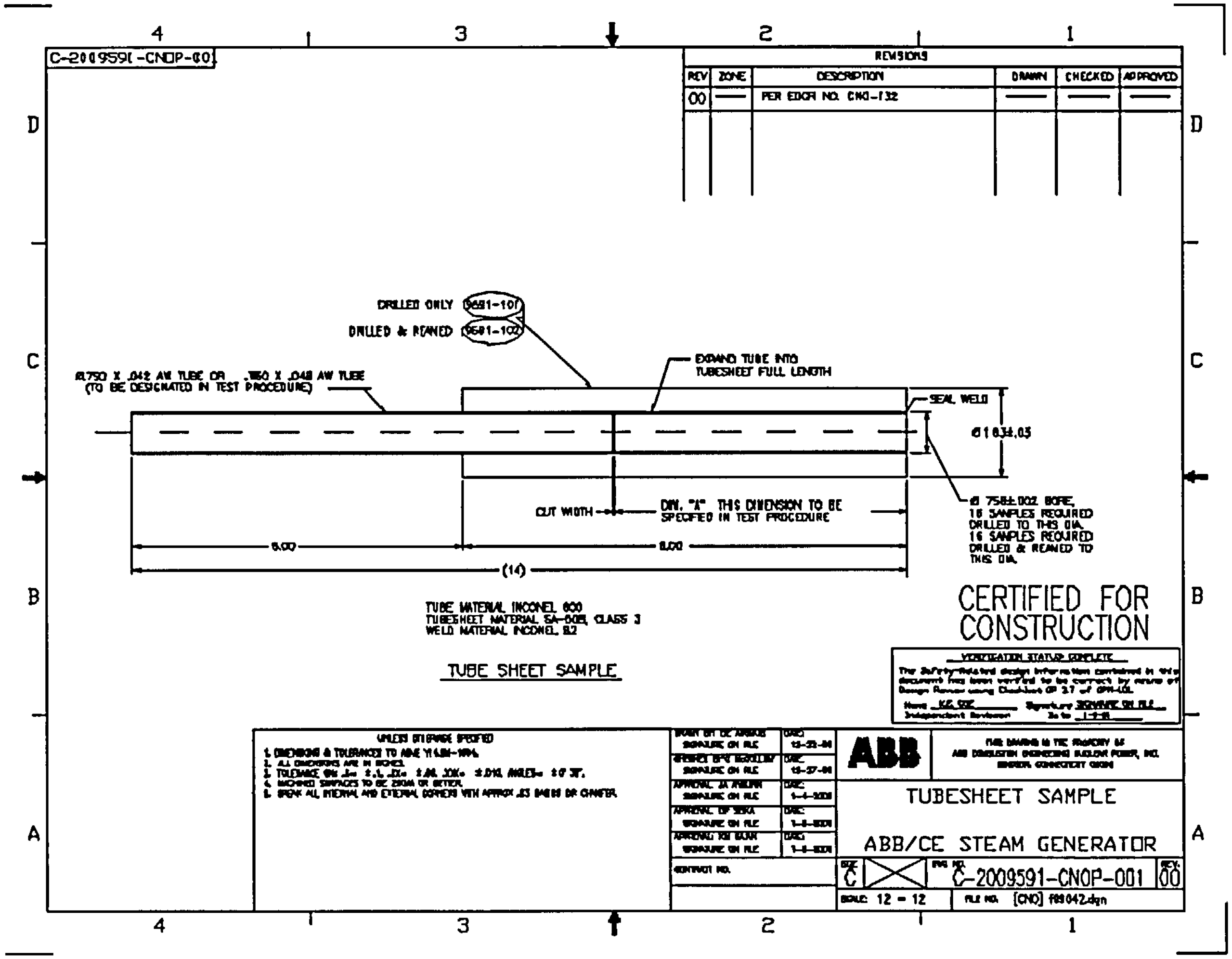
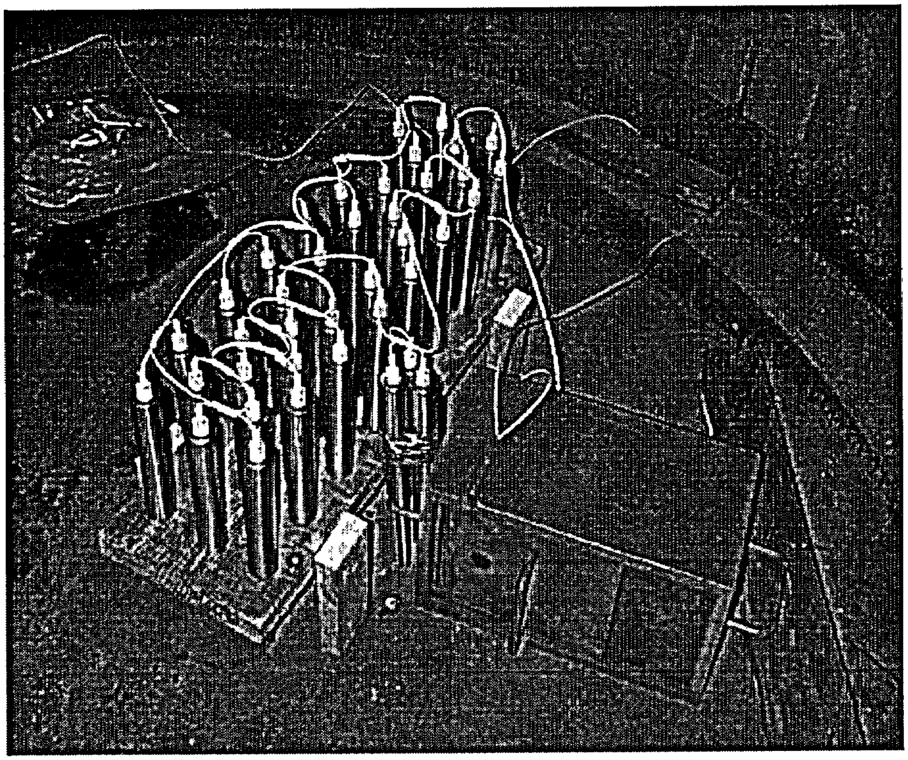


