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INFORMATION

TECHNICAL EVALUATION REPORT

EVALUATION OF TMI-1 STEAM GENERATOR TUBE/TUBESHEET REPAIR

REVIEW AND EVALUATION OF PROCEDURES DEVELOPED FOR ONSITE REPAIR OF TMI-1 STEAM GENERATOR TUBES BY EXPLOSIVE EXPANSION

FRC PROJECT C5506

FRC ASSIGNMENT 10

NRC CONTRACT NO. NRC-03-81-130

FRC TASKS 311, 312, 313

Prepared by

Franklin Research Center
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Prepared for

Nuclear Regulatory Commission
Washington, D.C. 20555

Lead NRC Engineer: J. Rajan

July 8, 1983

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FOREWORD

This Technical Evaluation Report was prepared by Franklin Research Center under a contract with the U.S. Nuclear Regulatory Commission (Office of Nuclear Reactor Regulation, Division of Operating Reactors) for technical assistance in support of NRC operating reactor licensing actions. The technical evaluation was conducted in accordance with criteria established by the NRC.

Contributors to the technical content of this report were L. Leonard, T. Shook, V. Luk, C. Davey, D. DeCleene, and R. Brooks of Franklin Research Center.

1. INTRODUCTION

In November 1981, steam generator tube leaks were discovered at Three Mile Island Unit 1 (TMI-1) during pressurization for functional testing following an extended cold shutdown period. The conclusion reached by the Licensee, GPU Nuclear, after the performed failure analysis was that sulfur contamination caused intergranular attack and cracking in the upper ends of the Inconel 600 tubes in the regions of the weld heat-affected zones and the 2-in roll seals. Because most tube cracks were in the upper 2 in of the 24-in-thick tubesheet, the Licensee proposed establishment of a new load-bearing and leaktight seal below the defects as the optimum manner in which the generators could be restored to service. The Licensee further proposed that the new seal be formed by kinetic (explosive) expansion of the individual tubes and that an expanded length of 6 in be qualified as meeting the load-carrying and leaktightness objectives.

To verify the adequacy of the proposed repairs and to demonstrate that the kinetic expansion would not compromise the structural integrity of the generator, GPU Nuclear, in association with Babcock and Wilcox (B&W) and Foster Wheeler Energy Application (Foster Wheeler), conducted a series of tests and analyses.

As a further check on the proposed repair process, Franklin Research Center (FRC), under contract to the NRC, conducted an independent testing program and reviewed the Licensee's data and analyses regarding the repair's effects on the generator.

Expansions were carried out on mock-ups that simulated the actual materials and surface conditions in the once-through steam generators (OTSGs); leak testsand pullout tests and dimensional measurements were performed on the expanded samples, both in the as-expanded condition and after they had been subjected to load and thermal cycling that simulated 5 years of typical service. In addition, full-scale expansions were performed on a comparable B&W steam generator to evaluate the stresses imposed by the repair process and their effects on the OTSG structure.

The results of the various testing and analyses programs indicated that GPU Nuclear should implement the repair process, and the procedure was carried out. At the time of publishing this report, FRC had not received documentation of the evaluation of the repairs by eddy current, dimensional, and hot functional testing.

Included in the present report are (1) a discussion of the Licensee's testing and analyses, (2) a presentation and discussion of FRC's tests and analyses, and (3) FRC's conclusions concerning the expected adequacy of the repair procedure and its influence upon the structural integrity of the generators.

The appendices present documents received, meetings attended, test procedures, test data, and the statement of a consultant with considerable experience and expertise in the field of explosive expansion techniques who was retained by FRC for this project. Photographs of the test assemblies are also included.

2. SCOPE

The scope of the evaluation was as follows:

1. Review the Licensee's development and testing programs and conduct independent testing to evaluate whether the Licensee-developed kinetic expansion repair procedure is capable of producing a tube/tubesheet seal with less than a specified leak rate and greater than a specified pullout strength.

2. Carry out independent analytical and experimental work to determine whether the kinetic expansion repair procedure has any adverse effects on the OTSG's structural integrity.

3. EVALUATION CRITERIA

The Licensee specified that the repair process must satisfy all applicable design parameters originally used for the TMI-1 OTSG and must comply with the requirements stated in the following documents:

GPU Nuclear TMI-1 OTSG Tube Repair Preliminary Specification No. 1101-22-006, Rev. 4, including codes and standards listed in Paragraph 3.2 [1]

Babcock and Wilcox (B&W) Company's Explosive Expansion Qualification Requirements for Mechanical Testing (61-1134292-00) for Explosive Expansion Repair of OTSGs [2].

Specifically, the kinetic expansion repair process was to result in a tube-to-tubesheet seal with a leak rate less than 3.2×10^{-5} lb/h per tube and a pullout strength greater than 3140 lb.

4. TECHNICAL EVALUATION

4.1 LICENSEE'S REPAIR QUALIFICATION PROGRAM

4.1.1 Description of the Licensee's Repair Process

Based upon a developmental test program, GPU Nuclear, in association with B&W and Foster Wheeler, developed a tube repair method using an explosive (kinetic) technique [3] to expand a sufficient length of undamaged tube below the defects to form a new tube/tubesheet seal. Although specific details of the expansion process are considered proprietary by GPU Nuclear, it can be

explosive expansion was deemed optimum to effect a new seal without inducing distortion in the tubesheet. In this procedure, a detonating cord charge is inserted in a polyethylene tube or "candle" which, in turn, is placed in the tube to be expanded. The explosive force from the charge drives the candle against the tube, forcing it against the tubesheet.

The total length of the expansion joint and the portion of that length to be qualified for specific leak rate and pullout strength goals were selected primarily on the basis of the locations of the tube defects and the maximum number of tubes that would be repairable by a standardized procedure. Accordingly, all repairable OTSG tubes were expanded over 17 in. Those tubes with defects more than 11 but less than 16 in below the top surface of the tubesheet were expanded over a 22-in length in all cases. The lower 6 in of the expansion is the qualified seal.

The tube/tubesheet seal is a mechanical interference rather than a metallurgical weld between the tube and the tubesheet and is influenced by such variables as the size and nature of the explosive charge, the mechanical characteristics of the tube and tubesheet materials, the spacing between the components, and the nature of the components' surfaces.

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4.1.2 Historical Background of Repair Process

The use of explosive energy to form metals is not a new technique; its applications and successes predate the aerospace age [4], and the process for explosively expanding rings has been discussed in some detail [5]. In forming a specific shape, the explosive drives the workpiece metal into a forming die. In order to distribute the pressure uniformly over the workpiece and to eliminate local hot spots and fragments from the detonated explosive, a transmitting intermediary medium, usually water, is placed between the workpiece and die. In addition, the space between the workpiece and die is usually evacuated.

In the repair process for the TMI-1 OTSGs, the tubesheet served as the die, a tube was the workpiece, and the transmitting medium between the explosive charge and the tube was a polyethylene tube or "candle." This application of explosive expansions to seal a tube into a tubesheet is not a new process, and a few examples should suffice to demonstrate the effectiveness of this technique. In 1967, a leaking heat exchanger was successfully repaired by explosive expansion. Operating pressures of 1500 psi and poor surface finishes in the tubesheet holes and variation in their bore size did not adversely affect the integrity of repaired joints [6].

A number of feedwater heaters have been explosively expanded in their original fabrication in a manner similar to that proposed for the TMI repair [7]. As of August 1970, Foster Wheeler had built 200 feedwater heaters using explosive expansion, with up to 3000 expansion joints per heater.

Leaking heat exchangers have been explosively repaired while under 1500 psi steam pressure [8]. For example, the Yimpact section of Yorkshire Imperial Metals used explosive expansions to seal against leakage under pressures up to 170 atmospheres in a waste-heat exchanger which had rolled and welded tube/tubesheet joints [9]. Subsequently, all joints were expanded as an additional safeguard against leakage.

Explosive expansion of carbon steel, brass, and Monel tubes into carbon steel tubesheets has been achieved in retubing operations on feedwater heaters [10]. Hydrostatic, vibration, and thermal cycling tests have been applied to

verify the integrity of explosively expanded joints. For example, Monel (SB 163) tubes expanded into a carbon steel tubesheet achieved pressure seals to 12,000 psi after 100 thermal cycles and 500 h of vibration cycles.

In the Conner's Creek plant of Detroit Edison Company, in-place repairs were made to replace existing tubes with 304 stainless steel tubes against SA 179 carbon steel tubesheets [10]. In this case, concentric grooves were cut into the tubesheet to provide good seals and to increase pullout strength.

4.1.3 Analytical and Experimental Background of Repair Process

The magnitude of the explosive charge
required to achieve a tube/tubesheet seal to meet the requirements indicated in Section 3 of this report were determined in an experimental development and testing program conducted by Foster Wheeler in conjunction with B&W and the Licensee [11, 12, 13, 14].

Using the method in Reference 5, FRC calculated an approximate pressure intensity necessary for tube expansion and found fair agreement with the appropriate explosive charges determined in the Licensee's experimental program. Because information on the dynamic stress-stress behavior and work hardening of the tube material, Inconel 600, was not available, the relative intensity of the expansions was determined solely by experimental testing.

It was demonstrated experimentally by both the Licensee and FRC that this procedure produced an adequate tube pullout resistance [15]. In addition, leakage data derived as a result of the experiments conducted for the Licensee and at FRC showed that, although some leaks may be expected immediately after expansion, the leak rate tends to decrease with time at the operating pressure of the OTSGs.

Although the repair process (described earlier) of kinetically expanding tubes onto tubesheets is not new, this is the first application of this method to repair a nuclear steam generator tube in what is, in metallurgical terms, a

sensitized condition, i.e., grain boundary precipitation of carbides had resulted from the stress-relieving heat treatment applied to the generators following their original fabrication, which involved mechanical tube rolling and seal welding of the tubes on the outside surface of the tubesheet. Forming a new seal length below the old one and thus eliminating the upper cracked region of tubing from consideration is also a novel application. Finally, the tube/tubesheet crevices were in an oxidized or corroded state stemming from both service operation and idle downtime exposure.

Based upon the history of successful applications of the explosive expansion of tubes into a tubesheet, both in fabricating new heat exchangers and in repairing in-service ones, there did not appear to be any serious questions concerning the technical feasibility of the expansion process. Rather, efforts were concentrated on assuring that the procedure would be adequate to meet the tube/tubesheet qualification specifications (Section 3) for strength (pullout) and leaktightness, while at the same time not adversely affecting the structural integrity or fatigue resistance of the generators as a whole.

Accordingly, to evaluate the adequacy of the repair process, the Licensee and FRC conducted comprehensive qualification testing programs using small scale models [12. 13]. In addition, the effect of the kinetic expansion process on the structural integrity and the performance of the tube/tubesheet assembly and its supporting system was assessed [3, 15].

Conditions representative of those in the OTSGs were reproduced in test samples. The Inconel 600 tube samples were from the same production heats as those used in the OTSGs and were of two different strength levels. The tubesheet steel met the same specification -- SA508 Cl 2 -- as the tubesheets in the OTSGs. All materials were heat treated to simulate the stress relief treatment to which the generators were subjected and to oxidize or corrode the tube/tubesheet joint surfaces to a condition similar to the actual ones in the OTSGs.

Single tube/tubesheet expansion samples (Figure 1.1 in Appendix D) were used for initial evaluations and for developing procedural specifications. Tubes were then expanded into 10-tube mock-up assemblies on which leak and

pullout tests could be carried out (Figure 1.0 in Appendix D). The presence of cracks in the OTSG tubing was taken into account in the mock-ups with a simulated 360° crack. Two separate tube lengths were placed in each tubesheet hole. A 2-in stub length was initially rolled into the tubesheet test block and then it and a longer test section, which included the 6 in to be qualified as the new joint, were explosively expanded.

The assemblies, which permitted an evaluation of the effects of after hits on individual tube/tubesheet seals, were subjected to leakage tests under representative pressure differentials between the inner and outer diameters (ID and OD) of tubes. In addition, the assemblies underwent thermal and axial load cycles to simulate 5 years of operating service, including start-ups, shutdowns, power changes, and accident conditions such as loss of cooling (LOCA), main steam line break (MSLB), and feedwater line break (FWLB).

Tests have also been run on an out-of-service B&W steam generator at Mt. Vernon, Indiana, to investigate the effect of the kinetic expansion process on equipment similar to the TMI-1 OTSGs.

4.1.4 Adequacy of the Seal Between the Primary and Secondary Sides of the Tubesheet

As stated in Section 3, the design objective for the kinetic expansion was to produce a seal to limit the total primary-to-secondary leakage from the TMI-1 OTSGs to 1 lb/h per plant under plant operating conditions, or 32×10^{-6} lb/h per tube (there are 31,062 tubes per plant). The technical specification limit for the plant is 1.0 gal/min (500 lb/h) total leakage for both generators.

The water leak tests were conducted by the Licensee in accordance with Reference 11 and the logic chart in Figure 2-16 of Reference 15. Seven expanded assemblies, consisting of the 10-tube corroded blocks with 360° fully severed tubes as described previously, were subjected to a series of leak tests using demineralized water at 70°F $\pm$ 15°F. The tests evaluated the effects of the expansions and of thermal and axial load cycling equivalent to 5 years of plant operation (Section 2.4.2 of Reference 15) on the leakage rate.

The test specimens were subjected to a pressure of 1275 psi on the primary side to simulate normal operating conditions (Para. 4.4.2 of Reference 1) and 1275 psi on the secondary side to simulate the LOCA condition (Para. 5.3.1 of Reference 16). A water leak test was performed on a block subjected to 2500 psi to simulate the worst accident, the MSLB condition (Para. 5.3.1 of Reference 16).

The leak test results indicated a 99% statistical confidence level that the water leakage rate for 99% of the as-expanded tubes was less than 132.4×10^{-6} lb/h per tube [3],* which exceeds the qualification goal of 32×10^{-6} lb/h per tube. The tubes subjected to thermal cycling yielded leak rates varying from 1.18×10^{-6} to 187.4×10^{-6} lb/h per tube. The leak rate results for tubes after room-temperature axial load cycling were 30×10^{-6} lb/h per tube after 90 hours of curing [17]. One test block was tested at temperatures ranging between 10°F and 400°F, and the leak rate results showed insignificant variations.

According to Reference 3, during the repair process at TMI, 15 new eddy current test indications were detected in the 6-in qualification zone out of approximately 435 initial expansions in both steam generators. The Licensee determined that these new indications most likely were not from new defects caused by the expansion process, but rather from defects which were below the threshold of detectability of the eddy current testing technique employed prior to expansion. Based on fiberscope examination, these defects appeared to be pits and scratches of a size that would not influence the reliability of the joints.

4.1.5 Effects of the Kinetic Expansion Process on the Tubesheet Dimensional Integrity

The objective of the kinetic expansion process was to explosively expand tubes into the tubesheet without altering the ligament and the pitch distance of the tubesheet. It was therefore essential to maintain, after the kinetic

*The statistical confidence level of 99% for 99% of the tubes, referred to as 99/99, is also used in the tube pullout evaluation in Section 4.1.9.

expansion process, the dimensional integrity of the tubesheet, which has a direct bearing on the tubesheet ligament strength. Using charges determined in the test program, the Licensee found a minimal effect on the diameter of adjacent tubesheet holes in the 10-tube test blocks due to the expansion process.

Full-scale tube expansion testing in a similar steam generator at Mt. Vernon using strain gages and profilometry also showed no degradation of the tubesheet ligaments [3].

In this test, a maximum tensile stress of 95,000 psi was recorded during the expansion process. In spite of the fact that the static yield stress of the tubesheet was 67,000 to 70,000 psi, no residual strains were noted following the expansion. The Licensee concluded that the dynamic yield strength of the steel, which can be up to twice the static yield, was not exceeded and thus no deformation would occur in the TMI-1 OTSGs.

However, since only a limited number of tubes were expanded at Mt. Vernon, it is not clear that this is a valid conclusion. Furthermore, there will be tubes distributed throughout the TMI-1 OTSG tubesheet which will require 22-in reexpansions, and this additional, nonuniformly distributed deformation could induce some tubesheet warpage. Accordingly, it is recommended that measurements be made on the tubesheets at TMI following the repair process to establish the degree of warpage, if any.

At the time of this final report preparation, FRC had received no information as to whether tubesheet warpage had been evaluated by the Licensee.

A number of welds at the top of the upper tubesheet at TMI were cracked during the expansion process. The mechanism responsible for this cracking and its effect on the tubesheet ligaments in the immediate vicinity of the damaged welds have not been identified and evaluated. At the time this report was written, FRC was informed that the cracks on the outside face of the tubesheet were ground away to eliminate any stress risers. Since the actual qualified tube/tubesheet seal is in the last 6 in of the 17-in expansion, these welds no longer serve any leak-prevention or load-bearing purpose; thus, grinding of the welds should not present any problems.

4.1.6 Effects of the Kinetic Expansion Process on the Design Adequacy of the Welded Connections in the Tubesheet/Shell Section

The kinetic expansion process may affect the structural integrity of welded connections in the vicinity of the tubesheet, especially in the tubesheet/shell junction. To determine the nature of this effect, the Licensee used strain gages and an accelerometer to measure loads imposed at two locations on an out-of-service steam generator at Mt. Vernon [18, 19]. One location was the junction between the inlet header and the tubesheet, and the other was at the shell weld location underneath the tubesheet. The strain gage measurements were taken at the two ends of a diametral row of 132 tubes expanded at the same time. On the basis of these data, the peak stresses and stess intensity were calculated for fatigue evaluation. An accumulative usage factor* of 0.12 was calculated on the basis of the conservative assumption that every expansion, including those in faraway rows, will produce the same stresses at these locations. The low usage factor led the Licensee to conclude that the welded connections in the tubesheet/shell section would not be affected by the expansion process and that it is acceptable to use simultaneously a maximum number of 137 charges, a combination of 132 charges in the longest row plus up to five misfires from the previous row.

