NEW APPROACH
TO
ONE-FOR-ONE
TITANIUM CONDENSER RETUBING
IMPROVES RELIABILITY
FOR
CONTINUED UNIT OPERATION

by

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Presented at
EPRI CONDENSER TECHNOLOGY CONFERENCE

St. Petersburg, Florida
September 29 - October 1, 1993

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ABSTRACT

Today's economics require that a condenser retubing results in extra reliability for continued unit operation. This paper describes a new approach to an old activity to aid other utilities contemplating a retubing. It extends the existing guides on the subject to up-to-date retubing procedures for thin walled tubing. Discussed is the modern technology and innovations utilized in the 1991 retubing of a 30-year-old 160 MW seacoast condenser and the working partnership of the utility, the engineering advisor, and the retubing contractor that resulted in a very successful project.

Within the paper, the planning and engineering of the project are described including the approach to the work; specification features for replacing the existing copper alloy tube and tubesheet materials with titanium; the contribution of pre- and post-retubing inspections; the role of the finite element stress analysis performed on the new tubesheets; tube joint enhancement and its field installation; tube pullout and stake mockup tests; shop inspections; the application of advanced tube vibration analysis; the method of accommodating the complex tube bundle pattern to the anti-vibration staking in the field; steam impingement protection; and a cost effective work plan for the tube removal and field repairs.

Consideration of the retubing advances discussed in the paper when planning a future retubing project can result in extra operational reliability of the condenser.

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INTRODUCTION

The EPRI general guide to condenser retubing, (1), is now over a decade old. This paper addresses modern refinements to guidelines which should be considered for today's choice of thin-walled, corrosion resistant replacement tubing, e.g., titanium. These refinements, based on a case study, ensure the retubing work itself goes smoothly at minimal costs, improve the future condenser operational reliability, and establish a better basis for the required mechanical integrity of the major condenser components. The paper also discusses the team approach brought together and fostered by the utility with a team consisting of the utility, technical advisor, and retubing contractor.

This paper will not discuss when to retube. It will be presumed that decision has been previously made on the basis of economics, availability, operation, or some combination thereof as presented for example in (2).

The focus of the paper will be a case study of the condenser at Norwalk Harbor Unit No. 1 that was retubed in 1991. The station is a fossil fired (oil) 160 MW plant located along Long Island Sound in South Norwalk, Connecticut. The condenser was put into service in 1960 and was fabricated by C. H. Wheeler. It is a single pass, vertically divided, spring supported unit designed with 10,280, 30-ft long, 7/8-in. - 18 BWG tubes of aluminum brass in two tube bundles. The basic tube bundle pattern exhibits a small, uniform tube spacing variation in both the horizontal and vertical directions much like a spider web. The original tubesheets were muntz metal. Two separate circulating water pumps convey a total of 101,000 gpm through a temperature rise of 13.6°F to condense the exhaust steam from a double flow, low pressure General Electric steam turbine. The condenser is positioned transverse to the turbine shaft axis.

A retubing was required due to the numerous episodes of circulating water in-leakage resulting from internal tube corrosion failures. These continually interrupted operation with a sharply increasing occurrence and had involved over 12% of the total tubing at the time of the retubing. The replacement tubing selected by the utility was 22 BWG titanium because of its virtual immunity to corrosion and cost competitiveness with other alloys. The existing, somewhat corrosion damaged two-piece tubesheets, were replaced with a single-piece, solid titanium material tubesheet to ensure galvanic compatibility with the tubes and to eliminate the internal waterbox joint that was a source of air in-leakage. Mechanically expanded tubes formed the tubesheet joint. Additionally, an induced current cathodic protection system and an epoxy based waterbox coating were added for additional galvanic corrosion protection.

PRE-OUTAGE ACTIVITIES

Schedule

The project was planned and initiated more than 12 months before the retubing plant outage. This was necessary because the specification, bidding, material purchase, fabrication, and delivery cycle for titanium products required 30 to 40 weeks at that time. The outage at Norwalk Harbor ran 5 weeks, typical of a usual fossil plant major maintenance outage. Though other outage activities were simultaneously pursued, the retubing, combined with a waterbox replacement program, represented the critical path of the outage. The latter normally involved two 10-hour shifts 6 days each week. Some plant work was accomplished before and after the outage as is described later.