Figure 3.13
Single Tube Mockup Explansion Setup



4.0 PULL-OUT LOAD TEST RESULTS

4.1 Boston Edison Steam Generator

This section presents the results of the Boston-Edison steam generator pull tests. The test results are summarized in Table 4-1. The data are plotted on Figure 4.1 in terms of force vs. position.

The relationship between force and engaged length is essentially linear for the tubes pulled from the Boston Edison steam generator. This is evident on Figure 4.1. The slope of the force vs. engaged length curve decreases with length, but it remains positive. Reference 8 showed that in the yield range, a tube begins to neck down radially and pulls away at the top of the tube joint decreasing the contact surface and thereby the contact force. Therefore, as the joint lengths increase and the force required to move the tube approach and exceed the yield, the differential increase in force will decrease as indicated by the trend curvature. These results are consistent with expectations.

Composite force vs. position curves provided in Reference 25 shows that on average, there are about 30 mils of movement at a load of about 3,000 lbf. This movement is attributed primarily to settling in of the various contact points of the tube pull device, and not to tube elongation. Only about 6 mils of elongation (20% of the 30) can be supported by calculation (provided below). This approaches the yield point of the tubing, which occurs at 5,091 lbf and about 10 mils of elongation. The maximum pull force the tube could sustain is about 7,500 lbf, as determined by the following calculation:

Material Properties of Alloy 600	Basic Equations
	$E = \frac{\sigma}{\varepsilon}$
$\sigma_y = 54.5\ ksi = \text{yield stress}$	$\sigma = \frac{F}{A} = \text{stress, psi}$
$\sigma_u = 80\ ksi = \text{ultimate stress}$	
$E = 31\times10^6\ psi = \text{modulus of elasticity}$	$\varepsilon = \frac{\Delta L}{L_0} = \text{strain, unitless}$
	$\mathrm{A} = \frac{\pi}{4}\left(D_o^2 - D_i^2\right) = \text{area, in.}^2$

$$A=\frac{\pi}{4}\left(0.75^2-0.666^2\right)=0.09342\text{ in.}^2$$

$$\Delta L\text{ at }3{,}000\text{ lbf}=L_0\varepsilon=L_0\frac{\sigma}{E}=\frac{L_0F}{AE}=\frac{(6)(3{,}000)}{(0.09342)\left(31\times10^6\right)}=0.006216\text{ in.}\approx 6\text{ mils}$$

$$F_y=\sigma_y A=(54{,}500)(0.09342)=5{,}091\text{ lbf}$$

$$\Delta L_y=L_0\varepsilon_y=L_0\frac{\sigma_y}{E}=\frac{(6)(54{,}500)}{\left(31\times10^6\right)}=0.010548\text{ in.}\approx 10\text{ mils}$$

$$F_u=\sigma_u A=(80{,}000)(0.09342)=7{,}473\text{ lbf}\approx 7{,}500\text{ lbf}$$