4.1.7 Adequacy of Residue Removal

The kinetic expansion process produces sulfur residue and polyethylene cartridge debris which must be removed. There were concerns over the inherent sulfur residue derived from the explosive material used in the repair process (pentaerythritoltetranitrate), even though the sulfur content as sulfates does not normally exceed 0.5% as sulfuric acid [20]. This concern was partially alleviated by the Licensee's specification that any material, i.e, candles or explosives, to be introduced into the OTSGs contain no more than 250 ppm sulfur and 250 ppm total chlorides and fluorides. Also, the polyethylene cartridge captures a large portion of the reaction products from the detonation. The

*The usage factor is defined as the percentage of the useful life consumed through cyclic loading.

surface contamination problem was further mitigated by precoating the exposed surfaces of the steam generator with which is a water-soluble cleaning agent with no critical contaminants and for which there are extensive application data [15]. The Licensee successfully demonstrated the application of in test mock-ups and Mt. Vernon tests [15].

A remaining concern is the polyethylene cartridge perforation. During preliminary and qualification testing, "blow-throughs" occurred in cartridges [21]. Testing and analyses were conducted by the Licensee to examine the expanded tubes that have experienced blow-through. Metallographic analyses were performed on test specimens to assess the condition of the tube ID at blow-through locations which might experience higher local stresses than any other portions of expanded tubes. The Licensee has not addressed this issue in Topical Report 008 [3], and FRC has not been informed of any action concerning this aspect of the expansion process evaluation.

4.1.8 Effects of the Kinetic Expansion Process on Tube Pretensioning

All tubes of the steam generators were pretensioned at the fabrication stage so that they would not be in compression when cold. According to Para. 3.5.3 of Reference 1, the repaired tube tensile preload shall not be changed by more than ± 30 lb at ambient temperature. This design objective of maintaining the tube preload tension is necessary in order not to change the vibrational characteristics of the tubes.

The change in the pretension in the tubes due to the kinetic expansion process is a direct function of the change in the length of the tubes caused by the repair process. The Licensee conducted induced strain tests on test blocks to take length measurements of tubes before and after the . From the viewpoint of material behavior,

. The net change in length of tubes after may therefore be insignificant, leading to the general belief that the change in tube pretensioning due to the repair process will also be minimal. The Licensee's test results confirmed this belief. Induced

strain measurements taken before and after the expansion process showed maximum longitudinal strain values

which is less than the design limit of 30 lb.

4.1.9 Adequacy of Tube Pullout Strength

The bonding at the interface of the tube and tubesheet produced by the kinetic expansion process is purely mechanical, and the holding strength is the frictional force derived from the contact surface pressure between tube and tubesheet. It is therefore important to maintain tight contact in order to sustain the desired holding strength at the bonding surface.

According to Para. 3.5.2 of Reference 1, the repaired tube is expected to sustain the maximum design basis axial tensile load of 3140 lb from the 177-FA MSLB accident analysis (see Table 5-7 of Reference 16). Satisfying this qualification objective requires that no slippage will occur at a 3140-lb load. The Licensee conducted tube pullout strength tests in accordance with Foster Wheeler Test Procedure No. 5054-QT-9 [11]. The effects of thermal cycling, axial loading, and the number of after-shots on the tube pullout strength were evaluated. Seven 10-tube test blocks were subjected to pullout tests at an ambient temperature of 70°F ± 5°F, and one test block was maintained at an elevated temperature of 330°F during testing.

Several factors interact to influence the elevated temperature pullout strength. These factors include the relative coefficients of thermal expansion of the tubesheet and tubes, the degree of relaxation of the circumferential residual stresses contributing to the tube-tubesheet seal, and the lowering of the yield strength of both the materials. The latter factor is important since overcoming the friction between the two surfaces involves yielding of surface irregularities on the interacting, unbonded components.

The differences in the coefficients of expansion lead to a tighter joint at elevated temperatures, while stress relaxation and a lowered yield strength would degrade pullout capacity both at the elevated temperature and subsequently at lower temperatures. The short-term effect of 610°F temperature

exposure was demonstrated by the Licensee's pullout results after 30 cycles of 70°F to 610°F to 70°F. A slight decrease in pullout at room temperature was noted,

Accordingly, it is unlikely that a more prolonged 600°F exposure would critically degrade the room temperature pullout strength.

The Licensee's pullout tests at 330°F on one 10-tube block which had been thermally cycled as described above gave and a 99/99 statistical confidence of pullout As pointed out by the Licensee, this in mean pullout load at elevated temperature is statistically significant, and it is attributed to the reduction in yield strength of the material at elevated temperature.* No testing was done at the 650°F design temperature. However, when the 330°F data were extrapolated to the 650°F design temperature, a mean slip load of was obtained, and, assuming that the standard deviation would be the same at 650°F as at the 330°F test temperature, it was concluded that the 3140-lb goal would be "easily met". Although it is not clear that the extrapolation is valid, the 3140-lb pullout load goal is so conservative [17] that there appears to be no cause for concern that tube slippage will occur at 650°F under an MSLB.

Additional confidence concerning the adequacy of the repair procedure was gained after the tube pullout test conducted at Mt. Vernon showed a load-carrying capability

4.1.10 Stress Concentration in the Tube Transition Length of Expansion

A requirement imposed on the repair process was that the magnitude of the residual stresses at the transition region between the expanded and unexpanded portions of the tubes on the downstream side of the expansion be minimized in order to reduce the possibility of stress-corrosion cracking. Since an abrupt transition results in higher residual stresses and larger stress concentrations, the goal was to limit the transition length to between 1/8 and 1/4 in

*See footnote on page 9.

(Para 3.6.1 of Reference 1). It was further required that the residual tensile stresses (both circumferential and axial) in the transition region should be less than 45% of the 0.2% offset yield stress at room temperature (Para. 3.6.2 of Reference 1). Stress examinations were conducted at Pennsylvania State University using special X-ray diffraction and strain gage techniques to find post-kinetic expansion tube stresses in the transition area at the bottom of the expansion and at a second point near the middle of the expansion. The Licensee stated that the requirements were met [3]; however, the detailed test results were not made available to FRC at the time of this writing.

4.2 LICENSEE'S EVALUATION PROGRAM OF STRESS AND PERFORMANCE OF TUBE/TUBESHEET ASSEMBLY

4.2.1 Stress and Performance of the Expanded Tubes Subjected to Various Load Conditions

An evaluation was made of the stresses on and the performance of the expanded tubes when subjected to the following load conditions:

a. normal operating pressure

b. thermal transient

c. flow-induced vibration

d. seismic accelerations and displacements

e. loss-of-coolant accident

f. main steam line break.

4.2.1.1 Normal Operating Pressure

The normal operating differential pressure is 1275 psi (Para. 4.4.2 of Reference 1). Seven 10-tube blocks were subjected to a series of water leak tests specified in Foster Wheeler Document No. 5054-QP-1, Rev. 1, Para. 5.4 [11] and Test Procedure No. 5054-QT-6, Rev. 0 [11]. The operating pressure was supplied on the primary side of the tube for six of the test blocks; the seventh block was pressurized on the secondary side (discussion of this is found in Section 4.2.1.5). Results of the leak rate tests performed by GPU Nuclear have demonstrated that the seal between the primary and secondary

throughwall cracks) in tubes, they would remain stable and would not propagate under these loads.

4.2.1.4 Seismic Accelerations and Displacements

According to Para. 3.2.2 of Reference 1, the repaired tube is a Seismic Category 1 component in accordance with Regulatory Guide 1.29 and a Class 1 component in accordance with Regulatory Guide 1.26. The seismic boundary (the portion of the tube/tubesheet configuration which should be seismically qualified) for the expansion extends down to the end of the qualified 6-in length. This change in the structural configuration of the expanded tubes is minor and will probably not produce any significant effect on the performance of tubes subjected to seismic displacement and accelerations. However, the Licensee has not addressed this issue in the Topical Report 008 [3].

4.2.1.5 Loss-of-Coolant Accident

The loss-of-coolant accident (LOCA) is simulated by the pressure loading test described in Section 4.2.1.1. The test pressure of 1275 psi from the secondary side of the tubes is conservative in view of the value of 925 psi given in Reference 16 (pp. 5-6).

4.2.1.6 Main Steam Line Break

A main steam line break (MSLB) subjects the tube to a tension of 3140 lb [16], the highest tension of any design condition. In order to simulate this condition, a pressure of 2500 psi was applied on the primary side (Para. 5.3.1 of Reference 16) in the water leak tests discussed in Section 4.1.4 of this report.

4.2.2 <u>Tubesheet Ligament Strength</u>

An evaluation was made of tubesheet ligament strength due to:

a. change in ligament width after repair
b. warping of the tubesheet.

sides of the tubesheet is functionally effective with leak rates well below the technical specification limit but slightly higher than the repair design objective of a maximum water leakage rate of 1.0 lb/h per plant.

4.2.1.2 Thermal Transient

Reference 22 (the specification for the Licensee's thermal cycling program) states that transient No. 1 (heatup/cooldown) goes from 70°F to 557°F and back to 70°F, and that there are 240 full design cycles to simulate 40 years of service. Also, there are 64 design cycles related to thermal transient loading for reactor trips. To simulate 5 years of service, the test procedure required thermal cycle conditioning of seven 10-tube test blocks from 70°F to 610°F and back to 70°F 38 times (30 heatup/cooldowns and 8 reactor trips) [1]. The effects of these cycles on leak rates and pullout strengths are discussed in Sections 4.1.4 to 4.1.9.

4.2.1.3 Flow-Induced Vibration

A tube vibration test was conducted during the design stage in the 1960s using a typical OTSG Inconel tube with 0.625-in outer diameter, a length of 52 ft 1.375 in, and a wall thickness of 0.035 in [23]. The test specimen, which represented the exposed portion of tube, was fixed at the ends to simulate the effect of the tubesheet and was supported between the ends by supports similar to those in the full-sized unit. The test results demonstrated satisfactory performance of tubes during vibration. Since the expanded portion of the tube inside the tubesheet was not included in the vibration test, the kinetic repair process did not affect the established test results.

According to Reference 3, the Licensee evaluated the effect of a high cycle flow-induced vibration bending load plus a thermally induced steady axial load on tubes. A maximum axial tension of 500 lb can be exerted on tubes due to the shell-to-tube temperature difference during steady state operation. The flow-induced vibration loading combined with a cooldown of 100°F/h can generate a maximum tube tension of 1107 lb. The Licensee's study showed that if there were any undetectable defects (i.e., defects with less than 40%

4.2.2.1 Change in Ligament Width After Repair

According to Reference 3, the test results from test blocks and the Mt. Vernon steam generator showed minimal changes in tubesheet ligament width due to the expansion process.

4.2.2.2 Warping of Tubesheet

There is concern as to whether the process will cause the tubesheet to warp due to nonuniform expansion of the holes through the thickness. It has been postulated by the Licensee that the unit A tubesheet might have already been warped, based on the high concentration of defective tubes in the peripheral area of the tubesheet.

This problem should be addressed by the Licensee (Para. 3.5.4 of Reference 1).

4.2.3 Effect of the Change of Tube Pretension Load

An evaluation was made of the effect of the change of tube pretension load on:

a. frequency of vibration of expanded tubes
b. fatigue life of expanded tubes
c. buckling of expanded tubes.

4.2.3.1 Frequency of Vibration of Expanded Tubes

The amount of pretension to which a tube is subjected affects the natural frequency of the tube, i.e., the higher the pretension, the higher the frequency. If the pretension is altered due to the direct effect of the repair process on the tube or the indirect effect on the tube due to warping of the tubesheet, the natural frequency will change. Various analyses [23] have shown that the change in frequency due to change in tension will be less than 6.5 Hz for a 200-lb difference in tension. The Licensee's test results showed a maximum reduction of   in tube pretension due to the expansion process. Thus, the repair process has a minimal effect on the frequency of vibration of the tubes.

4.2.3.2 Fatigue Life of Expanded Tubes

Since the tube pretension change is small, there is no reason to expect that the fatigue calculations, based on transient loads presented in Reference 16, Para. 6.2.3, would significantly alter the fatigue life of expanded tubes.

4.2.3.3 Buckling of Expanded Tubes

In the absence of pretension, the largest negative load (compression) of -775 lb in the tube occurs during transient No. 1 [Reference 16, Table 5-4]. Since the pretension is 1000 lb, a small perturbation in pretension should not put a tube in danger of buckling, which will occur at about -700 lb [23].

4.3 INDEPENDENT TEST PROGRAM

4.3.1 Test Specimens

All tubes and tubesheet samples tested were supplied by Babcock & Wilcox, along with data characterizing the materials. All samples were heat treated to simulate strength levels and surface conditions in the OTSGs. Drawings of the test assemblies, which were either single-tube or 10-tube mock-ups, are shown in Appendix D.

The test specimens consisted of two 10-tube/tubesheet mock-ups, six single tube/tubesheet mock-ups, and insert assemblies which provided the means of detonation for the expansion process.

One of the 10-tube assemblies was shipped directly to FRC for expansion and subsequent tests. The second was expanded by Foster Wheeler Corp. and then shipped to FRC for similar testing. These two (identical) units are depicted in Figure 1 of Appendix D. The single-tube assemblies and the plastic insert primacord assemblies are seen in Figures 1.1 and 1.2a, respectively, of Appendix D.

4.3.2 Test Procedures

The tests which comprised the independent test program are listed below. A detailed description of the test procedures is given in Appendix D. Some

test data appear in the text of the report; the remainder of the data appear as Appendix E.

The tests were patterned after those conducted by the Licensee [11], thereby providing an independent evaluation of the explosive expansion process. Unless otherwise specified, the tests listed below were performed on one or both of the 10-tube test assemblies. The tests were as follows:

- o receiving and inspection/measurements and marking
- o high yield and low yield tubes identified and marked
- o roll expansion and explosive expansion of one 10-tube assembly (The other was expanded by Foster Wheeler Corp. and delivered to FRC for further testing.)
- o explosive expansion of three single-tube assemblies
- o bubble tests
- o axial load cycling
- o pullout strength tests
- o leak tests (secondary-to-primary, and primary-to-secondary)
- o residual stress measurement
- o micrography.

Dimensional measurements were made at various junctures in the test program.

Certain elements of the test program were deleted, including thermal cycling of all test assemblies. The rationale for deletion of thermal cycling is as follows:

> During service transitions, the maximum temperature difference that can exist between the tubes and the tubesheet at the joint must be very small compared to the temperature difference between the tube in the main body of the generator and in the massive tubesheet. Since the latter temperature differences are responsible for the axial stresses that are included in the axial cyclic tests, and since cycling of hoop and radial stresses will have a negligible influence on tube pullout strength in comparision with that of axial cycling, tubes were not cyclically "conditioned" to simulate thermal gradients betwen the tube and the tubesheet.

A number of tests on the single-tube assemblies were deleted due to budget and schedule considerations. The original intent of these test samples was that they would serve only as "practice" pieces prior to the tests on the larger 10-tube assemblies. The tests which were deleted are so noted in Appendix D.

Two of the single-tube assemblies were instrumented with strain gages in an attempt to measure instantaneous strain during the expansion process. These tests were unsuccessful primarily due to the inability of the strain gages and external wiring to remain mechanically intact during the expansion process.

The requirements that a specific minimum joint strength and a maximum allowable leak rate be maintained for a minimum of 5 years of service operation defined the test parameters. The loading that the tube/tubesheet joint will experience in service over a period of 5 years owing to temperature transitions, including start-ups and shutdowns, was simulated by axial cycling. Following a "conditioning" with the appropriate number of cycles at each service stress range, the tubes were tested for leakage under pressure conditions representative of normal operations and of loss of pressure on either the primary or secondary side. Next, the load required to pull tubes out of the tubesheet was determined.

Thermal conditioning was performed in Foster Wheeler Corporation's qualification test program. Some of these tests were witnessed, and the pullout and leakage data were reviewed (see Section 4.1.7) for tubes so conditioned. Thus, this aspect of simulated service life was more than adequately covered.

No conditioning with simultaneous thermal stress and representative load variations was or will be carried out in any of the various evaluation programs. Such testing should not be required since pullout and leakage results after axial conditioning indicate the tube seal is acceptable.

For some specified tubes, the residual stresses induced in the tubesheet were determined by strain gaging sections of the tubesheet and then machining out the expanded tube.

4.3.3 Leaktightness Tests

Two 10-tube blocks were initially subjected to a low pressure (125 psi) primary-to-secondary bubble test (N11) (Appendix D) to assure that no gross leakage was present prior to any of the load cycling tests. As shown in the test results (Appendix E), a few bubbles did emanate from most tubes, but there was no evidence of a total lack of a tube/tubesheet seal.