Specifications

Several specifications were written. There were specifications for the replacement tubing, replacement tubesheet, anti-vibration staking, and retubing work. Other specifications could also have been prepared for the tubesheet joint improvements, rigging, impingement protection, asbestos gasket removal, and interference removal and replacement. However, these latter requirements were able to be effectively incorporated in the retubing contractor's scope of work.

All the condenser retubing related specifications discussed the usual minutiae of contract specifications. These include a well defined scope, technical and commercial requirements, locations and site conditions, Q/A, inspections and tests, sub-suppliers, communications, applicable industry standards, schedules, and lists of what the utility and what the contractor must supply, etc. During the course of this project, however, it became clear by discussions between the utility, retubing contractor, and advisor that there were several unique facets to the condenser retubing with thin walled tube materials that should also be developed. The most noteworthy of these new specification items are summarized as follows:

Tubing Specification

- A relatively few spare tubes were needed. Since it was expected tubesheets and support plate holes would be suitably prepared and the work done carefully, and because corrosion resistant retubing has a high abrasion resistance, few installation problems should occur. Thus much less than 1/2% spares were necessary to be purchased.

- Only the minimum tube length necessary was specified. By measuring an original spare tube, and checking and confirming that length by sliding a tape down an existing, in-place tube during a bundle shut down, the minimum was determined. (Extra tube length for margin, however small, costs money and adds nothing of technical value to the job.)

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- Peripheral tubes were purchased to be of the same wall thickness as the body of the tubing. The main tubing thickness was reasonably conservatively selected on the basis of experience. Other reasons for this choice follow. Heavier tubing at the outside of the bundle may delay impingement effects but will not arrest them; generally, a heavier wall alone does not aid in inhibiting tube vibration since a suitable intermediate support is a more effective way of avoiding problems: thicker tubing does improve the strength of the joint but usually is unnecessary.

  In summary, heavier wall outboard tubes were determined to cost much more on a unit basis and make the tube joint rolling procedures more complicated.

- Titanium tubes were purchased to be basically compatible with ASTM B338, Gr. 2 material properties, tests, handling, and metallurgical product characteristics. Excessive extra requirements were not thought to buy more quality.

Tubesheet Specification

- Titanium material was specified to be in general accordance with ASTM B265, Gr. 2, and the same remarks about the tubing metallurgy apply.

- To minimize air in-leakage, a stringent flatness and finish of the tubesheet flange area (i.e., over the 6 peripheral in.) was specified. A flatness level of under 0.02 in./ft and 125 RMS sufficed, and was within the capability of the manufacturer.

- Since bolt hole diameters are usually drilled to be only 1/8 in. larger than the bolt for the original equipment, an extra 1/8 in. was added to facilitate fit-ups in the field.

- Tube bundles drilled before the mid 1960s were laid out by hand, center punched, and drilled without benefit of numeric machine control. Today all drilling is computer generated and machine controlled. Hence it was recognized that significant care must be exercised to ensure all aspects of the old bundle pattern and waterbox bolting matched. Field templates and complex, extensive check measurements were required by the specification before tubesheet drilling was released. Because condenser tubes are somewhat flexible, exact tube hole location is not absolutely required. However, accurate location of through bolt holes is essential.

- Shop inspection hold points by the utility and technical advisor for detailed examination of the pattern, flatness, and finish were also included to ensure total compatibility.

Replacement Work Specification

- This specification included both the removal/ installation of tubes, tubesheets, and waterboxes. An inspection of the steam space, interior waterboxes, and exterior aided in writing an effective document because it served to define the field conditions and special problems and extra work requirements. (The inspection will be discussed later in the paper.)

- To demonstrate the contractor's capability, the specification required detailed manloading, procedures, and schedules.

- This specification encompassed virtually all aspects of the work though a contractor could for example, subcontract interference removal, replacement, and rigging to others. The contractor supplied all supervision, labor, and equipment.

- Support plate holes were required to be clean, smooth, and without burrs.