4.2 Single Tube Mockups

Pullout loads were applied using the two different load cell processes as previously described for the Chattanooga and Windsor test locations. Two single tube mockup specimens were tested in Chattanooga as a cross-reference between the Chattanooga and Windsor load cell tests to show that the test setups would provide comparable results. The difference in processes leads to some variability in the results as indicated by the two single tube mockup specimens (specimens 20 and 21) tested in Chattanooga and the remainder of the rough bore single tube mockup specimens tested in Windsor. Specimens 20 and 21 were made up of tubes with wall thicknesses of 42 mils, whereas all other samples were made up of 48 mil wall thickness tubes. The difference in wall thickness was not anticipated to be a significant contributor to the variation in the resulting maximum pullout loads (see Section 3.1.1). Specimen number 21 did not behave as expected as compared to the Boston Edison test results using the Chattanooga load cell. [

]$^{(b)}$. The first movement was evident by a sudden drop in load, generally accompanied by an audible ping. After the initial load drop, there were subsequent increases followed by sudden drops in the load. For most mockups, the maximum loads occurred after the first drop in load as the load built back up. However, for some specimens, the load at first movement was the maximum load. The engaged lengths of all the mockups were severely gouged and scratched after being pulled from the mockups, shown in the following pictures (Figures 4.2 through 4.4).

The OD surfaces of the tubes all had visible impressions of the mockup hole machining marks. These permitted accurate determination of the location of the secondary face of the mockups, which in turn permitted a comparison of the actual versus target engaged lengths of the tubes. The pullout load as a function of length for the rough bore specimens is presented in Table 4-2. The loads are plotted with the Boston Edison steam generator results for comparison on Figure 4.5. A bounding curve of the combined data including adjustments to the data accounting for material properties, process, and tube wall thickness differences would also satisfy the burst criteria at two inches (Figure 4.6).

Table 4-1
Boston Edison SG Pull Test Data

(b)