Following the axial load cycling to simulate 5 years of service conditions, in which no tube exhibited any sign of slippage, the test blocks were subjected to both primary-to-secondary and secondary-to-primary leakage tests as detailed in the test plan (N17 and N18). The leakage rates after 72 h are summarized below:

Tube Assembly	Pressure (psig)	Pressure Direction	Average Leak Rate per Tube (lb/h)
F-1	1275	Secondary to Primary	6.37×10^{-5}
F-1	1275	Primary to Secondary	2.49×10^{-5}
F-1	2500	Primary to Secondary	2.96×10^{-5}
F-2	1275	Secondary to Primary	1.07×10^{-5}
F-2	1275	Primary to Secondary	1.28×10^{-5}
F-2	1275	Primary to Secondary	1.90×10^{-5}

The qualification leakage goal set by GPU Nuclear was 3.2×10^{-5} lb/h per tube based on a total leakage of 1 lb/h from both OTSGs, whereas the technical specifications limit is 1.0 gal/min (500.22 lb/h) total leakage for both generators. For comparison, the Licensee's tests ranged from 1.18×10^{-6} to 187.4×10^{-6} lb/h per tube. From the data above, it is clear that the leakage rate from block F-1 was about twice that of block F-2. The latter block met the acceptance level goal, whereas the former slightly exceeded this goal for one test condition but was well below the technical specification limit of 500 lb/h. Accordingly, it must be concluded that these tests indicate the kinetic expansion does lead to an adequate leaktight seal between the tube and tubesheet.

4.3.4 Tube Interference Fit and Tubesheet Residual Stress

There were several approaches to evaluating the degree of the interference fit between a tube and the tubesheet. In the 10-tube assembly (F-2) expanded at FRC, the ID and OD of each tube and the ID of the tubesheet hole were measured prior to expansion and the ID of each tube was measured following each expansion. The tubes in F-2 were in two sections: the first 2 in were separate lengths to simulate a full circumferential crack at the 2-in location. These "stub" ends, which initially had been roll-expanded, were exposed to the kinetic expansion process with the 6-in test region. In the data in Table 1, the D_o measurements at the 1-in location reflect the use of different tubing for these stubs, which were not part of the qualification tests.

After the first expansion, the D_1 measurements were essentially the same for all sections of the tubes including the stub ends. The first expansion clearly induced an interference as indicated by the fact that the diametral change due to the first expansion was greater than the tube hole clearance. The diametral change due to the second expansion was at least one order of magnitude smaller than the change from the first expansion. This difference indicates that the second expansion contributed only slightly to the interference fit and that excessive deformation of the tubesheet was not a concern.

The test data for the single-tube blocks 3A and 3D contrast with those for the 10-tube block in several aspects. Not only is the first step diametral change in the single tube less than that for the first step in the tube in the 10-tube assembly, but the total accumulated diametral change after the second expansion, which caused about 1/4 to 1/5 of the total tube expansion, was also less than that for the 10-tube first step. Furthermore, this total diametral change was less than the original tube/tubesheet clearance, indicating a relatively poor tube/tubesheet joint. The basis for this phenomenon appears to be the fact that the simulated tubesheet tube in the single-tube mock-up increased in outside diameter after each expansion, and thus, did not effectively restrict the explosive energy to expanding the

Table 1. Tube and Tubesheet Dimensional Data Demonstrating Effects of Two Expansions

Block F-2
Inside diameter of tube
At 1-in location

Tube	D_o	D_1	D_2	D_1-D_o	D_2-D_1
1	0.5615	0.5653	0.5655	0.0038	0.0002
2	0.5615	0.5652	0.5657	0.0037	0.0005
3	0.5619	0.5657	0.5659	0.0038	0.0002
4	0.5625	0.5652	0.5655	0.0027	0.0003
5	0.5625	0.5649	0.5665	0.0024	0.0016
6	0.5621	0.5662	0.5667	0.0041	0.0005
7	0.5621	0.5661	0.5665	0.0040	0.0004
8	0.5625	0.5678	0.5680	0.0053	0.0002
9	0.5615	0.5673	0.5680	0.0058	0.0007
10	0.5629	0.5668	0.5681	0.0039	0.0013
At 2 1/8-in location					
1	0.5500	0.5653	0.5660	0.0153	0.0007
2	0.5500	0.5649	0.5653	0.0149	0.0004
3	0.5508	0.5660	0.5666	0.0152	0.0006
4	0.5500	0.5649	0.5657	0.0149	0.0008
5	0.5503	0.5645	0.5655	0.0142	0.0010
6	0.5500	0.5653	0.5657	0.0153	0.0004
7	0.5498	0.5657	0.5660	0.0159	0.0003
8	0.5510	0.5662	0.5662	0.0152	0.0000
9	0.5502	0.5652	0.5655	0.0150	0.0003
10	0.5495	0.5650	0.5657	0.0155	0.0007
At 3 1/4-in location					
1	0.5502	0.5648	0.5653	0.0146	0.0005
2	0.5495	0.5665	0.5670	0.0170	0.0005
3	0.5510	0.5660	0.5658	0.0150	-0.0002
4	0.5502	0.5660	0.5661	0.0158	0.0001
5	0.5510	0.5663	0.5667	0.0153	0.0004
6	0.5504	0.5648	0.5651	0.0144	0.0003
7	0.5500	0.5659	0.5661	0.0159	0.0002
8	0.5512	0.5655	0.5655	0.0143	0.0000
9	0.5504	0.5653	0.5658	0.0149	0.0005
10	0.5498	0.5652	0.5655	0.0154	0.0003

D_o = inside diameter of tube before expansion.
D_1 = inside diameter of tube after first expansion.
D_2 = inside diameter of tube after second expansion.
D_1-D_o = diametral change due to first expansion.
D_2-D_1 = diametral change due to second expansion.
Note: All dimensions are inches and measured from the face of the block.

Table 1 (Cont.)

Block F-2

Clearance (calculated from data on first page of Table 1)

At 2 1/8-in Location

Tube	D_{TS}	D_T	$D_{TS}-D_T$	$D_{IN} = (D_1-D_O)-(D_{TS}-D_T)$
1	0.6403	0.6284	0.0119	0.0034
2	0.6400	0.6285	0.0115	0.0034
3	0.6395	0.6284	0.0111	0.0041
4	0.6400	0.6287	0.0113	0.0036
5	0.6390	0.6281	0.0109	0.0033
6	0.6390	0.6289	0.0101	0.0052
7	0.6395	0.6284	0.0111	0.0048
8	0.6400	0.6284	0.0116	0.0036
9	0.6395	0.6283	0.0112	0.0038
10	0.6390	0.6284	0.0106	0.0049

At 3 1/4-in location

Tube	D_{TS}	D_T	$D_{TS}-D_T$	D_{IN}
1	0.6403	0.6284	0.0119	0.0027
2	0.6400	0.6287	0.0113	0.0057
3	0.6395	0.6281	0.0114	0.0036
4	0.6400	0.6285	0.0115	0.0043
5	0.6390	0.6282	0.0108	0.0045
6	0.6390	0.6286	0.0104	0.0040
7	0.6395	0.6281	0.0114	0.0045
8	0.6400	0.6283	0.0117	0.0026
9	0.6395	0.6280	0.0115	0.0034
10	0.6390	0.6283	0.0107	0.0047

D_{TS} = diameter of tubesheet hole before expansion.

D_T = outside diameter of tube before expansion.

$D_{TS}-D_T$ = clearance.

D_{IN} = interference.

Note: All dimensions are in inches.

Table 1 (Cont.)

Test Specimen 3A

At 1-in location

	D_o	D_1	D_2	D_1-D_o	D_2-D_1
Tube inside diameter	0.5495	0.5590	0.5610	0.0095	0.0020
Block outside diameter	1.1420	1.1425	1.1440	0.0005	0.0015
clearance = 0.0112					

At 2 1/8-in location

	D_o	D_1	D_2	D_1-D_o	D_2-D_1
Tube inside diameter	0.5498	0.5580	0.5598	0.0082	0.0018
Block outside diameter	1.1415	1.1440	1.1450	0.0025	0.0010
clearance = 0.0111					

At 3 1/4-in location

	D_o	D_1	D_2	D_1-D_o	D_2-D_1
Tube inside diameter	0.5496	0.5580	0.5602	0.0084	0.0022
Block outside diameter	1.1425	1.1440	1.1445	0.0015	0.0005
clearance = 0.0110					

Note: All dimensions are in inches.

Table 1 (Cont.)

Test Specimen 3D

At 1-in location

	D_o	D_1	D_2	D_1-D_o	D_2-D_1
Tube inside diameter	0.5494	0.5585	0.5610	0.0091	0.0025
Block outside diameter	1.1435	1.1455	1.1455	0.0020	0.0000
clearance = 0.0111					

At 2 1/8-in location

	D_o	D_1	D_2	D_1-D_o	D_2-D_1
Tube inside diameter	0.5520	0.5582	0.5598	0.0062	0.0016
Block outside diameter	1.1435	1.1440	1.1450	0.0005	0.0010
clearance = 0.0132					
Tube inside diameter	0.5496	0.5583	0.5610	0.0087	0.0027
Block outside diameter	1.1428	1.1448	1.1450	0.0020	0.0002
clearance = 0.0110					

Note: All dimensions are in inches.

tube. On the other hand, the larger mass of the 10-tube tubesheet appears to have forced the deformation of the tube.

In an attempt to monitor the strain incurred at the OD of the single-tube tubesheet, strain gages were mounted on the ODs of test blocks which were then subjected to expansion (Tasks N3 and N4). Unfortunately, the shock waves detached the gages or the wire leads; thus, no meaningful data were obtained from these tests.

Strain gages were successfully used in measuring the tubesheet ligament springback which occurred when expanded tubes were machined out of 10-tube block F-1 (Task N21). Based on these tests and the data in Table 2, the following observations were made:

1. In general, some amount of strain relaxation in the tubesheet ligaments occurred in the immediate vicinity of a tube that was partially machined and removed. This phenomenon was more pronounced for tubes with low yield strength, i.e., in ligament 7-10.

2. The stress state of the tubesheet ligaments away from a tube subjected to machining appeared unaffected by the tube removal process.

3. The accuracy of measuring a small amount of strain relaxation in the tubesheet ligaments did not appear to have been affected by the machining process. There were no noticeable rises in the ligament temperature in the area where machining and strain gage data reading took place.

4. The small measured amounts of strain relaxation in the tubesheet ligaments indicate that the kinetic expansion did not induce excessive plastic deformation in the tubesheet nor did it alter the dimensional integrity.

4.3.5 Tube Pullout

The data for tube pullout tests on mock-ups F-1 and F-2 are summarized in Table 3. As discussed previously, six of the tubes in assembly F-1 were left intact in the "tubesheet" so that residual strain measurements could be conducted on the ligaments between tubes on cross sections of the assembly. The qualification pullout load goal of 3140 lb was based on the worst case,

Table 2. Residual Strain Measurements on 10-Tube Block, F-1

Ligament	Strain Levels in Micro Strains (μ in/in)							
	1-4*	1-5	4-5	5-6	6-7	6-10	7-10	Cut Depth (in)
Before clamping	0	0	0	0	0	0	0	
Clamped	-1	0	0	0	+2	-1	+2	
After Tube 1	-60	-24	-1	0	+3	-2	+3	1/4 N-S
Machining out	-56	-35	+1	-1	+3	-2	+3	1/2 N-S
	-44	-27	+2	0	+3	+2	+4	3/4 E-W
After Tube 4	-54	-27	-1	-1	+4	-3	+6	1/2 N-S
	-54	-26	-4	-1	+5	-3	+7	1/2 E-W
	-54	-26	- (a)	-	-	-	-	3/4 E-W
	-54	-27	-3	-2	-	-	-	3/4 N-S
After Tube 5	-	-34	-30	-12	+7	-4	+11	3/4 N-S
	-51	-36	-30	-46 (b)	+7	-5	+11	3/4 E-W
After Tube 6	-51	-	-38		-19	-12	-2	3/4 EWNS
After Tube 7	-50	-40	-35		-48	-16	-115	3/4 NSEW
After Tube 10	-50	-41	-35		-36	+15	-223	3/4 NSEW
Unclamped	-50	-42	-36		-35	+17	-226	

Note: N-S and E-W are arbitrary north-south and east-west locations at which the tube was milled away to the tubesheet to the depth indicated.

*See Figure 1.2.b.
a. - indicates reading did not change.
b. Gage disconnected, reading doubtful. No further readings possible.

MSLB-induced thermal length changes of the tube and tubesheet/shell assembly. Since an elongation strain of 0.0016 in/in in each tube would nullify the thermal length change differences [15], the stress on each tube is strain limited. Accordingly, in the qualification tests, if there was no slippage or reduction in load prior to 0.0016 in/in elastic plus plastic strain, the joint would clearly be adequate for generator service. However, the load to cause this strain could be less than 3140 lb, and in keeping with the original qualification goals, the tests on block F-1 were continued until the maximum load that could be sustained by the joint was achieved.

As shown in Table 3 for test block F-1, the total elongation at maximum load of each tube relative to the bottom surface of the tubesheet was well above 0.016 in, the elongation corresponding to 0.0016 in/in strain in a 10-in-long tube. The elongations on the high yield (HY) tubing were about half those for the low yield (LY) tubing, consistent with the larger amount of plastic deformation in the latter. These results clearly indicate the ability of the joint to satisfy the pullout strength goals.

For block F-2, the total tube movement (elastic and plastic deformation plus any slippage) was monitored and loads were determined for yielding (when the load versus time curve under constant loading rate deviated from linearity). As can be seen in Table 3, as expected, the load on each low yield tube at yielding was close to or below the 3140-lb goal. At elongation of 0.030 in (0.003 in/in strain) and 0.060 in (0.006 in/in strain), the maximum load had not yet been reached in any tubes, but the elongations were so much larger than could be expected on actual steam generator tubes that tests were not continued to actual pullout.

4.4 ONSITE MONITORING OF REPAIR PROCESS

Repair processes performed on the TMI-1 A and B steam generators were monitored by means of a series of telephone conversations with the resident NRC inspector, Mr. Skip Young, and by visiting the site to confirm that repairs were proceeding in a generally satisfactory manner.

Table 3. Summary of Tube Pullout Testing

A. Block F-1

Tube	Strength	Max. Load (lb)	Tube Elongation at Max. Load (in)
2	HY	4100	0.051
3	LY	4000	0.105
8	HY	4050	0.041
9	LY	3800	o.092

B. Block F-2

Tube	Strength	Yield Load (lb)	Load (lb) at 0.030 in	Load (lb) at 0.060 in
1	HY	3800	3900	4120
2	HY	3500	3740	3900
3	LY	3200	3275	3500
4	HY	3750	3800	4000
5	HY	3700	3820	4000
6	LY	3034	3275	3450
7	LY	2900	3090	3275
8	HY	3750	--	4060
9	LY	3170	3430	3675
10	LY	3150	3300	3500

It was determined that there were some early problems with ignition of the ordnance cord. This cord communicates detonation from a single point, an electric blasting cap, located outside the steam generator, to each part of located within plastic tubes (candles) in the tubes of the generators. Where detonation failed to occur, in the bundle did not receive enough energy to initiate them reliably; the problem was solved by using

Another factor contributing to the early difficulties was what was thought to be a "bad batch" Subsequent batches performed reliably and this, resulted in a very high percentage of successful detonations.

At the time of the first site visit, diametral measurements were being made at 1-in spacings along the longitudinal axis of the tube. Although there was some difficulty in the interpretation of the results, it was determined that the expansions were within previously defined diametral limits. No adverse reports have been received following the initial problems.

Eddy current testing for crack detection was begun immediately after the first expansions were made. First examinations showed indications of defects that had not been detected earlier. As discussed in Section 4.1.4, the Licensee concluded that these indications were primarily pits and scratches which were detected by eddy current testing equipment more sensitive than that used previously and that these defects would not influence the reliability of the joints.

Cleanup after expansions was difficult. The plastic candles adhered tenaciously to the tube wall and blasting air from the bottom of the generator was ineffective. Pressure from the underside of the candle was increased to 700 psi to make the process more efficient.

It appears that the repair procedures were conducted according to the qualification program set forth by GPU Nuclear and its contractors. In the case of the early detonation failures, the number of repeated hits on tubes that had already been expanded could increase chances of leakage, but planned bubble leak tests should indicate such leakage. It would be well to pay particular attention to the regions of the generators where these repeated hits occurred.

5. OPEN ITEMS

As ..dicated previously, at the time of issuance of this report, several open items remain to be addressed by the Licensee. While some or all of these may have been dealt with, no information on them has been received. Thus, these topics are listed below:

a. an evaluation of warpage distortion, if any, of the tubesheets of the TMI-1 OTSGs

b. a consideration of the number and severity of candle "blow-throughs," the possible effects of these blow-throughs on the cleanup of tubes, and the residual stresses and stress-concentrating effects associated with these blow-throughs

c. an evaluation of the validity of extrapolating ?30°F pullout load test data to 650°F

d. the conclusions concerning the X-ray measurements of the residual stresses in kinetically expanded tubes (work done at Pennsylvania State University).

It is not expected that any of the above items will be critical to the generator's return to service. However, an accurate appraisal of the expected long-term life of the generator requires that they be fully taken into account.

6. CONCLUSIONS

Based on the evaluation of the Licensee's qualification program and the results of the independent test program, the following conclusions have been reached:

1. The kinetic (explosive) expansion technique is an effective means for repairing the cracked tubes in the TMI-1 once-through steam generators (OTSGs). By forming a new tube/tubesheet seal joint below the cracks in the tubes, the cracked regions are essentially removed from the system.

2. expansion procedure accomplishes a tight seal without excessive deformation of the tubesheet.

3. In order to maximize the number of tubes that can be salvaged, all tubes were expanded for 17 in. The lower 6 in of this was the length qualified in the Licensee's test programs and evaluated in FRC's independent test program. It is expected that tubes with defects up to 11 in below the upper face of the tubesheet can be repaired in this manner and that tubes with defects between 11 and 16 in below the upper face of the tubesheet will be repaired by reexpanding a 22-in length.