- The installation contractor had innovative tooling for installing grooves in the tubesheets to improve joint tightness. This work was originally included in the tubesheet specification, but no manufacturing bidders were capable of supplying the shallow grooving required. Only the installation contractor was willing to develop the necessary new tooling and perform the grooving just prior to the retubing at the site.

- The contractor was required to conduct and report on tube pullout tests to determine the optimum expander torque. The identical optimum settings were then used in the field work reproducing torque within $\pm$ 0.2 ft lb of the test to recheck every 50 tubes. To achieve uniform rolling, five roll expanders were specified since these were thin-walled materials.

- The contractor's tube roller personnel were required to have a qualification certification based on a test.

- Staking material and stake mockup tests were included in this specification because the tube bundle was unusual. More discussion of this subject is provided later in the paper.

- Requirements for a 24-hour shell side hydrotest, remedial expansion procedures, and an in-service waterbox test were included to verify tube-to-tubesheet joint and waterbox bolting integrity.

- The minimal finish and flatness requirements for the shell side flange and repair measures including welding repair were specified.

Initial Inspection of Condenser

It was mentioned previously that an initial inspection of the condenser prior to releasing bids for replacement work was found to be very useful. The purpose of this inspection was to define the condition of the condenser and determine any unusual replacement or installation work requirements or unforeseen items. These work requirements and conditions were then described in the replacement work specification to ensure a planning and cost awareness during bidding by the successful contractor.

This initial inspection was effectively conducted by the utility with the technical advisor. The utility provided knowledge of the specific problems of the condenser and its operational history; the technical advisor supplied a baseline perspective due to his broad understanding of typical condenser problems and conditions within the industry.

First, the condenser exterior was examined to provide an orientation and to identify items such as the cover and age of anti-sweat insulations over the waterbox bolts, staging areas, potential rigging paths, interferences, and structural support problems.

Next, the steam side of the condenser was inspected (after adequate ventilation, lighting, and safety measures were in force). The tubing was examined for signs of steam impingement, and the areas were noted. Problems of access, etc. that could interfere with the work were observed. Numerous photographs were taken to be utilized in subsequent pre-bid and other meetings with the contractor to show conditions that could affect costs. See for example Figures 1 and 2 for some of the conditions uncovered at Norwalk Harbor that were effectively defined by photographs. They ranged from omega shaped tube shielding that must be removed prior to pulling tubes.

Finally, the waterside tube and bolt hole locations were verified against the proposed tubesheet drilling pattern. (At this point in time, the tubesheets were in the process of manufacturing.) The types of tube plugs were also reviewed to estimate the number and their degree of removal difficulty. Figure 3 shows a typical photo of this area at Norwalk Harbor.

The inspection findings and results, including a brief operational history, were documented with photographs in a report for review by the prospective retubing contractor(s). The replacement specification reflected important findings of this report.

ADDITIONAL ENGINEERING STUDIES

In addition to the studies suggested in (1), several new studies were conducted to improve the retubed condenser reliability. First, the traditional estimates were outlined as follows:

To be certain turbine casing or hold-down bolts do not receive excessive force, it was required that an estimate be conducted of the modified uplift forces due to the appreciably lower weight of the tubing. Older condensers (like Norwalk Harbor) that are supported by springs required a spring adjustment if the lower weight becomes totally counteracted by the vacuum load. (Condenser-turbine flexible expansion joint arrangements required an assessment of the hold-down bolting stress and/or anchors.)

Seismic analysis revisions should be considered if this "g" coefficient represents a large horizontal loading mode. Hydraulic grade lines should change slightly too. This could require a re-estimate to ensure the flow, waterbox, and system pressures do not vary significantly or exceed some threshold-like a vacuum. To reiterate, these estimates are outlined in (1) with data from (3).

Two additional engineering studies were accomplished. The first was a finite element stress analysis (FEA) of the new tubesheet. The FEA, now a cost-effective modern method, was used to determine areas of high tubesheet stress and peripheral tube pullout loadings. The second was a tube vibration study. The latter, an improvement of prior art, defined the extent and depth of potentially damaging tube vibration. This tool was used to locate and size vibration arresting intermediate tube support, i.e., stakes.