Table 4-2
Single Tube Mockups: Pull Test Data

Figure 4.1
Boston Edison SG Pull Test Data

Figure 4.2
Single Tube Mockup 4, 2.5" Crevice, Ambient Pull

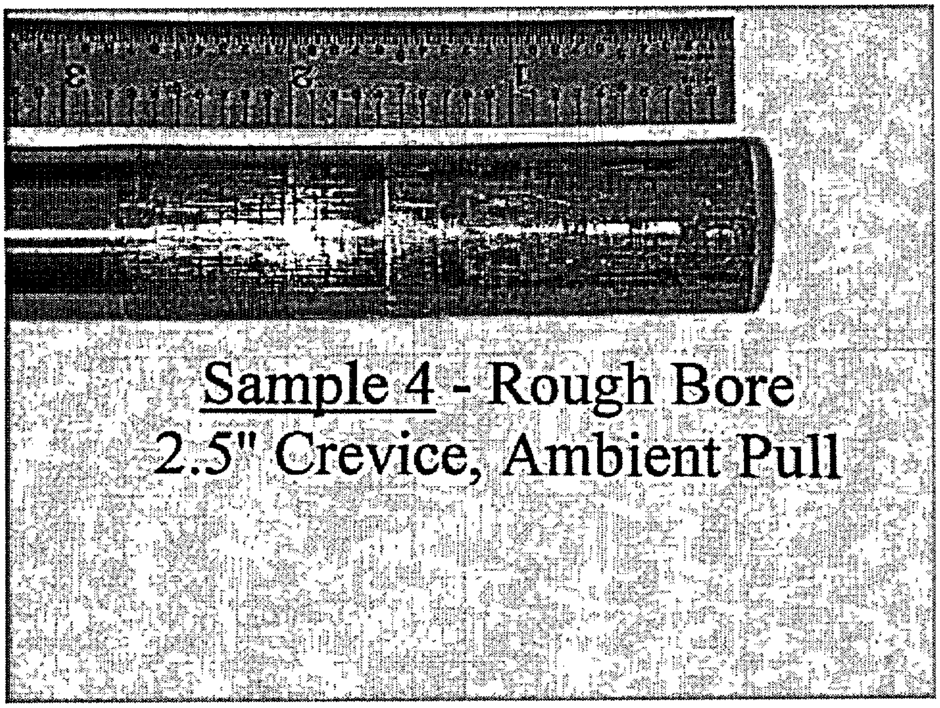


Figure 4.3
Single Tube Mockup 6, 2.5" Crevice, Ambient Pull

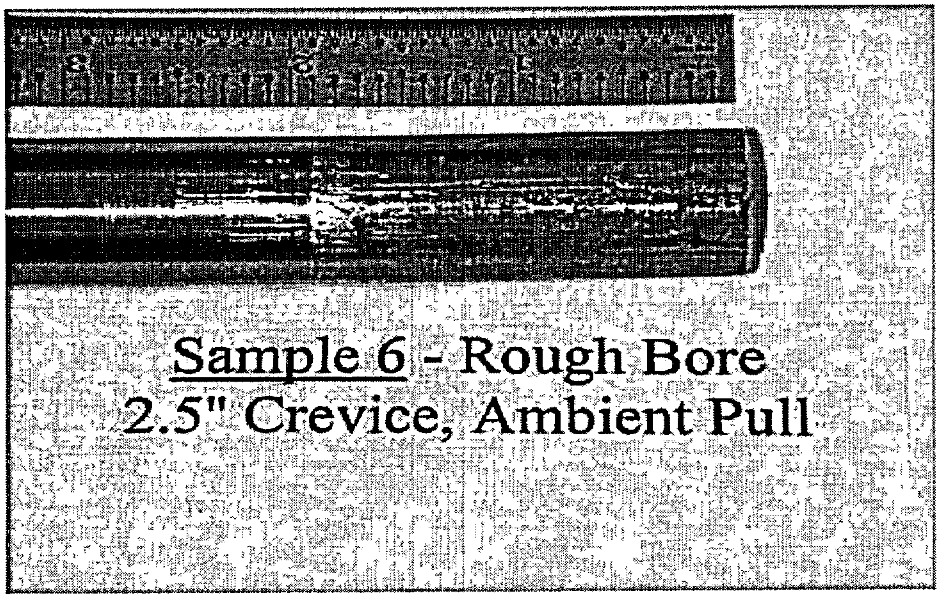


Figure 4.4
Single Tube Mockup 8, 3" Crevice, High Pressure Pull

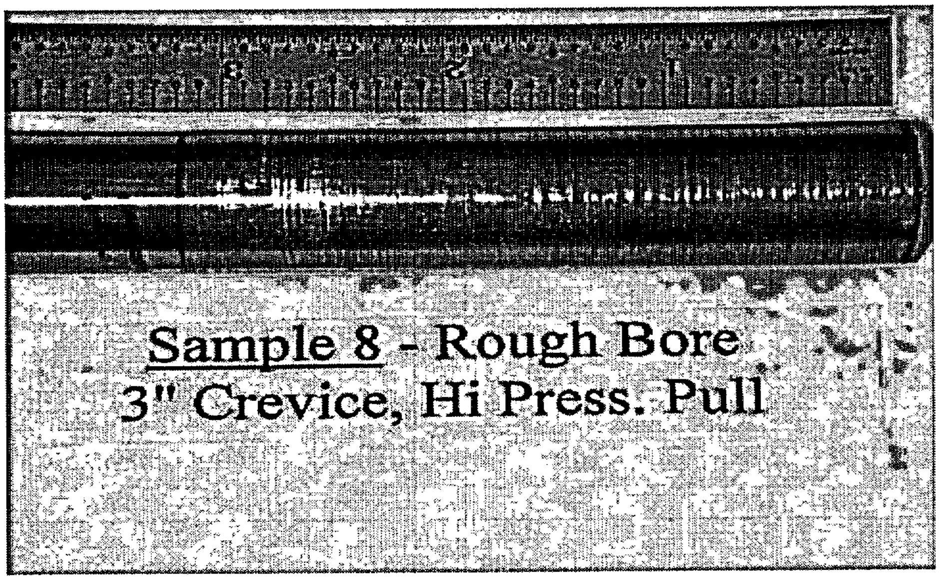


Figure 4.5
Single Tube Mockup Pullout Force vs. Joint Length

Figure 4.6
Single Tube Mockup Pullout Force vs. Joint Length – Adjusted Bounding

(b)

5.0 LEAK RATE TEST RESULTS

Leak rate tests provided data for determining the joint length necessary to meet the leakage criteria of [ ]$^{(c)}$ per steam generator.