4. It is anticipated that after the tubes have been expanded, a seasoning will be required to reduce leakage to acceptable levels. Both the Licensee's and FRC's test programs have shown that the probable leak rate is well below the Technical Specification of 0.016 lb/h per tube, and approaches the qualification goal of 3.2×10^{-5} lb/h per tube.

5. In general, the results of testing and analysis have been favorable in terms of having met the Licensee's qualification requirements. Thus, to the extent that the test assemblies represent a reasonable simulation of the TMI-1 OTSG, the repair process implemented at TMI-1 should meet its objectives.

   A list of open or unresolved items (to FRC) is presented in Section 5. It is not expected that any of these items will be critical to the generator's return to service. However, an accurate appraisal of the expected long-term life of the generator requires that they be fully taken into account.

It should also be emphasized that there are some fundamental differences between the test assemblies and the actual generator which could affect the success of the repair process. These differences are as follows:

a. length of expansion
b. number of tubes simultaneously expanded
c. tube length (different impedance to expansion)
d. geometry of tubesheet
e. variation in tube-to-tubesheet crevice conditions.

It is not anticipated that these differences will have a major adverse impact on the effectiveness of the repair process. In this regard, the hot functional tests in the start-up program should critically evaluate the state of the generators.

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Test Procedure No. 5054-QT-3, Rev. 2, Kinetic Expansion of Tubes in Tube Blocks

Test Procedure No. 5054-QT-4, Rev. 0, Kinetic Expansion Proof Load Test

Test Procedure No. 5054-QT-5, Rev. 1, Kinetic Expansion Thermal Cycle Conditioning

Test Procedure No. 5054-QT-6, Rev. 0, Kinetic Expansion Hydrostatic Leak Testing

Test Procedure No. 5054-QT-9, Rev. 1, Kinetic Expansion Tube Pullout Tests

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PROPRIETARY

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APPENDIX A

DOCUMENTS RECEIVED

APPENDIX A

DOCUMENTS RECEIVED FOR C5506, ASSIGNMENT 10

1. M. J. Graham
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   E&L: 4434

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   Equipment Specification for Once Through Steam Generator
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3. R. E. Ham
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7. C. E. McCracken
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10. J. D. Jones, R. L. Jones, and J. S. Olszewski
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QA Data Package: 10-Hole Tubesheet Mockup with Low and High Strength Short and Long Tube Pieces
Babcock & Wilcock, 18-Aug-82
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Foster Wheeler Development Corp., 09-Aug-82
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Babcock & Wilcox, 00-Oct-80
BAW-10146

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36. R. Marshall
Letter to T. A. Shook, FRC. Subject: Transmittal of Comments Regarding Kinetic Expansion Demonstration of August 5, 1982
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5054-PT-2, Rev. 2

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Affidavit Concerning the Designation of Proprietary Material
Babcock & Wilcox, 22-Sep-82

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Foster Wheeler Development Corp., 22-Sep-82
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40. TMI-1 Steam Generators Repair Qualification Program for Kinetic Tube Expansion: Kinetic Expansion Induced Strain Test
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Letter to T. Shook, FRC. Subject: TMI-1 Kinetic Expansion Repair Program; Residual Stress Measurements Procedure
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58. V. Benaroya
Memo to J. Stolz. Subject: Evaluation of TMI-1 Plant Safety Subsequent to Recovery from OTSG Corrosion Problems
USNRC, 28-Jan-83

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Letter to H. D. Hukill, GPU Nuclear. Subject: Assessment of TMI-1 Plant Safety for Return to Service After Steam Generator Repair. Request for Additional Information.
USNRC, 07-Feb-83

60. C. McCraken
Memo to L. Frank, S. Kirslis, J. Rajan, D. Sellers, P. Wu. Subject: Preparation of TMI-1 SER for Restart Subsequent to the OTSG Repairs
USNRC, 08-Mar-83

APPENDIX B

MEETINGS ATTENDED

APPENDIX B - Meetings Attended

Date	Site	Purpose
June 11, 1982	Bethesda, MD	Finalize scope of work on Assignment 10
June 22	Livingston, NJ	FW presentation of technical details of explosive process
June 28, 29	Bethesda, MD	GPUN presentation of background details of OTSG failure analysis
July 21	Livingston, NJ	Qualification program schedule
August 5	Mt. Vernon, IN	Multiple tube expansion demonstration; meeting with consultant
August 12, 13	Livingston, NJ	Witness expansion of 10-tube block assembly
August 20	Lynchburg, VA	Discuss details of FRC RAI
August 26	Livingston, NJ	Witness Licensee tests
September 10	Philadelphia, PA	FW/BW witness of 10-tube block expansion
September 15	Bethesda, MD	GPUN presentation on repair process
October 18	Bethesda, MD	Finalize Licensee plans
October 28	Harrisburg, PA	Witness production tube expansion

APPENDIX C

STATEMENT OF CONSULTANT

Franklin Research Center
A Division of The Franklin Institute
The Benjamin Franklin Parkway, Phila., Pa. 19103 (215) 448-1000

TRIP REPORT

KINETIC EXPANSION DEMONSTRATION
MT VERNON, INDIANA

AUGUST 5, 1982

The kinetic expansion demonstration performed by Foster Wheeler and B & W in the B & W Mt Vernon plant.

As we are all aware, the kinetic technique for expansion of tubes in steam generators is a very acceptable one that has been used by suppliers for the last twenty (20) years. There is no question that this technique is a very acceptable one for Three Mile Island steam generator, however, I cannot over stress the importance of using the right variables in this program.

Some of the more important considerations are:

1) The air gap between the candle and the tube prior to the expansion. Large air gaps will tend to fragment the candle. It was noted in this demonstration that a large number of candles were fragmented which adds to the time required in high radiation levels for clean up.

2) It is important to have knowledge to the hardness factor range of the tubes in a unit since this is directly related to the required force for proper expansion.

3) To minimize the amount of candle rupture there have been some techniques used in the past that may be considered, such as: bringing the candle temperature down by refrigeration into the 40-45 degree range prior to installation. Again, the main concern being the amount of time it would take for the cleaning of the unit.

48TB-311

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September 24, 1982

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Mr T A Shook
Franklin Research Center
A Division of Franklin Institute
20th and Race Streets
Philadelphia, Pennsylvania 19103

Dear Mr Shook:

Attached for your review are my comments regarding the Kinetic Expansion Demonstration at Mt Vernon, Indiana on August 5, 1982.

Should you have any questions concerning the information contained in the attachment, please feel free to contact me at the above referenced address.

Very truly yours,

R Marshall

RM:jkb:hs
Attachment

cc: J E Ramondo - NYO

It has been the writer's experience using this expansion technique that, upon the performance of a hydro on completion of the program, there will be numerous slight tube weepage. This weepage will disappear when the unit is subjected to a hot flow of water through the secondary side which will develop an iron oxide in the annulus between the tube and the tube sheet. Much research in this area has been done by the industry and this reaction has been verified.

Because of the high radiation levels in the units and the potential airborne contamination that will develop during this program, I cannot over stress the importance of the development in techniques to shorten the exposure time in the placement, removal and cleanup.

Robert Marshall

APPENDIX D

TEST PROCEDURES

Franklin Research Center
A Division of The Franklin Institute
The Benjamin Franklin Parkway, Phila., Pa. 19103 (215) 448-1000

TASK N1 - RECEIVING, INSPECTION, AND MARKING OF SPECIMENS

1.1 GENERAL

All materials (tubes and tube blocks) received will be subjected to the following procedure:

-Inspect for conformance of configuration of the 10-tube blocks in accordance with B&W Dwg. 1134899D, Rev. 4 (Figure 1.0) and of the one-tube blocks in accordance with B&W Dwg. 1134900A (Figure 1.1).

-Visually inspect and confirm oxide coatings on tube holes and the tubes, and note presence of any contaminants and rust. Do not disturb oxide coatings except to measure tube dimensions outside of test region.

-Visually inspect for identification per B&W certificates to verify traceability and for damage, including evidence that moisture protection had not been maintained during shipment.

-Record inspection acceptance or discrepancy on test log sheet.

-Review certificates, test reports, etc. received for each item received as follows and as applicable:

(a) Stress Relieve Treatment
(b) Oxide Coatings Parameters
(c) Material Test Reports
(d) Dimensional Data Report
(e) Certificates of Conformance

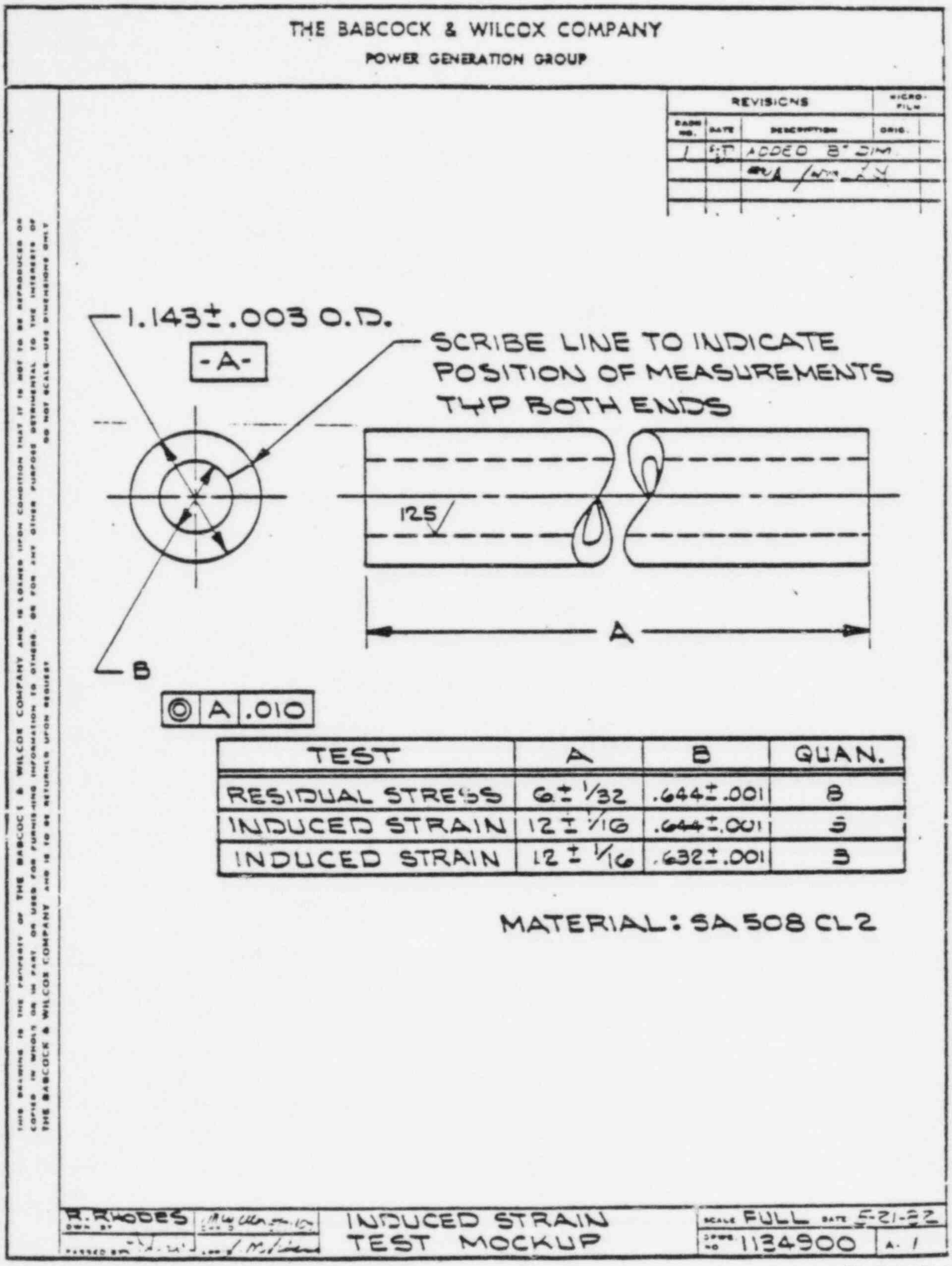
-Verify markings of acceptable items for maintaining traceability to B&W markings, heat numbers etc.

-Test blocks shall be stored to prevent oxide coatings deterioration by placing in an oven or in a plastic bag with B&W-supplied desiccant. Prevent contact of desiccant with oxide surface.

-Items will be allowed to come to ambient temperature prior to test.

1.2 TUBES

ASME SB-163 Inconel 600 tubes (0.625-in OD x 0.034-in minimum thickness), after stress relieving and with surface conditioning simulating oxidation conditions at TMI-1 steam generator upper



TEST	A	B	QUAN.
RESIDUAL STRESS	6 ± 1/32	.644 ± .001	8
INDUCED STRAIN	12 ± 1/16	.644 ± .001	5
INDUCED STRAIN	12 ± 1/16	.632 ± .001	3

Figure 1.1. Induced Strain Test Mock-up

tubesheet crevice, will be supplied by Babcock & Wilcox. It is essential that this oxide condition at tube OD in the region to be expanded remain undisturbed during all pre-expansion steps. Tubes may be either high yield or low yield specimens. Each tube shall be identified as to whether it is a high yield or low yield specimen. Tubes shall be marked with "H" for high yield and "L" for low yield. Tube yield strength data obtained from tube tensile tests (Procedure No. 5054-QT-2) will be recorded on data sheets when available.

1.3 10-TUBE TEST BLOCKS

Stress-relieved ASME SA-508 CL. 2 test blocks (12 in thick) with 10 gun-drilled holes per block will be used. Details of the assembly are seen on Figure 1.0. The holes will be drilled to a triangular pitch of 0.875 in. The nominal hole diameter will be 0.644 in. The hole surface will be conditioned to simulate oxidation conditions at TMI-1 steam generator upper tubesheet crevice. It is essential that this oxide condition remain undisturbed during all pre-expansion steps. The block OD will be sized to accommodate a standard Schedule 160 pipe cap for sealing during leak testing. Two test blocks with the above description will be supplied by B&W and protected from moisture during shipment. One test block will be supplied completely assembled with tubes expanded. The other test block will be supplied with tube (part 7) rolled in place with remainder of assembly by FRC.

Care must be taken while handling the blocks to prevent disturbing the oxide conditioning in the block holes in the region to be expanded.

1.4 ONE-TUBE BLOCKS

Stress-relieved ASME SA-508 CL. 2 test blocks (12 in thick) with a gun-drilled hole will be used. See Figure 1.1 for schematic. The hole surface will be conditioned to simulate oxidation conditions at TMI-1 steam generator upper tubesheet crevice. It is essential that this oxide condition in the holes in the regions to be

expanded remain undisturbed during all expansion steps. Six test blocks with the above description will be supplied by B&W and protected from moisture during shipment.

1.5 POLYETHYLENE INSERTS

Low-density polyethlene pentrothene NA 301, polyethylene resin, melt index 1.2, density 0.917 inserts will be procured from the Thielex Plastic Corporation. They will have a configuration shown in Figure 1.2a. Dimensions for inserts will be inspected to the requirements of Figure 1.2a.

1.6 DETONATION CORD

Detonation material for the kinetic expansion will be purchased from the Ensign Bickford Company.

Grain size certifications will be filed in the data log sheet. The cord will be analyzed for grains/ft every 50 ft and recorded in the data log book. Detonation cord will be stored in an isolated magazine area.

1.7 Six (6) test specimens No. 3 shall be supplied. They shall be marked 3A, 3B, 3C, 3D, 3E, and 3F. The Licensee shall supply

The tube block shall be marked by etching on the outside surface at no more than 1 in from end of tube block. Marked end shall be considered the secondary end of the tube block. The tubes shall be marked by etching on the outside surface at no more than 1 in from end of tube. Marked end shall be the secondary end of the tube. Tubes 3A, 3B, and 3C are to be high yield tubes. Tubes 3D, 3E, and 3F are to be low yield tubes.

1.8 Keep the test specimens 3C and 3F unassembled in case additional tests need to be performed.

1.9 Take the assembled tube/tubesheet and, with reference to Dwg. 1134899D, Rev. 4 (Figure 1.0), mark "F1" on test specimen parts No. 2, No. 3, No. 5 and No. 6; subsequently, unscrew part No. 3 and mark the tubes at the primary side from 1 to 10 as show in Figure

1.2b. Mark the primary side with "P" located above tube 2 as shown in Figure 1.2b.

For reference, row 1 consists of tubes 1, 2, and 3, row 2 consists of tubes 4, 5, 6, and 7, and row 3 consists of tubes 8, 9, and 10.

1.10 Unscrew part No. 5 and mark the secondary side with "S" located above tube 2, and mark the tubes at the secondary side from 1 to 10 corresponding to the numbers at the primary side as shown in Figure 1.2c.

1.11 Take the unassembled tube/tubesheet components and, with reference to Dwg. 1134899D, Rev. 4 (Figure 1.0), mark "F2" on the parts No. 2, No. 3, No. 5, and No. 6.

1.12 Identify the location of tube hole 2 on the primary side, reference end with tubes rolled in place, and location of high yield and low yield tubes, part No. 7, and mark the primary side of part No. 2 with "P" located above tube hole 2 as shown in Figure 1.2b. Mark all holes at the primary side from 1 to 10 as shown in Figure 1.2b.

1.13 Mark the secondary side with "S" located above tube hole 2 and mark the tube hole at the secondary side from 1 to 10 corresponding to the numbers at the primary side as shown in Figure 1.2c.