Finite Element Analysis

The condenser represents a combination of interdependent mechanical components. Waterboxes, tubes, tubesheets, shell structures, shells, and flanges, etc. have a compex way of bending, flexing, and loading that generally defies simplified analysis. FEA is ideally suited to solve this type of problem. The major components are represented as plates, springs, and beams. A "mesh" of nodes is created representing the three-dimensional geometry of the major features of the condenser and connected by "elements." Each element is assigned a specific characteristic - a beam or plate with the material properties of the actual condenser component. Boundaries of the FEA model are established to focus the analysis. Loadings representing the design waterbox pressure and condenser vacuum are applied. Equations of the forces, moments, and geometric capability of all the model elements are formed and solved by the computer to determine the stresses. There is more detail in (4) on this type of study that can be applied to condensers with thin-walled titanium tubes.

FEA was an intimidating, costly study until graphic input-output display advances occurred, FEA codes for PCs were developed, solution software efficiency was improved, and high speed computer chips were widely available. Figures 4 and 5 show the Norwalk Harbor FEA mesh model and one output.

At Norwalk Harbor, the two small muntz tubesheets were replaced by one large titanium tubesheet. The muntz sheets were connected through a structural beam from one side of the waterbox to the other side. The objective of the FEA was to ensure that the thickness of the tubesheet was adequate in the absence of the bridge beam, and to determine if the new tubesheet stresses were satisfactory to establish the forces acting on each peripheral tube for pullout when the waterbox was at its design pressure of 25 psig.

These objectives were attained. It was determined the tubesheet stresses without the bridge bar support were safely below the yield strength for Grade 2 titanium with a peak of 15 KSI and that the maximum pullout loads were 350 lb, about 10% of the capability of the improved joints. Thus, it was concluded that the titanium tube-to-tubesheet joints were more than adequate for normal operation. They also had significant extra mechanical integrity in the event of unexpected hydraulic loads such as a waterhammer.

Advanced Tube Vibration Analysis

A vibration analysis to define a tube support span that should avoid damaging vibration is detailed in (3). It is based on a static load algorithm that does not reflect the actual dynamics of vibration. In addition, the estimate of (3) was developed for new condensers with full depth support plates. Therefore, it gives no information on the necessary bundle depth of intermediate tube supports to stop the onset of damaging tube vibration when retubing. That is, it does not dictate how deep stakes should be inserted into the tube bundle.

Most of the heat exchanger industry agrees that tubes that experience damage are subject to a whirling vibration that recurs at a certain threshold of steam velocity sweeping past the tube. One of the authors of this paper has observed this behavior in a laboratory simulation of condenser tube vibration. The onset of this type of vibration was first quantified for crossflow tube arrays by H. Connors (5) and is known as the "Conners Criteria." Applying it to a particular condenser requires defining the threshold constant - a function of the general tube array pattern, the tube fundamental natural frequency, damping coefficient, bundle steam velocity and density, unit weight, and diameter of the tubes.

To ensure a conservative estimate of the stake lengths at Norwalk Harbor, the longitudinal steam condensation pattern was determined based on the design performance of the condenser. The geometry of the tube bundle pattern was then defined in terms of flow area, etc. and the bundle was separated into banks of tubes to estimate the transverse condensation capability and to compute the steam velocity at intervals in the flow path. Tube material frequencies were computed on the basis of typical support plate hole clearances. The lowest condenser pressure expected at Norwalk was then utilized (along with the normal steam moisture and a variable accentuation of the turbine exhaust velocity-based on previous tests) to ensure the steam velocity is conservatively stated. The Conners criteria (5) was developed axially and at intervals inside the bundle. The maximum stake length was, however, installed in all bays at the mid-span to simplify the results. Figure 6 shows the results of the calculations and the variations expected. The design installation procedure developed and type of stake employed are separate subjects that will be covered later.

SPECIAL TESTS

The team of the utility, technical advisors, and retubing contractor decided it was useful to conduct two tests to support the retubing plan. The first test was a tube pullout test and the second a stake mockup test.