5.1 Boston Edison Steam Generator Leak Rate Results

The Boston Edison leak rate data provides room temperature information of the as-built leak rate from the tests conducted on 12 tubes in the BE steam generator mockup. Detailed data are provided in Appendix B. Figure 5.1 plots the average of three tests for each specimen and illustrates that the trend of the data is reasonable despite the scatter. These tests being at room temperature provide an indication of the variability of as-built steam generator joints. [

]$^{(c)}$ which is the value of 1 assigned pump stroke in a forty minute test. These tests were completed as a real-world benchmark for comparison to the single tube mockup data and provide an order of magnitude for the expected variability and the total leakage amounts as a function of joint length.

Some non-quantifiable factors that could have influenced the leak rate results include the mechanical jacking that was used to remove the Flow Distribution Baffle (FDB) from the assembly, and to a lesser extent, an MDM cutting influence. The jacking was completed before the tubes were MDM cut in the tubesheet region and would most likely have only affected those tubes that caused the tube to FDB interference fit that resulted in the difficulty in removing the FDB (discussed in Section 7). These factors would influence the results in a conservative direction by tending to weaken the joint tightness. Despite the possible non-quantifiable factors, the data appear reasonable because the variation is restricted to very small absolute values, i.e., on the order of 10^{-5} gpm.

The condition of the tubesheet precluded a confirmation of leakage by visual observation of water on the secondary face of the tubesheet because the line of sight view was obstructed. However, testing of the single tube mockups, as described below, provided confirmation that the leakage indicated by the pump strokes was occurring through the tubesheet crevice and did not represent leakage through seals, fittings, etc. of the pressurizing system. A review of the individual test pressure versus time plots indicated that the leak rates generally decreased with time (interval between pump strokes increased). Possible reasons for this include:

- the crevices above and below the MDM cuts were filling during the first parts of the test,
- particulates from the MDM cutting were carried into and became lodged in the crevices, however, no particulates were noted in the post-test surface examinations, or
- corrosion occurred during the tests (which would also occur during SG operation).

Thus, it seems likely that the crevices above and below the MDM cuts were filling with water during the first part of the test.

5.2 Single Tube Mockup Leak Rate Result

Table 5-2 provides the results of the leak rate tests as a function of joint length. The room temperature tests were conducted to compare the single tube mockups to the Boston Edison room temperature results to gauge the difference in the mockup configuration results to an as-built steam generator condition.

Despite the fact that most of the tests resulted in data supporting reasonable NDE inspection lengths, some data do not fit with expectations. Figure 5.2 illustrates the single tube mockup data plotted with the BE SG data. The data except for specimen 10 is reasonably consistent and is indicative of a flat leak rate near the lower limit of measurement for the test system. The specimen 10 leak rate at approximately [ ]$^{(c)}$ gpm does not appear to be representative in the comparison of rough single tube mockup data with Boston Edison SG data.

Figure 5.3 provides a comparison of trend lines of single tube mockup specimen leak test results. The normal operating temperature results are at the threshold for detection for the test setup.

The differential thermal expansion between Alloy 600 tubing and the carbon steel tubesheet is expected to be a significant factor in the joint force. Transient temperature changes during a design basis MSLB may play a role in lessening the effect resulting from initial SG pressure blowdown and the associated RCS cooling. However, the thermal capacitance of the tubesheet and the RCS reheat after several minutes into the worst case transient will re-establish the joint force due to the greater expansion of Alloy 600 tubes. To evaluate temperature effects on the leak rates of tubes with flaws within the tubesheet, tests on two of the drilled hole mockups with nominal joint lengths of 3 and 3.5 inches were conducted at a temperature of a CE design lower end bounding normal operating temperature of 585°F. The specimen 7 NOT test indicates the temperature effect but the room temperature and NOT leakage is near the detection threshold for this test setup. The specimen 10 results show a significant decrease with the temperature increase. This confirms that the temperature effect is significant. Considering the thermal effects, all tests demonstrate that the leakage is less than the leakage limit of [
]$^{(c)}$