1.14 Select the high yield and low yield tube specimens (part No. 8) for proper assembly in accordance with the tube specifications shown in Figures 1.2b and 1.2c. Mark the tubes from 1 to 10 for proper assembly with tube holes of part No. 2. The tubes shall be marked by etching on the outside surface at no more than 1/2 in from end of tube. Marked end shall be considered secondary side of tube.

TASK N2 - MEASUREMENTS OF TEST COMPONENTS

2.1 Prior to expansion, test specimens must be stored in an oven or in a plastic bag with B&W-supplied desiccant to prevent oxide coatings deterioration. Prevent contact of desiccant with oxide surface.

2.2 Take the assembled test specimen "F-1" and measure the inside diameter of each tube at 1, 2-1/8, and 3-1/4 in from the primary face of the tube block. Record data.

2.3 Before assembly of each single tube block (see Figure 1.1) and corresponding tube, measure the length of the tube and tube block and measure the outside and inside diameters at 1 in, 2-1/8 in, and 3-1/4 in from the primary (unmarked) end of both tube and tube block. Care must be taken to avoid disturbing the oxide conditioning in the tube block hole and on the tube outside diameter in the region to be expanded. Take dimensions at 90° to strain gage location (reference paragraph 3.2) after strain gages are installed.

2.4 Before explosive expansion of test specimen "F-2," measure the inside diameters of each rolled tube or tube hole at 1 in, 2-1/8 in, and 3-1/4 in from the primary face of the 10-tube block. Measure the outside diameter and inside diameter at 1/8 and 1-1/2 in from the expansion (unmarked) end of each tube. Care must be taken to avoid disturbing the oxide conditioning in the tube block hole and on the tube outside diameter in the region to be expanded.

TASK N3 - INSTALLATION OF STRAIN GAGES FOR SINGLE TUBE BLOCKS

3.1 Prior to expansion, test specimens must be stored in an oven or plastic bag with B&W-supplied desiccant to prevent oxide coatings deterioration. Prevent contact of desiccant with oxide surfaces.

3.2 Take single tubesheet specimens marked 3A and 3D and, before expansion, install two element rosette 90° planar strain gages along two axial lines, 180° apart, on the outside surface of each tubesheet. Three strain gages are to be located on each axial line at 1 in, 3-1/4 in, and 5-1/2 in from the primary end of the tubesheet. Axial lines shall be referenced A and B and readings shall be labeled 1A, 3-1/4A, 5-1/2A, 1B, 3-1/4B, and 5-1/2B. All strain gages shall be zeroed and connected to a magnetic recorder for recording of strain during explosive expansion.

TASK N4 - EXPLOSIVE EXPANSION OF SINGLE TUBE MOCKUPS

Install tube section for specimen 3C into corresponding single tube block so that the primary tube end is flush with the primary face of the block.

Maintain the tube and block temperature during these and subsequent operations between 60°F and 100°F.

Insert detonation cord lengths into each plastic so that the tapered end is flush with the detonating cord. Heat-fuse cord with its plastic on this end.

At the expansion site, into the test hole from the primary face for first step of expansion. Tape the end of the cord-plastic assembly and the tail cord together. Then tape the detonating cap to the end of the "tail" cord. Plastic insert shall rest on the tube end.

Remove spent items and clean the test specimen of deposit left by explosion.

Install tube sections for specimen 3F into corresponding single tube block so that the primary tube end is flush with the primary face of the block.

TASK N4 - EXPLOSIVE EXPANSION OF SINGLE TUBE MOCKUPS

Expand tube/tubesheet 3F in accordance with paragraphs 4.2 through 4.10.

Install tube section for specimen 3A into corresponding single tube block so that the primary tube end is flush with the primary face of the block.

Maintain the tube and block temperature during these and subsequent operations between 60°F and 100°F.

Insert detonating cord lengths into each plastic so that the tapered end is flush with the detonating cord. Heat-fuse cord with its plastic on this end.

At the expansion site, connect tape recorder for recording of strain readings during explosion expansion (reference paragraph 3.2 of task N3).

Remove spent items and measure and record the outside diameter and the length of the tube block and the inside diameter and length of the tube. Outside and inside diameters shall be taken at the three strain gage sections, 90° to strain gage locations, referenced at 1 in, 2-1/8 in, and 3-1/4 in from primary face of test block.

TASK N4 - EXPLOSIVE EXPANSION OF SINGLE TUBE MOCKUPS

Remove the strain gages and clean the test specimen of adhesive used for strain gages, debris, and deposits left by explosions.

Install tube sections for specimen 3D into corresponding single tube block so that the primary tube end is flush with the primary face of the block and explosively expand specimen 3D using the same procedure as for specimen 3A given in paragraphs 4.14 through 4.23.

Remove the strain gages and clean the test specimen 3D of adhesive used for strain gages, debris, and deposits left by explosions.

TASK N5 - BUBBLE TEST FOR SINGLE TUBE/TUBESHEET

5.1 For the test specimens 3A, 3C, 3D, and 3F, perform a secondary-to-primary-side bubble test, using 125 ± 10 psi nitrogen. The test shall be made at 70°F ± 15°F.

5.2 Connect N_2 bottle with pressure regulator, shutoff valve, and precision pressure gage (range 0 to 200 psi) at the extended tube end (secondary side).

5.3 Immerse the entire test setup in a container filled with distilled water.

5.4 Apply 125-psi pressure using N_2 bottle and pressure regulator at the secondary side of the tubesheet, and check for leakage in the test setup.

5.5 If there is no leakage between the above parts and the pressure at the secondary side is steady and equal to 125 psi, start the bubble test: close the shutoff valve and start the clock at the same time; record the pressure versus time until the pressure falls to 10 psi. NOTE: Any leakage at gage, valve, or tubesheet connection is unacceptable since it will give a false reading.

5.6 Note size, location, and rate of air bubbles if any.

5.7 Terminate test after 2 hours.

(Test deleted)

TASK N6 - PULLOUT AND AXIAL LOAD TEST FOR SINGLE TUBE/TUBESHEET

6.1 Remove excess length of tube (tubesheet assembly 3C) by cutting at approximately 2 in from secondary face of tubesheet.

6.2 Weld tube plug in secondary end of tube.

6.3 Measure extension of tube from the secondary face. Measure from tubesheet face to plug face.

6.4 Place tube/tubesheet assembly into Instron testing machine using fixtures as shown in Figure 6.0a.

6.5 Using Instron machine, perform the following axial load cycling test at ambient temperature of 70°F ± 10°F:

a. 100 cycles 780 lb compression to 1110 lb tension
b. 180 cycles 635 lb compression to 175 lb tension
c. 6040 cycles 510 lb compression to 125 lb compression

The specified cycles should be applied at not more than 1 Hz frequency. The tolerance on all cycling forces should be ± 5 lb. The tube subjected to the cyclic loads should be aligned with the center line of the actuator applying the load. Record all loading.

6.6 Remove tube/tubesheet and axial load fixtures from testing machine.

6.7 Measure extension of tube from secondary face. Measure from tubesheet face to plug face.

6.8 Place tube/tubesheet into testing machine for pullout (pushout) test using fixtures as shown in Figure 6.0.

6.9 Place grit into each tube to a level within 1/4 in of the secondary tubesheet face and install pushrod on top of grit.

6.10 Apply load gradually, approximately 10 lb/sec. Record load and tube movement relative to tubesheet at both primary and secondary faces. Visually monitor tube behavior. Continue test until relative movement at primary end is at least 0.030 in. Accuracy of relative displacement measurement should be ± 0.0001 in.

6.11 Remove tube/tubesheet and pullout fixture from test machine.

6.12 Measure extension of tube from secondary face. Measure from tubesheet face to plug face.

6.13 Repeat procedure of paragraphs 6.1 through 6.12 for tube/tubesheet assembly 3F.

(Test deleted)

TASK N7 - MICROGRAPHY

7.1 Cut the tube/tubesheet assemblies 3A and 3D at 1 in, 3-1/4 in, and 5-1/2 in from the primary face of the tubesheet (reference Figure 7.0). Care should be taken to avoid excessive roughing of the surface or inducing of strain in the tube or tubesheet during saw cutting.

7.2 Prepare the primary face (reference surface in Figure 7.0 marked 1P) of the 1 in to 3-1/4 in block and both faces of the 3-1/4 in to 5-1/2 in block (reference surfaces in Figure 7.0 marked 3-1/4P and 5-1/2S) for micrography by polishing these surfaces.

7.3 Perform micrography of the polished faces, references 1P, 3-1/4P, and 5-1/2S.

7.4 Etch faces 1P, 3-1/4P, and 5-1/2S and perform micrography of these polished and etched faces.

(Test Deleted)

TASK N8 - RESIDUAL STRESSES

8.1 After micrography is completed, install three (3) double strain gages on each of the polished and etched faces (reference surfaces in Figure 7.0 marked 1P, 3-1/4P, and 5-1/2S). Strain gages are to be mounted as close as possible to the inside diameter of the tubesheet at 120° intervals about tubesheet centerline.

8.2 Zero all strain gages and subsequently machine inside tubes so that they can be collapsed and removed. Remove inside tubes and record strain gage readings.

(Test deleted)

TASK N10 - EXPLOSIVE EXPANSION OF SPECIMEN "F-2"

10.1 Install the 10 tubes (part No. 8, Dwg. 1134899D, Rev. 4, Figure 1.0) from the secondary side, matching the numbers on the tubes with the numbers of the holes in the tubesheet and butting unmarked (primary) end of each tube (part No. 8) against rolled tube (part No. 7). All 10 tubes are to be in place during explosive expansion of any one tube. Secure in place without staking.

10.2 Maintain the tubes and block temperature during these and subsequent operations between 60°F and 100°F.

10.5 Cut detonation cord lengths for each tube expansion equal to the length of expansion

10.6 Insert detonating cord lengths into each plastic so that the tapered end is flush with the detonating cord. Heat-fuse cord

TASK N9 - ROLL EXPANSION OF SPECIMEN 2

9.1 Install the 10 tubes (part No. 7 in Dwg. 1134899D, Rev. 4, Figure 1.0) from the primary side, one by one, matching the numbers of the tube with the numbers of the holes. The tube should project 3/16 ± 1/64 in above the primary side of the tubesheet. Each tube shall be roll expanded at the primary end to 55 in-lb for a depth of 1-1/4 in from the tube end.

9.2 After roll expansion, measure inside diameters of rolled tubes per paragraph 2.4.

with its plastic on this end.

10.7 If applicable, prepare detonating cord "tails" to facilitate simultaneous expansion of more than one tube and to keep detonating "cap" debris away from test face.

10.8 At the expansion site, insert proper 8-in-long plastic insert primacord assembly from the primary face of the test block into the proper tube. Reference proper tube and primacord assembly from expansion sequence given in paragraph 10.4 above. Reference proper primacord assembly from paragraph 10.6. Tape the end of each cord-plastic assembly and the tail cord together. Then tape the detonating cap to the end of the "tail" cord. Plastic insert shall rest on the tube end. Cover unshot holes with rubber plugs to protect from debris.

10.9 Perform detonation, remove spent items, and record expansion on test log sheet. **If misfire occurs, take corrective action to expand tube. Do not proceed to subsequent sequence until tube has been expanded.**

10.13 **After completion of expansion of all tubes** **measure** and record the inside diameter of each tube hole at 1, 2-1/8, and 3-1/4 in from the primary face of the 10-tube block.

TASK N11 - BUBBLE TEST FOR SPECIMENS F-1 and F-2

11.1 For test specimens F-1 and F-2, perform a secondary-to-primary-side bubble test using 125 ± 10 psi nitrogen. The test shall be made at 70°F ± 15°F in distilled water and at a maximum depth of 15 in.

11.2 Weld tube plugs, part No. 9, in secondary end of tube (reference Figure 1.0, B&W Drawing 1134899D, Rev. 4). Welded plugs must be air-tight. Check air-tight welds by immersion of block in distilled water.

11.3 Assemble welded end cap, reference part (5) and (6), on secondary end of part (2) against a gasket to obtain a leak-free connection between tubesheet and end cap.

11.4 Connect N_2 bottle with pressure regulator, shutoff valve, and precision pressure gage (range 0 to 200 psi) at the provided coupling in part (6) (see Figure 11.0 for test setup).

11.5 Immerse the entire test setup in a container filled with distilled water.

11.6 Apply 125 psi pressure using N_2 bottle and pressure regulator. Check to insure that there is no leakage between parts (2) and (5), parts (5) and (6), or in any connection of the N_2 source.

11.7 Start the bubble test by setting pressure at 125 psi and then closing the shutoff valve. Record pressure versus time after closing of shutoff valve. Record by reading pressure gage at 5-psi or 1/2-hour intervals, whichever occurs first, for a minimum of 2 hours. Record water temperature at same intervals.

11.8 Check tube/tubesheet assembly for gas bubbles. Note the size, location, and frequency of any bubbles. Make a video record of bubbles.

11.9 For test specimens F-1 and F-2, perform a primary-to-secondary-side bubble test using 125 ± 10 psi nitrogen. The test shall be made at 70°F + 15°F in distilled water and at a maximum depth of 15 in.

11.10 Assemble end cap, reference part (3), on primary end of part (2) against a gasket in order to retain a primary side pressure.

11.11 Immerse the entire test setup in a container filled with distilled water.

TASK N11 - BUBBLE TEST FOR SPECIMENS F-1 and F-2

11.12 Apply 125 psi ± 10 psi pressure using N_2 bottle and pressure regulator. Check to insure that excessive leakage does not occur at the gasket and that pressure can be maintained for a minimum test period of 2 hours.

11.13 With pressure maintained at 125 psi ± 10 psi, start the test by checking the secondary end of the tubesheet for gas bubbles at the tube/tubesheet interfaces and at the weldment of each tube plug. Note and record the time, size, and location of any bubbles that are released from the specimen during 0 to 5 min, 30 to 35 min, 60 to 65 min, and 115 to 120 min of test period.

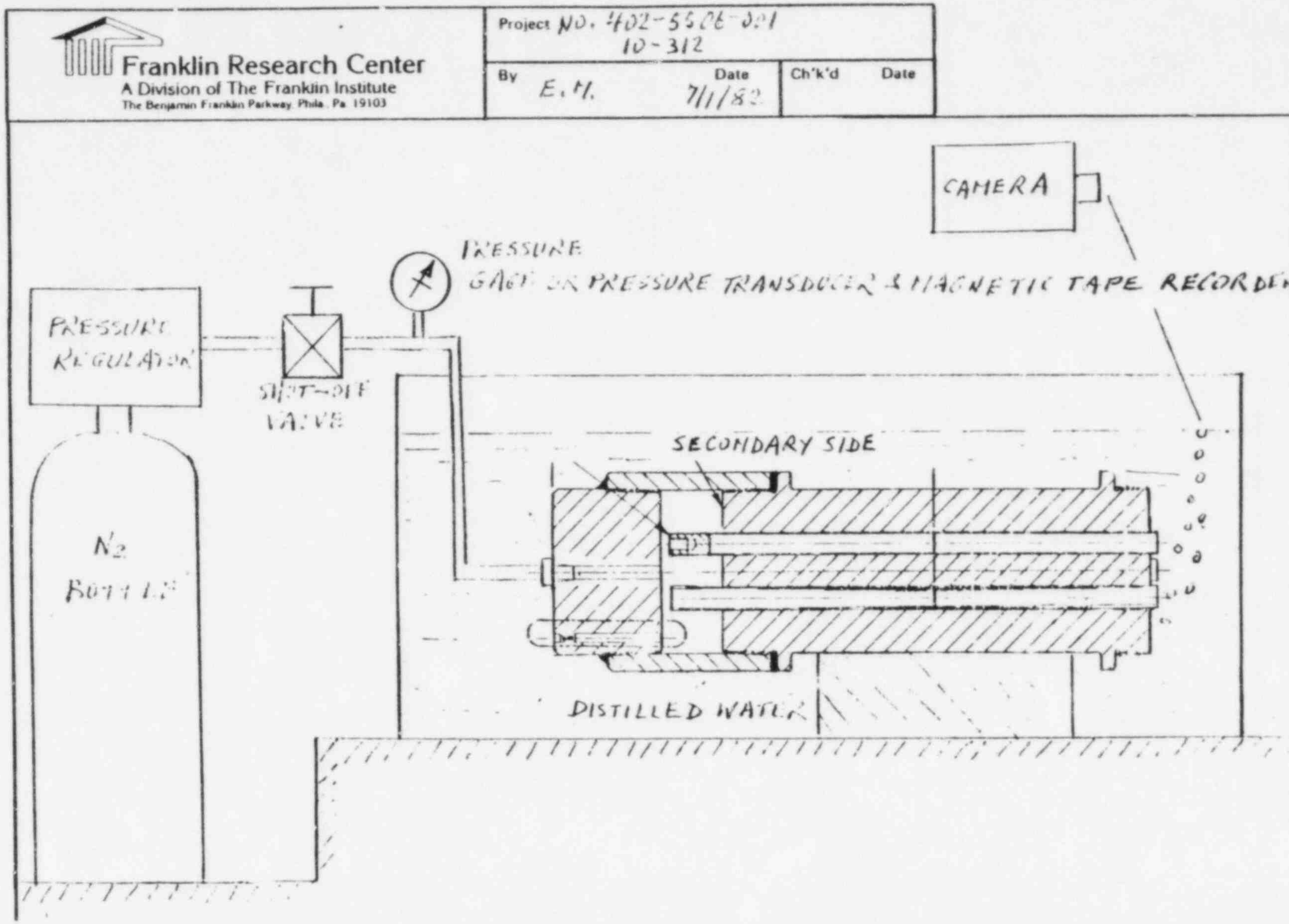


Figure 11.0. Secondary-to-Primary Bubble Test Setup

TASK N12 - THERMAL CYCLING

12.1 Install three thermocouples: two on the ID of tubes No. 9 and No. 10, 6 in from the primary side, and one on the OD of the tubesheet, also 6 in from the primary side (thermocouple range 50°F to 700°F).