Tube Pullout

The tube pullout test was performed to determine the optimum load capability of the tube joint and the influence of tubesheet grooves on that load. A sample tubesheet plate of identical thickness and titanium material was drilled by the tubesheet manufacturer with about 100 holes in the same pattern, tube hole finish, and diameter as the supplied tubesheets. Half of these holes were cut with eight shallow grooves by the retubing contractor. Identical short lengths of titanium were tightly crimped at one end and expanded into the holes in groups of about seven tubes each with various rolling torques. Careful measurements of the original and final diameters were made. Tooling and expansion procedures were exactly the same as those to be used in the field at Norwalk Harbor. The assemblage was placed on a sturdy frame, and the tubes were filled with sand to a point below the tubesheet. A calibrated hydraulic ram was then actuated and pushed on the sand in the tube until the tube was forced from the tubesheet indicating a failure of the joint. The maximum hydraulic load, the rolling torque, and wall measurements were recorded to define the pullout load in terms of torque and wall reduction. Figures 7 and 8 illustrate features of the test. A curve of the torque versus pullout load determined the optimum tube expansion used for Norwalk Harbor.

The same test was performed on the plain and the grooved tubesheet holes. These results indicated that the grooved holes provided over a 100% increase in pullout load when compared to the non-grooved holes. Figure 9 shows the grooves. During the rolling process, the tube metal had extruded into the grooves sealing and constricting the tube. Thus, it was concluded that the joint with grooves added an important extra strength and perhaps, more importantly, leak tightness to the retubed condenser. In fact, for the grooved tubesheets, tube stresses at pullout are in the plastic range, i.e., permanent tube deformation has occurred. This further suggests that the tube bundle integrity will be preserved in the event of heavy seismic or waterhammer events, since a large strain energy can be absorbed directly by the tubes without failure of the joint.

Stake Tests

The purpose of the stake mockup test was to develop a plan for field installing of the stakes and to maximize the ability of the stakes to fully capture all the tubes. Since the tube bundle pattern had varied spacing, and each tube was separated from adjoining ones, it was important to test these features.

To conduct this test, a small section of a bundle pattern was fabricated for three bays with tubes installed to a depth that was more than the anticipated stake depth. A stake was inserted at the mid-span of the center mockup assembly. Various stake banding and positioning schemes were tried until the one that produced tight tubes and was reasonably effective to install was chosen. Note that the variable dimpling of the stake satisfactorily tracked the tube spacing of the bundle and with the banding scheme, appreciably added to the ability of the stakes to prevent motion and thereby tube vibration.

TAILORED DESIGNS

The technical advisor, utility representative, and retubing contractor contributed to three unique designs employed at Norwalk. These were the intermediate tube support stakes, tubesheet grooves, and tube steam impingement protection racks.

Stakes

The tube bundle pattern is shown on Figure 10. To prevent tube vibration, the analysis indicated the tubes located within 3 ft of the periphery must be arrested from motion. The tube layout shows the difficulty in accomplishing this: each row of tubes has a slightly different spacing than neighboring rows. Fit-up tests demonstrated that if the fabricated stakes were dimpled in sets with six separate spacings, they accommodated the bundle sufficiently well. In addition, the stakes were banded at every other tube with a stainless steel band. This required a tubing installation plan that proceeded around the bundle row by row with the stakes in place and banded before moving to the next row. Figure 11 is a photograph of the stake.

Grooves

The tubesheet grooves employed were similar to those mentioned in (6). While these grooves had been used in Europe, the authors do not believe they were previously applied in a complete U.S. condenser installation. Specifically, the grooves selected were about 1/64-in. deep and were eight in number, separated by 1/16 of an inch and centered in the tubesheet. These dimensions were not considered as an exact prescription. Rather it was the opinion of the team provided the tube extruded fully into these shallow grooves during rolling, the seal and joint strength would be significantly improved. This action is in contrast to the incomplete flow of the relatively stiff titanium into a more traditional, wide serration. The wide serration reduces the strength of the joint because the tube wall does not fully fill the serration. As was indicated in the SPECIAL TESTS section, the joint strength improved by a factor of at least two with the grooves described.

Impingement Protection

Several areas of the tube bundle were subject to steam impingement as illustrated on Figure 2. The new protection assembly shown on Figure 12 was designed to be permanent, not rapidly erode like the existing carbon steel pipe rack protection, and also to provide a flexible design unit that could be installed relatively easily at Norwalk Harbor.