Table 5-1
Single Tube Mockups: Leak Test Data @ Room Temperature

(b)

Table 5-2
Single Tube Mockup: Leak Test Data @ NOT

(b)

Figure 5.1
Boston Edison Steam Generator Leak Data

(b)

Figure 5.2
Boston Edison SG and Single Tube Mockup Tests Averaged Leak Rates vs. Joint Length at Room Temperature

(b)

Figure 5.3
Rough Single Tube Mockups Leak Tests at RT and NOT

(b)

6.0 TUBESHEET DEFLECTION ANALYSIS

[ ]$^{(b)}$ It was planned that this load value would be based on the average for the pressure test samples, but the pressure test results did not support this approach due to a process anomaly as described in Section 4.2. An increased contact force effect due to pressurization is demonstrated by the supplementary in situ pressure test (ISPT) type tests. The pullout load results used for the development of the deflection load are sufficient, but very conservative.

Of the samples listed in Table 6-1, only specimens 2 and 6 were used in the development of the average load of [ ]$^{(b)}$ The NOT samples results discussed in Section 4 demonstrate a reduction of load. Because the beneficial effect of the pressure contact was not available to add and it would be expected to have a greater effect than temperature, it was decided to disregard the "NOT specimens" for this analysis. All specimens with loads greater than 6,000 lbf were also excluded because they exceed the tube yield by a large margin and would incorrectly reduce the result. Further, on the basis of a review of the Boston Edison SG pullout load results, the one single tube mockup load value that was 2,000 lbf less than the average of all results was considered anomalous on the basis of bore surface variability in single tube mockup fabrication.

The best estimate contact load for tube explansion is based on using a coefficient of friction of [ ]$^{(c)}$, which is bounded by the W* application (<u>10</u>) and the F* application (<u>20</u>), and results in a pullout load of [ ]$^{(b)}$ The resulting radial contact load for tube explansion is approximately [ ]$^{(c)}$ per inch of engagement.

An analysis of the tubesheet flexure stresses (<u>19</u>) and axial tube loads for normal operating differential pressure was performed. Tubesheet flexure reduces the effective contact load at the tube-to-tubesheet interface. For RCS pressures greater than SG pressure, the tubesheet flexes axially upward and the reduction in contact load is greatest at the top of the tubesheet. The contact load decreases almost linearly with depth into the tubesheet. Results of the single tube and tubesheet finite element analysis (<u>24</u>) indicated a total reduction in the contact load of [ ]$^{(b)}$ for the region from the secondary face to a depth of 1.75 inches. For the 1.75-inch depth, the normal contact load for tube explansion is [ ]$^{(b)}$. But with the reduction, the net contact load is [ ]$^{(c)}$.

[ ]$^{(c)}$ The resisting load exceeds the bounding pullout load criteria of 2,000 lbf determined at 3NODP. The results are considered very conservative.

It is concluded that a minimum depth of [ ]$^{(c)}$ will provide sufficient resistance to tube pullout to meet the structural integrity requirements.

Table 6-1
Single Tube Mockup Pull Test Data

(b)

7.0 OTHER FACTORS

7.1 MDM Cutting Effects

MDM cutting creates high heat in the cut area and tended to draw tube material away from the tubesheet bore hole reducing the engaged length of the joint. This was observed to be a small effect in the range of a few tenths of an inch and is conservative in that it would reduce the joint surface contact area.

7.2 Explansion Taper

Microscopic examination of tubes and tubesheet single tube mockups removed after pullout testing indicate that a taper is very small to non-existent. The W* topical report includes an addition of [ ]$^{(b)}$

The CE-designed joint process was reviewed in detail and it is reasonable to expect that a taper would not result because of the process design and controls. The explansion charge assembly illustrated on Figure 1.2 shows the plastic charge carrier extended beyond the secondary face of the tubesheet. The plastic served two purposes: (1) to hold the position of the primer cord and (2) to carry the explosive force uniformly through the range of the tubesheet. The explosive force carry function apparently is effective in providing a distinct transition from explanded to unexplanded tube diameter and negating any reduction in contact at or just below the bottom of the transition (i.e. taper). Explansion process documents reviewed as a part of this work indicate that any taper in the charge assembly plastic carrier was considered a defect and was rejected. NDE measurements of tubesheet joints do not indicate the presence of a taper in operating units or in the test mockups.