12.2 Using thermal blankets or an electric oven with a temperature control, perform the following thermal cycling:

a. 30 heatup/cooldown cycles from 70°F (+0/-25°F) to 610°F (+25/-0°F) to 70°F (+0-25°F)

b. 8 reactor trip cycles from 70°F (+0/-25°F) to 610°F (+25/-0°F) to 70°F (+0/-25°F)

c. 1 stuck-open turbine bypass valve cycle from 610°F (+25/-0°F) to 400°F (+0/-25°F) in 10 minutes.

During thermal cycling (a) and (b), the temperature difference between tube and tubesheet shall not exceed 100°F, and the rate of temperature change of the tubes shall not exceed 10°F/minute. The maximum temperature difference between the tube and tubesheet during thermal cycle (c) shall not exceed 30°F.

(Test Deleted)

TASK N13- BUBBLE TEST - POST THERMAL CYCLE

13.1 After thermal cycling, perform a primary-to-secondary-side bubble test in accordance with paragraphs 11.9 through 11.13.

(Test deleted)

TASK N14 - AXIAL LOAD CYCLING

14.1 Calibrate Instron machine and recording system using FRC known weights.

14.2 Measure extension of each tube from secondary face to plug face and record data.

14.3 Install tube/tubesheet assembly marked F-1 into Instron machine using fixtures and arrangements as shown in Figure 6.0.

14.4 Correct axial load (± 2 lb) and readout for dead weight of adaptors or fixtures, if any. Check to insure that the tube being subjected to cyclic loads is aligned with the centerline of the actuator applying the loads and that mounting is not susceptible to buckling or side loading.

14.5 Using the Instron machine, apply the following axial load cycling at ambient temperature of 70°F ± 10°F for each tube separately, starting with tube (1)

a. 100 cycles 780 lb compression to 1110 lb tension
b. 180 cycles 635 lb compression to 175 lb tension
c. 6040 cycles 510 lb compression to 125 lb compression.

The specified cycles should be applied at not more than 1 Hz frequency. The tolerance on all cycling forces is ± 5 lb.

14.6 Perform axial load cycling for all tubes, 1 through 10, in that order. Record load limits of each cycle.

14.7 Measure extension of each tube from secondary face to plug face and record data.

14.8 Perform axial load cycling for tube/tubesheet marked F-2 using the procedure in paragraphs 14.2 through 14.7.

TASK N15 - BUBBLE TEST - POST AXIAL LOAD

15.1 After axial load cycling is completed, perform a primary-to-secondary-side bubble test in accordance with paragraphs 11.9 through 11.13.

TASK N16 - MEASUREMENTS - POST AXIAL LOAD

16.1 After completion of axial load cycling, make the same measurements as in paragraph 2.2 and record them.

(Test deleted)

TASK N17- LEAK RATE TEST

17.1 Perform leak rate test with a secondary-to-primary ΔP of 1275 psi ($\pm$ 25 psi) at room temperature of 70°F $\pm$ 15°F.

17.2 Using an N_2 bottle with pressure regulator and the test setup as shown in Figure 17.0, charge the accumulator to 200 psi ($\pm$30 psi) by opening shutoff valve (4). Close valve (4) after accumulator has been charged.

17.3 Connect the handpump at shutoff valve (3). Make sure that shutoff valves (3) and (5) are open and charge the accumulator and the secondary side of the test specimen with distilled water at 1275 $\pm$ 25 psi. Use air vent plug to eliminate air at the secondary side of the test specimen. When the air is eliminated and the pressure reaches 1275 $\pm$ 25 psi, close shutoff valves (3) and (5) and disconnect the handpump.

17.4 Connect the handpump at shutoff valve (1). Make sure that shutoff valves (1) and (5) are open and shutoff valve (2) is closed. Charge the primary side of the test specimen with distilled water. Use air vent plug to eliminate air at the primary side of the test specimen. When the air is eliminated and the pressure reaches 20 psi (+ 10/- 0 psi), close shutoff valves (1) and (5) and disconnect the handpump.

17.5 Adjust N_2 pressure regulator and open valve (4) to maintain accumulator pressure at 1275 psi ($\pm$ 25 psi). Open shutoff valve (2) very slowly. Do not collect the water at valve (2) for the first 5 minutes. After 5 minutes, begin collection of the water. Record pressure and the collected leakage every 2 hours for a minimum period of 6 hours.

17.6 Maintain pressure and collection of leakage (seasoning) either for a period of 72 hours or until the amount of leakage in any 2-hour period is the same as the amount collected in the previous 2-hour period, or the change between the amounts collected in the last two periods is less than 10% of the change between the amounts collected in the two previous periods.

17.7 The leak rate test shall be initiated as soon as "seasoning" is completed by maintaining the pressure at the secondary side at 1275 psi ($\pm$ 25 psi) and recording the accumulated leakage. Record the accumulation of leakage water every hour up to and including the amount accumulated in an 8-hour period. (GPU specifications are 116 cu mm maximum in an 8-hour period.)

Project No. 402-5506-201 10-312			
By	Date 7/1/82	Ch'k'd	Date

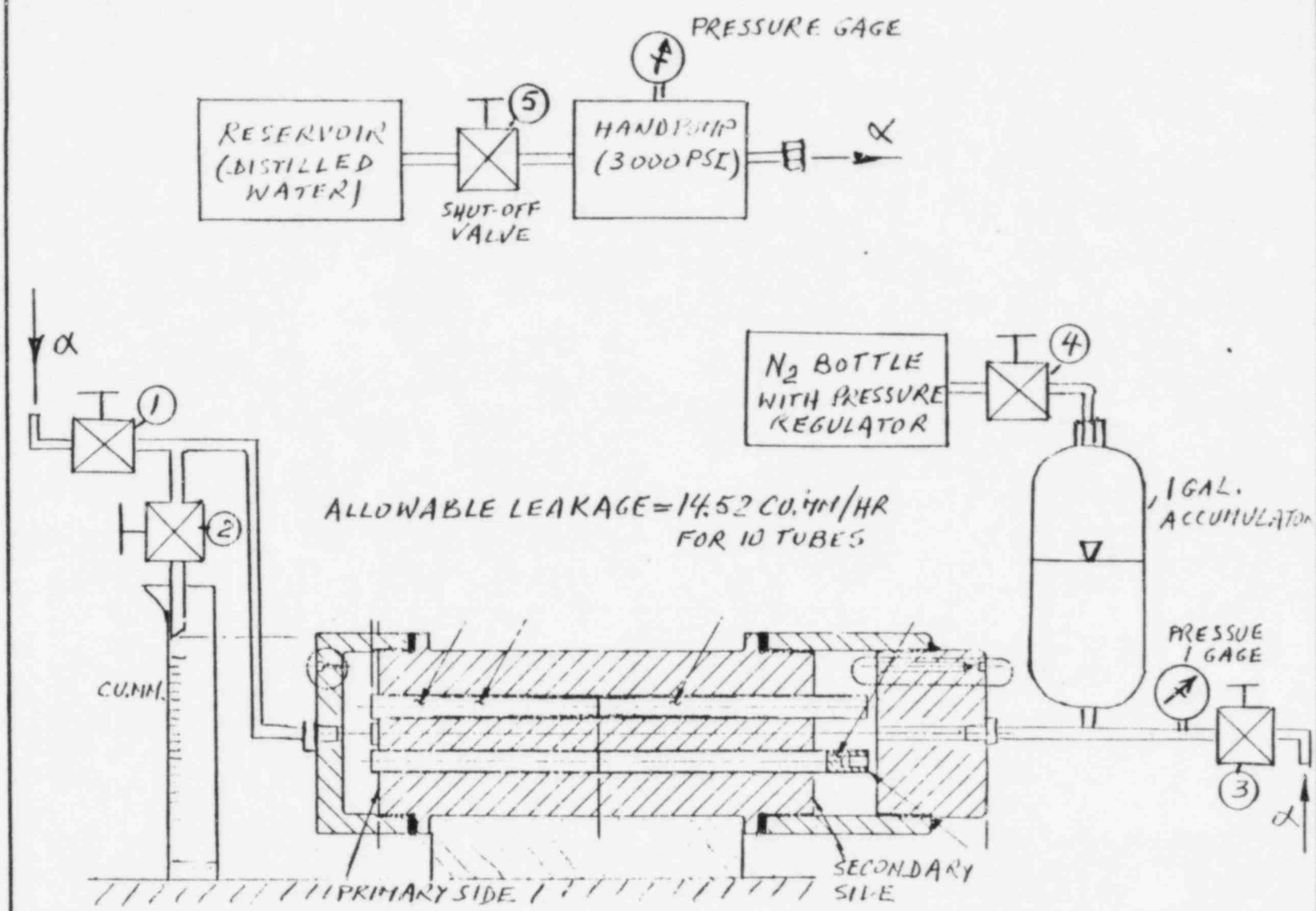


Figure 17.0. Test Setup for Leak Rate Tests

TASK N18 - LEAK RATE TEST

18.1 Perform leak rate tests with a primary-to-secondary ΔP of 1275 psi (± 25 psi) and with a primary-to-secondary ΔP of 2500 psi (± 25 psi). Maintain room temperature at 70°F ± 15°F.

18.2 Using an N_2 bottle with pressure regulator and the test setup as shown in Figure 17.0, but with the block reversed, charge the accumulator to 600 psi (± 30 psi) by opening shutoff valve (4). Close valve (4) after accumulator has been charged.

18.3 Connect the handpump at shutoff valve (3). Make sure that shutoff valves (3) and (5) are open and charge the accumulator and the primary side of the test specimen with distilled water at 1275 psi ± 25 psi. Use air vent plug to eliminate air at the primary side of the test specimen. When the air is eliminated and the pressure reaches 1275 psi ± 25 psi, close shutoff valves (3) and (5) and disconnect the handpump.

18.4 Connect the handpump at shutoff valve (1). Make sure that shutoff valves (1) and (5) are open and shutoff valve (2) is closed. Charge the secondary side of the test specimen with distilled water. Use air vent plug to eliminate air at the secondary side of the test specimen. When the air is eliminated and the pressure reaches 20 psi (+ 10/- 0 psi), close shutoff valves (1) and (5) and disconnect the handpump.

18.5 Adjust N_2 pressure regulator and open valve (4) to maintain accumulator pressure at 1275 psi (± 25 psi). Open shutoff valve (2) very slowly. Do not collect the water at valve (2) for the first 5 minutes. After 5 minutes, begin collection of the water. Record pressure and the collected leakage every 2 hours for a minimum period of 6 hours.

18.6 Maintain pressure and collection of leakage (seasoning) either for a period of 72 hours or until the amount of leakage in any 2-hour period is the same as the amount collected in the previous 2-hour period, or the change between the amounts collected in the last two periods is less than 10% of the change between the amounts collected in the two previous periods.

18.7 The leak rate test shall be initiated as soon as "seasoning" is completed by maintaining the pressure at the primary side at 1275 psi (± 25 psi) and recording the accumulated leakage. Record the accumulation of leakage water every hour up to and including the amount accumulated in an 8-hour period. (GPU specifications are 116 cu mm maximum in an 8-hour period.)

18.8 Adjust N_2 pressure regulator and open valve (4) to maintain accumulator pressure at 2500 psi (± 25 psi). Do not collect the water at valve (2) for the first 5 minutes. After 5 minutes, begin collection of the water. Record pressures and the collected leakage every 2 hours for a minimum period of 6 hours.

18.9 Maintain pressure and collection of leakage (seasoning) either for a period of 72 hours or until the amount of leakage in any 2-hour period is the same as the amount collected in the previous 2-hour period, or the change between the amounts collected in the last two periods is less than 10% of the change between the amounts collected in the two previous periods.

18.10 The leak rate test shall be initiated as soon as "seasoning" is completed by maintaining the pressure at the primary side at 2500 psi (± 25 psi) and recording the accumulated leakage. Record the accumulation of leakage water every hour up to and including the amount accumulated in an 8-hour period.

TASK N19 - PULLOUT LOAD TEST

19.1 Calibrate Instron machine and recording system using FRC known weights. Correct axial load (± 2 lb) and readout for weight of adaptors or fixtures, if any.

19.2 Install tube/tubesheet assembly marked F-1 into Instron machine with tube marked (2) positioned for pushout. Use fixtures and arrangement as shown in Figure 14.0.

19.3 Place grit into the tube marked (2) to a level within 1/4 in of the secondary tubesheet face and install pushrod on top of grit.

19.4 Apply load gradually, approximately 10 lb/sec. Record load and relative displacement between secondary face of tubesheet and secondary tube end. Visually monitor tube behavior. Continue test until relative displacement at secondary end is at least 0.060 in. Accuracy of relative displacement measurement should be ± 0.0003 in.

19.5 Remove tube/tubesheet assembly.

19.6 Repeat procedure of paragraphs 19.2 through 19.5 for tubes marked (3), (8), and (9) in that order. Take care not to load or disturb tubes marked (1), (4), (5), (6), (7), or (10) of tube/tubesheet assembly marked F-1.

19.7 Install tube/tubesheet assembly marked F-2 and repeat procedure of paragraphs 19.2 through 19.5 for tubes 1 through 10, in that order.

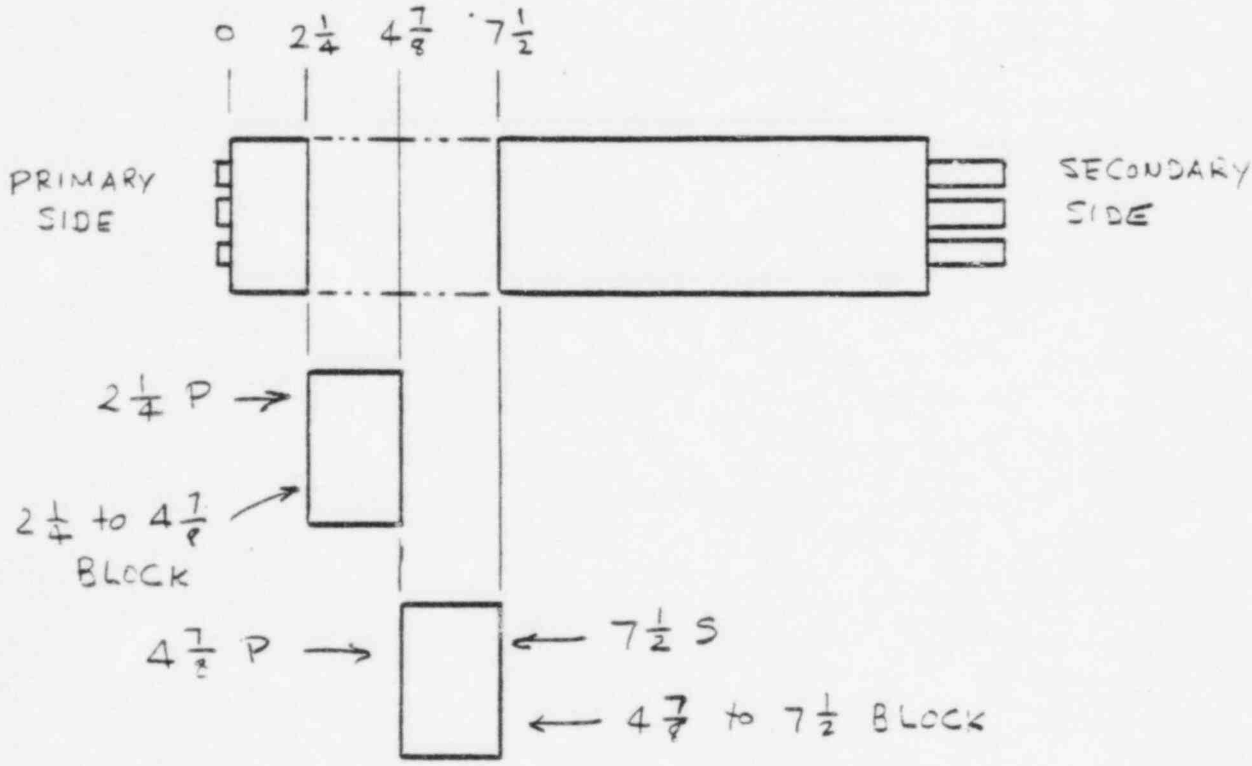
TASK N20 - MICROGRAPHY

20.1 Cut the tube/tubesheet assembly marked F-1 at 2-1/4 in, 4-7/8 in, and 7-1/2 in from the primary face of the tubesheet (reference Figure 20.0). Care should be taken to avoid excessive roughing of the surface or inducing of strain at the cut face of the tube sheet or tube.

20.2 Prepare the primary face of the 2-1/4 in to 4-7/8 in block (reference surface marked 2-1/4P in Figure 20.0) and both faces of the 4-7/8 in to 7-1/2 in block (reference surfaces marked 4-7/8P and 7-1/2S in Figure 20.0) for micrography by polishing these surfaces.

20.3 At the polished surfaces (references 2-1/4P, 4-7/8P, and 7-1/2S) perform micrography around tubes 4, 5, 6, and 7.

20.4 Etch faces 2-1/4P, 4-7/8P, and 7-1/2S and perform micrography of these polished and etched surfaces around tubes 4, 5, 6, and 7.