Further, the MDM cutting effect described in the section above provides a conservatism of a few tenths of an inch where the MDM method created a draw-back effect reducing the contact at the cut.

7.3 NDE Axial Position Uncertainty

NDE probe axial position uncertainty during inspections can be addressed on a plant-specific basis and is not expected to be a significant factor.

8.0 RESULTS EVALUATION

In general, the single tube mockup pullout test results were reasonably consistent.

The rough bore specimens pullout results were generally greater than the Boston Edison steam generator results. The differences in results can be attributed to material properties, pull test process variability, and tube wall thickness.

8.1 Tube Engagement Length Based on Burst Criteria

–The engagement length for burst is [ ](b). –

The pullout testing results from both the rough bore single tube mockup and the Boston Edison steam generator tests at room temperature show that a two inch threshold is very conservative. Credit for increases in joint contact force due to temperature and pressure were not necessary because the leak rate results discussed below are more limiting than a less than two inch pullout basis. This means that a [ ](b) joint length is sufficient for holding a tube in the tubesheet at 3NODP. This is a factor of greater than 1.7 times the MSLB accident maximum differential pressure.

8.2 Tube Engagement Length based on Leakage Criteria

– The engagement length for leakage is [ ](b). –

A comparison of the Boston Edison and single tube mockup leak test room temperature results presented on Figure 5.2 and the NOT results in Figure 5.3 indicate that the leakage (except for one rough single tube mockup outlier) is consistently at the minimum level of detection for the test equipment for the range of joint lengths tested in both test beds. The minimum length tested was [ ](b) for both but the data trend appears to be flat and would be expected to stay near the minimum value near the [ ](b) joint length. This is in agreement with the results of leak testing in Reference 10. A [ ](b) joint length single tube mockup specimen was tested at NOT. The calculated number of allowable leaking tube joints (with throughwall flaws) is in the range of [
](c)

As the surface friction resistance to flow is theoretically linear and directly proportional to surface area and therefore the joint length, then leak rate, using a laminar flow model, is assumed to increase as an inverse function of the square root of the joint length. Then, neglecting any credit for choke flow conditions that may exist at MSLB conditions, it is still reasonable engineering judgment to project that the flow rate increase could substantially increase at a [
](b) joint length. However, given all the conservatisms noted in this report and the substantial effect of the internal pressure to increase the radial contact force it is the judgment provided in this report that the criteria established in this project - [

]$^{(c)}$ – will be satisfied at the [ ]$^{(b)}$ joint length.

8.3 Tubesheet Dilation Correction Factor

The tubesheet hole dilation factor is added to the limiting threshold length (i.e., threshold length for leakage). The factor for:

– *St. Lucie Unit 2 Dilation Correction* = [ ]$^{(b)}$ –

8.4 Required Tube Engagement Area Length

The limiting tube engagement area length based on burst and leakage criteria and results is [ ]$^{(b)}$. The addition of the tubesheet dilation correction factor of [ ]$^{(b)}$ inches results in a required tube engagement area length of [ ]$^{(b)}$ inches.

– *St. Lucie Unit 2 TEA Length* = [ ]$^{(b)}$ –

8.5 Inspection Extent for NDE Inspection

With the addition of [ ]$^{(c)}$ inches of additional conservatism, the NDE inspection extent is conservatively set at five inches for the St. Lucie 2 SGs. This additional conservatism bounds NDE uncertainty in axial location.

– [ ]$^{(b)}$ *TEA Length* + [ ]$^{(c)}$ *Additional Conservatism* = [ ]$^{(b)}$–

– *St. Lucie Unit 2 Inspection Extent Length* = [ ]$^{(b)}$ –

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Appendix A

TEST MATRIX PLAN

Appendix B

Boston Edison Steam Generator Pull Test Data

(b)

BE SG
Leak Test Data

(b)

Appendix C
Single Tube Mockup Tests Leak Data at Rom Temperature

(b)

Leak Rate at NOT

(b)

Single Tube Mockup Tests Pull Data

(b)