0
2 1/4
4 7/8
7 1/2
PRIMARY SIDE
SECONDARY SIDE
2 1/4 P
2 1/4 to 4 7/8 BLOCK
4 7/8 P
7 1/2 S
4 7/8 to 7 1/2 BLOCK

Figure 20.0

TASK N21 - MEASUREMENT OF RESIDUAL STRESSES

21.1 For the test specimen marked F-1, perform measurement of residual stresses in the tubesheet ligaments shown in Figure 21.0a.

21.2 After micrography is completed, install double strain gages on each of the seven ligaments shown in Figures 21.0a and 21.0b. Repeat this pattern at each of the polished and etched faces (references 2-1/4P, 4-7/8P, and 7-1/2S in Figure 20.0) for a total of 21 strain gages. Strain gages are to be mounted equidistant from each tube hole.

21.3 Zero all strain gages and subsequently machine inside tubes so that the tubes can be collapsed and removed. Remove tubes and record strain gage readings.

APPENDIX E

TEST DATA

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Task N2

Project 5506-10-312

Data are in Table 1 of the report.

Task N3

Project 5506-10-312

1. Installation of strain gages was completed on specimen 3A. expansion was accomplished on September 30, 1982. Impact of explosive expansion caused strain gages to separate from specimen and caused separation of the lead wires to the strain gages. No useful data obtained.

2. Strain gage mounting procedures and lead wire arrangement were modified and two gages were installed expansion was accomplished with modified strain gage installation in order to evaluate strain gage mounting and wiring procedure. Procedure appeared satisfactory. Gages and lead wires appeared to have remained in place However, no valid data were obtained.

Title DATA SHEET - RECEIVING, INSPECTION, AND MARKING Task N1

1. As received in shipping box, the plastic bag containing the 10 hole tubesheet block was torn on both ends by the tubesheet threads. The bag has 6 holes approximately 1/2" long, 3 holes approximately 1" long and 1 hole approximately 2" long. In addition, there are four splits previously taped sheet. Marking on the bag is as follows:

 10 Hole Tubesheet
 Mockup
 Corrosion Conditioned
 Per TP-526
 S??? 5045-SP2-76D85?-1-2
 7-22-8?

 Also received, six tubes approximately 24" long and sealed in plastic bag. Also received, additional tubesheet block with tubes in place. As received, tubesneet block with tubes in place was sealed in double plastic bag.

2. Torn plastic bag containing tubesheet block placed inside additional bag and resealed for later inspection.

3. Tubesheet blocks removed from bags, marked and resealed.

4. Six single tube blocks received in sealed individual bags. Six tubes received in sealed bag marked low yield.

5. Ten (10) tube/tubesheet block removed from plastic bags for inspection. Desiccant in internal vented bag has mostly blue color indicating it is still active. Some crystals are white. Small amount (about teaspoon) of dessicant is loose in bag with tubesheet. Inspection of holes under high intensity lighting indicates slight reddish oxide near end of holes (approximately 1/4" and very insignificant). Inside diameter of holes looked clean and free of loose reddish oxide. Unit was resealed with fresh desiccant. (9/9/82)

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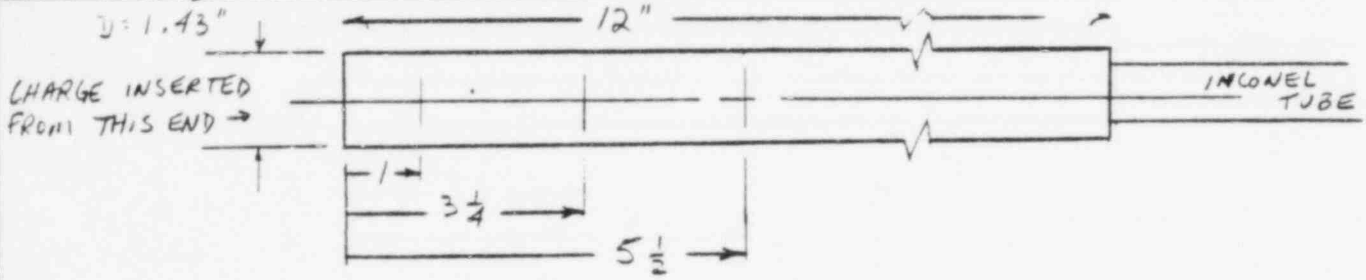
By C. ROBINSON Date 10/?/82	Ch'k'd Date	Rev. Date

Title
Task N3; EXPLOSIVE EXPANSION OF TUBE 3D



SIX BIAXIAL STRIAN GAGES LOCATED IN THREE DIAMETRALLY OPPOSITE PAIRS, AT THREE AXIAL LOCATIONS AS SHOWN

5-Vdc bridge excitation; Wideband FM Tape Recorder to 40 KHz

TAPE RECORDER CHANNEL	STRAIN GAGE SIGNAL (A - AXIAL, C - CIRCUMFERENTIAL)	VISHAY GAIN SETTING	CABLE NUMBER & AMP NUMBER	MEASURED INITIAL STRAIN PEAK in μE
1	1 CIRC	X 300 (5X100)	21	−2900
2	1 AXIAL	X 300	22	+ —
3	2 CIRC	X 300	23	+ —
4	2 AXIAL	X 300	24	+5400
5	3 CIRC	X 300	25	Repeat Analysis
6	3 AXIAL	X 300	26	+ —
7	4 CIRC	X 300	27	+380 or −950
8	4 AXIAL	X 300	28	−1100
9	5 CIRC	X 300	29	−2400
10	5 AXIAL	X 300	30	−800
11	6 CIRC	X 300	31	+2500 or −3900
12	6 AXIAL	X 300	32	−800
13	DETONATION PULSE			

FORM CS-FRC-81

Title: Task N3; EXPLOSIVE EXPANSION OF TUBE 3D — 10/20/82

Calculation of Strain Sensitivity

Assumed Example:	Present Situation:
5 Vdc bridge excitation	5 Vdc excitation
2.00 gage factor	2.03 GF
500με expected strain	500με strain
1600 amp. gain	200 gain
2.0 Vdc output voltage	→ output voltage?

$$(2.0\ \text{Vdc})\left(\frac{2.03}{2.00}\right)\left(\frac{200}{1600}\right)\left(\frac{1}{500\,\mu\epsilon}\right) \rightarrow \frac{260\,\text{mV}}{500\,\mu\epsilon} = \boxed{0.52\ \text{mV}/\mu\epsilon = K}$$

$$\text{Strain Level (in } \mu\epsilon) = \left(\frac{1}{K}\right)(\text{Bridge Output Voltage})$$

$$\boxed{\text{Strain } (\mu\epsilon) = \left(1.92\ \frac{\mu\epsilon}{\text{mV}}\right)(\text{Voltage})}$$

Task N9

Project 5506-10-312

Data are in Table 1 of the report.

Title
DATA SHEET - TASK N11 - BUBBLE TEST FOR SPECIMEN F1

1. Secondary to primary bubble test on tube/tubesheet marked F-1, started at 11:15 on August 30, 1982. Pressure set at 125 psi. Water temperature 73°F. Small leak at gasket between parts 2 and 5. Test terminated and gasket resealed. Bubble test restarted at 0930 on August 31, 1982. Pressure decay verse time as follows:

Time	PSIG	°F
0930-8/31/82	125	73
1030	125	73
1130	124.8	73
1230	124.0	73.8
1330	123.8	73.8
1442	122.4	73.8
1530	122.0	73.8
1630	121.8	74.0
1705	121.0	74
0830-9/1/82	109.0	75
0952	108.0	75
1037	107.8	75
1130	107	75
1250	106	75
1330	105.8	75
1430	105	75
1530	104	75
1549	104	75

Test Terminated at 1549

Title DATA SHEET - TASK N11 - BUBBLE TEST FOR SPECIMEN F1 (CONT.)

Secondary to primary bubble test on tube/tubesheet marked F-1 started at 0930 on 8/31/82. No leak at gasket. Pressure steady and no apparent leaks or bubbles. Very small bubble stream observed between tube and tubesheet at tubes #4 and #8 at 1130. Also at 1130 bubbles of various size are discovered inside top of all tubes. Unable to determine whether bubbles result from air entrapped in tube before starting test, or whether air is escaping past tube plug, or whether air is collecting from air originallydissolved in water. Small probe is used to move bubbles at upper inside surface of tubes. Small bubble stream continues at tubes #4 and #8 after removal of bubbles at inside of tubes. Videotape of bubbles at tubes #4 and #8 taken at 1145 hours. No additional leaks discovered at 1406 but bubbles inside tubes have reformed, source unknown. At 1454 hours leak between tube and tubesheet at #4 continue with bubbles being slightly larger and of much lower frequency (18 to 35 sec interval). At 1705 leak still visible at tubes #4 and #8. At 0830 on 9/1/82, all tubes have large bubbles entrapped inside tubes, small bubbles escaping at tube #4 at 10 to 15 second interval and can no longer detect bubbles at tube #8. At 1200 hours, can no longer detect bubbles at tube #8, bubbles at tube #4 escaping at 10 to 15 second intervals. At 1430 hours, cannot detect bubbles escaping at tube #8, bubbles at tube #4 escaping at 60 to 90 second intervals. Large bubbles continue to reform slowly inside each tube, approximately at butting of tubes. Test terminated. Still impossible to determine whether bubbles forming inside tube result from leakage past tube or past tube plug or possibly slow migration of oringally entrapped air.

Title

DATA SHEET - TASK N11 - BUBBLE TEST FOR SPECIMEN F1 (CONT.)

1. Primary to secondary bubble test started on tube/tubesheet marked F-1 at 906 hours on October 4, 1982. Pressure set and maintained at 125 psi ± 10 psi. Average frequency of bubbles at tube and tubesheet interface noted as follows:

Tube #1	2 minute 39 second interval
#2	58 second interval
#3	very slow
#4	2 minute 37 seconds
#5	1 minute 53 seconds
#6	very slow
#7	no bubbles observed
#8	4 minutes 58 seconds
#9	1 minute 30 seconds
#10	3 minutes 25 seconds

No bubbles observed at tube plugs.

Bubble size is estimated at 1/16 to 1/8" diameter.

2. At 1000 hours on October 4, 1982, average frequence of bubbles noted as follows:

Tube #1	1 minute 36 seconds
#2	5 minutes 56 seconds
#3	4 minutes 25 seconds
#4	2 minutes 9 seconds
#5	2 minutes 55 seconds
#6	1 minute 52 seconds
#7	no bubbles observed
#8	one bubble observed
#9	5 minutes 38 seconds
#10	11 minutes 25 seconds

No bubbles at tube plug.

3. At 1055 hour on October 4, 1982, average frequency of bubbles at tube and tubesheet interface noted as follows:

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Title: DATA SHEET - TASK N11 - BUBBLE TEST FOR SPECIMEN F1 (CONT.)

Tube #1	5 minutes 4 seconds
#2	2 minutes 28 seconds
#3	no bubbles observed
#4	2 minutes 11 seconds
#5	2 minutes 15 seconds
#6	one bubble observed
#7	no bubbles observed
#8	one bubble observed
#9	3 minutes 23 seconds
#10	5 minutes 38 seconds

No bubbles observed at tube plug.
Bubble size is approximately 1/8" diameter.
Test terminated at 1106 hours.

Title
DATA SHEET - N11 - BUBBLE TEST FOR SPECIMEN F2

1. Secondary to primary test on tube/tubesheet marked F-2, reference paragraphs 11.1 to 11.8, deleted because test does not identify source of the leak.

2. Primary to secondary bubble test started on tube/tubesheet marked F-2 at 1355 hours on October 4, 1982. Pressure set and maintained at 125 PSI ± 10 PSI. Average frequency of bubbles at tube and tubesheet interface noted as follows:

Tube #1	no bubbles observed
#2	no bubbles observed
#3	55 seconds
#4	no bubbles observed
#5	no bubbles observed
#6	37 seconds
#7	no bubbles observed
#8	41 seconds
#9	13 seconds
#10	20 seconds

No bubbles observed at tube plugs.
Bubble size estimated at 1/16" to 1/8" diameter.

3. After 1 hour, the average frequency of bubbles was noted as follows:

Tube #1	no bubbles observed
#2	no bubbles observed
#3	one bubble observed
#4	no bubbles observed
#5	30 seconds
#6	15 seconds
#7	one bubble observed
#8	25 seconds
#9	13 seconds
#10	18 seconds

Title
DATA SHEET - N11 - BUBBLE TEST FOR SPECIMEN F2 (CONT.)

4. At 1555 hours on October 4, 1982, average frequency of bubbles noted as follows:

Tube #1	no bubbles observed
#2	no bubbles observed
#3	one bubble observed
#4	no bubbles observed
#5	1 minute 5 seconds
#6	10 seconds
#7	1 minute 1 second
#8	37 seconds
#9	13 seconds
#10	20 seconds

No bubbles noted at tube plugs.
Bubble size estimated at approximately 1/8".
Test terminated at 1559 hours.

Task N14

Project 5506-10-312

Full chart recordings of all axial load cyclings are on file at FRC.

DATA SHEET, TASK N15

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1. Primary to secondary bubble test started on tube/tubesheet marked F-1 after axial load test at 0945 hours on October 8, 1982. Pressure set and maintained at 125 psi ± 10 psi. The number of bubbles at the tube and tubesheet interface observed in a 5-minute observation period of 0945 hours to 0950 hours is as follows:

Tube	Number of Bubbles
#1	4
#2	2
#3	4
#4	4
#5	3
#6	0
#7	1
#8	1
#9	2
#10	1

No bubbles observed at tube plugs.
Bubble size is estimated at 3/16 to 1/8" diameter.

2. In a 5-minute interval from 1500 hours to 1055 hours on October 8, 1982, the number of bubbles observed at the tube and tubesheet interface is as follows:

Tube	Number of Bubbles
#1	2
#2	2
#3	4
#4	3
#5	2
#6	0
#7	2
#8	1
#9	1
#10	0

3. In a 5-minute interval from 1150 hours to 1155 hours on October 8, 1982, the number of bubbles observed at the tube and tubesheet interface is as follows:

Tube	Number of Bubbles
#1	3
#2	2
#3	4
#4	2
#5	2
#6	0

3. (Cont'd)

Tube	Number of Bubbles
#7	0
#8	2
#9	1
#10	0

No bubbles observed at tube plug.
Bubble size is approximately 1/8" to 3/16" diameter.
Test terminated at 1155 hours.

DATA SHEET, TASK N15

Project 5506-10-312

1. Primary to secondary bubble test started on tube/tubesheet marked F-2 after axial load test at 1300 hours on October 19, 1982. Pressure set and maintained at 125 psi ± 10 psi. The number of bubbles at tube and tubesheet interface observed in a 5-minute observation period of 1300 hours to 1305 hours is as follows:

Tube	Number of Bubbles
#1	4
#2	13
#3	4
#4	7
#5	19
#6	7
#7	2
#8	1
#9	2
#10	1

No bubbles observed at tube plugs.
Bubble size is estimated at 3/16 to 1/8" diameter.

2. In a 5-minute interval from 1330 hours to 1335 hours on October 19, 1982, the number of bubbles observed at the tube and tubesheet interface is as follows:

Tube	Number of Bubbles
#1	5
#2	12
#3	4
#4	3
#5	24
#6	11
#7	4
#8	6
#9	4
#10	1

3. In a 5-minute interval from 1400 hours to 1405 hours on October 19, 1982, the number of bubbles observed at the tube and tubesheet interface is as follows:

Tube	Number of Bubbles
#1	3
#2	9
#3	6
#4	1
#5	18
#6	13

3. (Cont'd)

Tube	Number of Bubbles
#7	0
#8	6
#9	1
#10	1

4. In a 5-minute interval from 1500 hours to 1505 hours on October 19, 1982, the number of bubbles observed at the tube and tubesheet interface is as follows:

Tube	Number of Bubbles
#1	6
#2	13
#3	5
#4	0
#5	28
#6	13
#7	1
#8	8
#9	1
#10	3

Title

Task N17, Secondary to Primary Side Leak Rate Test, Specimen F-1

Test started at 10:15 on October 9, 1982.
Liquid collected in graduated flask.

Date	Time	Pressure	Temp.	Liquid Collected
Oct. 9	1015	1275	75°	0
Oct. 9	1020	1275	-	0
Oct. 9	1220	1275	-	0 (Small droplet on inside of tube but not measureable)
Oct. 9	1420	1275	-	0 (Small droplets on inside of tube but not measureable)
Oct. 9	1530	1275	-	Note (1)

Note 1) Unable to measure water leakage since water droplets adhere to inside of tube and are not collected in graduated flask. A one-quarter inch (6.35 mm) I.D. tube was mounted vertically against a 1/64" graduated machinist scale. Distilled water was added to primary side to bring water level up to the base of machinists scale. Secondary side pressure was maintained at 1275 psi. Readings were taken as follows:

Date	Time	Pressure	Water Height	Temp.
Oct. 9	1535	1275 psig	42/64	78°F
Oct. 9	1735	1275	1-5/64	78°F
Oct. 9	1935	1275	1-33/64	77.5°F
Oct. 11	0845	1275	11-3/8	72°F

Note: Water was drained from tube, through valve (1), to reset water level at bottom of scale. Readings taken as follows:

Date	Time	Pressure	Water Height	Temp.
Oct. 11	0900	1275	32/64	72°F
Oct. 11	1107	1275	1-16/64	75°
Oct. 11	1300	1275	1-60/64	77
Oct. 11	1500	1275	2-44/64	77
Oct. 11	1700	1275	3-28/64	78
Oct. 12	0845	1275	8-48/64	76°F

Task N17, Specimen F-1 (Cont'd)

Note: After 72 hours of seasoning, 10/9/82 to 10/12/82, water was drained thru valve (1) to reset water level at bottom of scale and initiate eight (8) hour test. Readings taken as follows:

Date	Time	Pressure	Water Height	Temp.
Oct. 12	1015	1275	32/64	76°F
Oct. 12	1115	1275	55/64	77
Oct. 12	1215	1275	1-15/64	77
Oct. 12	1315	1275	1-36/64	77
Oct. 12	1415	1275	1-60/64	77
Oct. 12	1515	1275	2-20/64	77
Oct. 12	1615	1275	2-42/64	78
Oct. 12	1715	1275	3-1/64	78
Oct. 12	1815	1275	3-24/64	78

Test was terminated at 1815 after 8 hours of collection. Total water collected in 8 hours was

$$3\text{-}24/64 - 32/64 = 2\ 56/64 = 2.875 \text{ in.}$$

$$= 73.025 \text{ mm}$$

$$\text{Volume} = (73.025 \text{ mm}) \left(\frac{\pi}{4}\right) (6.35)^2 = 2312.64 \text{ cu. mm.}$$

or 289 cu. mm/hr.

Test started at 1700 hours on 10/22/82.

Date	Time	Pressure	Water Height	Temp.
Oct. 22	1700	1275	1-56/64	79°F
Oct. 23		NO READINGS		
Oct. 24		NO READINGS		
Oct. 25	0850	1275	7-24/64	73.5°F

Note: Reset water height to 1 inch at 0850 hours.

Oct. 25	1000	1275	1-6/64	75.5
Oct. 25	1115	1275	1-12/64	76
Oct. 25	1214	1275	1-17/64	76
Oct. 25	1300	1275	1-21/64	76.5
Oct. 25	1400	1275	1-29/64	77
Oct. 25	1504	1275	1-35/64	77
Oct. 25	1610	1275	1-42/64	77
Oct. 25	1710	1275	1-48/64	77

Note: 72 hours of seasoning completed. Eight hour test as follows.

Oct. 25	1730	1275	1-49/64	77°F
Oct. 25	1830	1275	1-53/64	77.4
Oct. 25	1930	1275	1-58/64	77.5
Oct. 25	2030	1275	1-62/64	77.5
Oct. 25	2130	1275	2-1/64	77.6
Oct. 25	2230	1275	2-5/64	77.5
Oct. 25	2330	1275	2-10/64	77.6
Oct. 26	0030	1275	2-14/64	77.6
Oct. 26	0130	1275	2-16/64	77.5

Test terminated at 0130 hours after 8 hours of collection. Total water collected in 8 hours was

$$2\text{-}16/64 - 1\text{-}49/64 = 31/64 = .484 \text{ inch} = 12.3 \text{ mm}$$

$$\text{Volume} = (12.3 \text{ mm}) \left(\frac{\pi}{4}\right) (6.35)^2 = 389.6 \text{ cu. mm}$$

or 48.7 cu. mm/hr.

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Task N18, Primary to Secondary Side Leak Rate Test, Specimen F-1

Test stated at 9:30 on 10/13/82.

Date	Time	Pressure	Water Height	Temp.
Oct. 13	930	1275	-	77°F
Oct. 13	935	1275	48/64	77
Oct. 13	1135	1275	3-57/64	78
Oct. 13	1335	1275	6-12/64	78
Oct. 13	1535	1275	7-40/64	77

Note: Reset at 1535 to 48/64 water height.

Date	Time	Pressure	Water Height	Temp.
Oct. 13	1735	1275	1-62/64	78
Oct. 14	835	1275	6-14/64	76

Note: Reset at 835 to 24/64 water height.

Date	Time	Pressure	Water Height	Temp.
Oct. 14	935	1275	40/64	77
Oct. 14	1135	1275	1-4/64	77
Oct. 14	1335	1275	1-32/64	77
Oct. 14	1535	1275	1-56/64	77
Oct. 14	1717	1275	2-12/64	77
Oct. 15	835	1275	4-24/64	75
Oct. 15	935	1275	4-32/64	76
Oct. 15	1135	1275	4-50/64	77
Oct. 15	1335	1275	5-12/64	77
Oct. 15	1535	1275	5-32/64	78
Oct. 15	1715	1275	5-51/64	78

Note: Reset at 1715 to 32/64 water height.

Date	Time	Pressure	Water Height	Temp.
Oct. 16	920	1275	2-20/64	-

Note: 72 hours of seasoning completed. Eight hour test as follows:

Date	Time	Pressure	Water Height	Temp.
Oct. 16	930	1275	2-20/64	83°F
Oct. 16	1030	1275	2-29/64	78.5
Oct. 16	1130	1275	2-40/64	78
Oct. 16	1230	1300	2-48/64	78

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Task 18, Specimen F-1 (Cont'd)

Date	Time	Pressure	Water Height	Temp.
Oct. 16	1330	1275	2-58/64	78.5
Oct. 16	1430	1275	3-4/64	79
Oct. 16	1530	1275	3-12/64	79
Oct. 16	1630	1275	3-20/64	79
Oct. 16	1730	1275	3-28/64	79

Test was terminated at 1730 after 8 hours of collection. Total water co lected in 8 hours was

3-28/64 - 2 20/64 = 1 8/64 = 1.125 inch
= 28.575 mm

$$\text{Volume} = (28.575\ \text{mm})\ (\frac{\pi}{4})\ (6.35)^2 = 904.9\ \text{cu. mm}$$
or 113 cu. mm/hr

Title

Task N18, Primary to Secondary Side Leak Rate Test, Specimen F-1

Test started at 1830 hours on 10/16/82

Date	Time	Pressure	Water Height	Temp.
Oct. 16	1830	2500	32/64	79°
Oct. 16	1835	2500	32/64	79
Oct. 17		NO READINGS		
Oct. 18	0830	2500	5-60/64	72

Note: Set water height to 32/64 at 830 hours.

Date	Time	Pressure	Water Height	Temp.
Oct. 18	1030	2500	56/64	76
Oct. 18	1230	2500	1-16/64	77
Oct. 18	1430	2500	1-40/64	75
Oct. 18	1630	2500	1-63/64	75.5
Oct. 18	1715	2500	2-4/64	76
Oct. 19	0830	2500	3-54/64	73
Oct. 19	1030	2500	4-8/64	78

Note: Reset water height to 32/64 at 1030 hours.

Date	Time	Pressure	Water Height	Temp.
Oct. 19	1230	2500	53/64	77
Oct. 19	1530	2500	1-20/64	76.5

Note: Reset water height to 1 inch at 1630 hours.

Date	Time	Pressure	Water Height	Temp.
Oct. 19	1630	2500	1	76.5
Oct. 19	1730	2500	1-10/64	76

Note: 72 hours of seasoning complete. Eight hour test as follows:

Date	Time	Pressure	Water Height	Temp.
Oct. 19	1830	2500	1-20/64	77°F
Oct. 19	1930	2500	1-31/64	77.6
Oct. 19	2030	2500	1-40/64	78
Oct. 19	2130	2510	1-50/64	78.4
Oct. 19	2230	2510	1-60/64	78.5
Oct. 19	2330	2525	2-8/64	78.8

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Task N18, Specimen F-1 (Cont'd)

Date	Time	Pressure	Water Height	Temp.
Oct. 20	0030	2525	2-18/64	79
Oct. 20	0130	2538	2-29/64	79
Oct. 20	0230	2550	2-41/64	79

Test was terminated at 0230 hours after 8 hours of collection. Total water collected in 8 hours was

$$2\text{-}41/64 - 1\text{-}20/64 = 1\text{-}21/64 = 1.328 \text{ inch}$$
$$= 33.73 \text{ mm}$$

$$\text{Volume} = (33.73 \text{ mm}) \left(\frac{\pi}{4}\right) (6.35)^2 = 1068 \text{ cu. mm}$$

or 133.5 cu. mm/hr.

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Task N18, Primary to Secondary Leak Rate Test, Specimen F-2

Test started at 1030 hours on 10/26/82.

Date	Time	Pressure	Water Height	Temp.
Oct. 26	1030	1275	1-56/64	77.5°F
Oct. 26	1158	1275	6-4/64	78
Oct. 26	1230	1275	7-28/64	78

Note: Reset water height at 1-2/64 at 1230 hours.

Oct. 26	1302	1275	2-8/64	78
Oct. 26	1430	1275	5	79
Oct. 26	1630	1275	8-24/64	79

Note: Reset water height at 1 inch at 1645 hours.

Oct. 27	0830	1275	12	76°F

Note: Reset water height at 16/64 at 0840 hours.

Oct. 27	1030	1275	57/64	78°F
Oct. 27	1230	1275	1-32/64	77.5
Oct. 27	1430	1275	2-3/64	77.5
Oct. 27	1632	1275	2-28/64	78

Note: Reset water height at 8/64 at 1634 hours.

Oct. 28	0843	1275	2-16/64	76°F
Oct. 28	1050	1275	2-32/64	77
Oct. 28	1307	1275	2-48/64	78
Oct. 28	1430	1275	2-54/64	78
Oct. 28	1620	1275	3	78

Note: Reset water height at 32/64 at 1621 hours.

Oct. 29	0843	1275	1-3/64	74°F

Note: 72 hours of seasoning completed. Eight hour test as follows:

Oct. 29	1030	1275	1-10/64	76.5
Oct. 29	1130	1275	1-12/64	76.5
Oct. 29	1230	1275	1-18/64	77
Oct. 29	1330	1275	1-24/64	77

Task 18, Specimen F-2 (Cont'd)

Date	Time	Pressure	Water Height	Temp.
Oct. 29	1430	1275	1-30/64	77
Oct. 29	1530	1275	1-34/64	77
Oct. 29	1630	1275	1-38/64	77
Oct. 29	1730	1275	1-42/64	78
Oct. 29	1830	1275	1-47/64	78

Test terminated at 1830 hours after 8 hours of collection. Total water collected in 8 hours was as follows.

$$1\text{-}47/64 - 1\text{-}10/64 = 37/64 = .578 \text{ inch}$$

$$= 14.68 \text{ mm}$$

$$\text{Volume} = (14.68 \text{ mm}) \left(\frac{\pi}{4}\right) (6.35)^2 = 465 \text{ cu. mm}$$

or 58.1 cu. mm/hr.

Test started at 1000 hours on 11/1/82.

Date	Time	Pressure	Water Height	Temp.
Nov. 1	1000	2500	32/64	78°F
Nov. 1	1200	2500	47/64	78
Nov. 1	1400	2500	1	79
Nov. 1	1600	2500	1-16/64	79
Nov. 2	1600	2500	2-42/64	80
Nov. 3	1426	2500	3-27/64	79
Nov. 4	0900	2500	3-46/64	76.5°F

Note: Reset water height to 1 inch at 0904 hour.

Note: 72 hours of seasoning completed. Eight hour test as follows.

Nov. 4	1000	2500	1-2/64	77°F
Nov. 4	1100	2500	1-9/64	78
Nov. 4	1200	2500	1-18/64	79
Nov. 4	1300	2500	1-25/64	79
Nov. 4	1400	2500	1-34/64	79
Nov. 4	1500	2500	1-40/64	79.5

Title: Task N18, Specimen F-2 (Cont'd)

Date	Time	Pressure	Water Height	Temp.
Nov. 4	1600	2500	1-48/64	79.5
Nov. 4	1700	2500	1-53/64	80
Nov. 4	1800	2500	1-57/64	80

Test terminated at 1800 hours after 8 hours of collection. Total water collected in 8 hours was as follows:

1-57/64 - 1-2/64 = 55/64 = .859 inch
= 21.83 mm

Volume = (21.83 mm) $(\frac{\pi}{4})$ $(6.35)^2$ = 691 cu. mm

or 86.4 cu. mm/hr.

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Task N19 - Pullout Load Test - Specimen F-2

Tube #1

Tube Displacement	Load
0	0
0	265
.0005"	1225
.001	1460
.0015	1700
.0025	1945
.003	2250
.0035	2500
.004	2650
.0045	2800
.005	3000
.0055	3200
.006	3375
.0065	3500
.007	3800 Yield
.030	3900
.060	4120

Tube #2

0	0
.0	40
.0035	210
.004	250
.005	310
.006	400
.008	500
.009	625
.010	835
.0105	1100
.011	1330

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Tube #2 (Cont'd)

Tube Displacement	Load	
.0115	1700	
.012	1875	
.0125	2050	
.013	2200	
.0135	2350	
.014	2500	
.0145	2660	
.015	2800	
.0155	2950	
.016	3050	
.016	3190	
.017	3300	
.0175	3380	
.018	3480	
.019	3500	Yield
.030	3740	
.045	3870	
.060	3900	

Tube #3

0	0
.0	25
.001	460
.0015	540
.002	800
.0025	1090
.003	1250
.0035	1400
.004	1700
.0045	2000
.006	2100
.0065	2220

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Tube #3 (Cont'd)

Tube Displacement	Load
.007	2300
.008	2490
.009	2600
.010	2700
.011	2800
.012	3100
.015	3200 Yield
.030	3275
.045	3380
.060	3500

Tube #4

0	0
.0	40
.0005	600
.001	1260
.0015	1300
.002	1600
.0025	1670
.003	1857
.0035	2000
.004	2100
.0045	2200
.005	2300
.0055	2400
.006	2500
.0065	2630
.007	2750
.0075	2830
.008	2900
.009	3070

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Task N19 - Pullout Load Test - Specimen F-2 (Cont'd)

Tube #4 (Cont'd)

Tube Displacement	Load
.010	3300
.011	3550
.012	3700
.013	3750 Yield
.030	3800
.060	4000

Tube #5

Tube Displacement	Load
0	0
.0	185
.0005	800
.001	1100
.0015	1300
.002	1500
.0025	1600
.003	1750
.0035	1900
.004	2000
.0045	2180
.005	2300
.0055	2430
.006	2500
.0065	2620
.007	2700
.0075	2800
.008	2900
.009	3100
.010	3300
.011	3500
.012	3600
.014	3668
.015	3700 Yield

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Task N19 - Pullout Load Test - Specimen F-2 (Cont'd)

Tube #5 (Cont'd)

Tube Displacement	Load
.030	3820
.045	3870
.060	4000

Tube #6

Tube Displacement	Load
0	0
.0	115
.0005	240
.001	300
.0015	380
.002	480
.0025	610
.003	730
.0035	850
.004	950
.0045	1090
.005	1200
.0055	1350
.006	1440
.0065	1550
.007	1700
.0075	1825
.008	1930
.0085	2000
.009	2100
.010	2350
.011	2570
.012	2750
.013	2875
.014	2975
.015	3034 Yield
.030	3275

Title

Task N19 - Pullout Load Test - Specimen F-2 (Cont'd)

Tube #6 (Cont'd)

Tube Displacement	Load
.045	3360
.060	3450

Tube #7

Tube Displacement	Load
0	0
0	158
.001	570
.0015	780
.002	1050
.0025	1700
.0045	1900
.005	2000
.006	2500
.0065	2364
.007	2400
.0075	2500
.008	2570
.0085	2630
.009	2690
.010	2760
.011	2800
.012	2900 Yield
.015	2956
.030	3090
.045	3172
.060	3275

Title

Task N19 - Pullout Load Test - Specimen F-2 (Cont'd)

Tube #8

Tube Displacement	Load
0	0
0	150
0 Reset	800
.0005	927
.001	1150
.0015	1300
.002	1530
.0025	1650
.003	1740
.0035	1800
.004	1970
.0045	2100
.005	2200
.0055	2400
.006	2475
.007	2600
.008	2800
.0085	3000
.009	3150
.010	3340
.011	3560
.012	3680
.013	3750 Yield
.015	3800
.045	3900
.060	4060

Tube #9

0	0
0	150
.0005	1075
.0015	1600

Title

Task N19 - Pullout Load Test - Specimen F-2 (Cont'd)

Tube #9 (Cont'd)

Tube Displacement	Load
.002	1774
.004	2000
.0045	2500
.005	2285
.0055	2400
.006	2550
.0065	2650
.007	2800
.0075	2875
.008	3000
.0085	3074
.009	3150
.0095	3200
.010	3270
.011	3170 Yield
.030	3430
.045	3540
.060	3675

Tube #10

0	0
0	170
.0005	530
.001	650
.001	1000
.002	1300
.0025	1575
.003	1760

Title: Task N19 - Pullout Load Test - Specimen F-2 (Cont'd)

Tube #10 (Cont'd)

Tube Displacement	Load
.0035	1900
.004	2080
.0045	2200
.005	2400
.0055	2500
.006	2675
.0065	2775
.007	2900
.008	2974
.009	3000
.010	3083
.012	3150 Yield
.015	3220
.030	3300
.045	3385
.060	3500

Title

Task N19 - Pullout Load Test - Specimen F-1

Tube No.	Tube Reference* at Start	Tube Reference* at Finish	Tube Displacement	Maximum Load
2	1.724	1.775	.051	4100 lb
3	1.750	1.875	.105	4000 lb
8	1.700	1.741	.041	4050 lb
9	1.755	1.847	.092	3800 lb

*Note, tube reference is dimension from tube plug face to Instron mounting plate for tubesheet.

Task N21

Project 5506-10-312

Data are in Table 2 of the report.

APPENDIX F

PHOTOGRAPHS OF TEST ASSEMBLIES

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