Selected was a type of venetian blind design which completely shadowed the peripheral tubes and was situated on the tube bundle directly under the four corner high flow areas of the turbine exhaust. Stainless steel blades at 45° and of 3/16 in. by 2 in. were welded to steel framing angles with a middle brace. The whole assembly was then welded to the existing tube support plates in a side by side fashion. While this design was essentially successfully applied, in about 10% of the protection racks, cracks were observed in some blades where they were attached to the framing angles. This occurred after about 4 months of low backpressure, winter operation and were determined to be a result of fatigue. The failed impingement racks were weld repaired as necessary and a third point brace was added to reduce bending stresses and to avoid any potential for resonant frequency effects. Note that the winter operation of a condenser represents the most severe impingement rack loading condition because of the high velocities which exist at low backpressures. Having survived one winter season, the continued successful service of the racks is anticipated.

An open carbon steel personnel grating was also welded to the top of the more quiescent areas of the tube bundle. This allowed people to travel more easily through the steam space without walking on tubes and prevented turbine missiles from striking and damaging the bundle. It was selected to be very open so that there was virtually no obstruction to the steam traveling into the bundle and thus, no increase in the backpressure.

SITE WORK

After consultation with the utility engineer, the retubing contractor developed a work plan and schedule for the outage. As was stated, Norwalk Harbor Unit No. 1 had two tube bundles of about 5000 tubes each. The extent of the work and size of the job indicated that in the first week, two supervisors and eight mechanics would be needed. The mechanic's work force swelled to about 20 people over a 4-week period and dropped to initial levels for the last week of the job. The separate tasks of interference removal and replacement, i.e., cutting, welding, and rigging, involved another five or more people.

Throughout the installation, the utility, technical advisor, and retubing contractor discussed any problems that arose and rapidly developed effective pragmatic solutions that did not impede the job effort.

Grooves were cut into the tubesheets during the week preceding the outage. Insulation and interferences were also removed to provide access to the condenser.

During the outage, as illustrated on Figures 13, 14, and 15 for examples, the work proceeded and consisted of the usual tasks in an efficient sequence. Both waterboxes were removed with the overhead crane and taken from the area. Tube plugs, insert sleeves, and steam side stainless steel tube protective shields were removed. The existing steam impingement racks were cut out. The inlet end tubes were internally cut off near the tubesheet, and the tubesheets were lifted off. A hydraulic tube extractor broke the tubes free of the outlet side roll. A special walker then pulled each tube from the tubesheet and simultaneously flattened it. The tubes were brought manually to a chopper where they were sectioned to 4-in. pieces and transported from the area in containers.

Racks and grating sections were moved into the steam space. Support holes were cleaned using ball burrs with rigid tolerances. All condenser components were inspected for dimensional verification, flatness, scratches, etc. Repairs, cleaning, and grinding were accomplished as necessary.

The single new tubesheets and gaskets were installed and held with collar bolts. Tube boxes were moved to the front of the condenser. Tubes were fitted with guides and installed through the tube holes. The interior tubes (refer to Figure 10) were first pushed. Then the retubing was moved row by row around the bundle as the stakes were simultaneously set and intermittently attached to tubes with bands. After all tubes were inserted, they were expanded on the inlet end to the optimum torque established in the pullout test. Tool rolling torque was checked after every 50th tube expansion to ensure consistent, reliable rolls. Clusters of tack tubes were rolled at the outlet end uniformly across the tubesheet with frequent checks to ensure the tubesheet was flat and aligned. The remaining tubes were then rolled. Steam impingement protection assemblies and grating were also welded in place during this time frame.

Gaskets and waterboxes were reinstalled. The completed work was hydrotested first on the shell side, where as is typical about 25 tubes required re-rolling, and then on the waterbox side to check the gasket tightness. The job then quickly demobilized, and the plant started up soon afterwards.

CONCLUSIONS

By introducing several engineering, tooling, and procedural innovations, the committed partnership of the utility, technical advisor, and retubing contractor completed the work effectively. A high reliability condenser installation has resulted. Subsequent physical inspections have indicated no waterside or steam side mechanical problems. There have been no circulating water leaks or tube failures. Unit thermal performance, as indicated by recent station data, has improved slightly despite the condenser tube replacement with a lower conductivity material. Everyone is happy!

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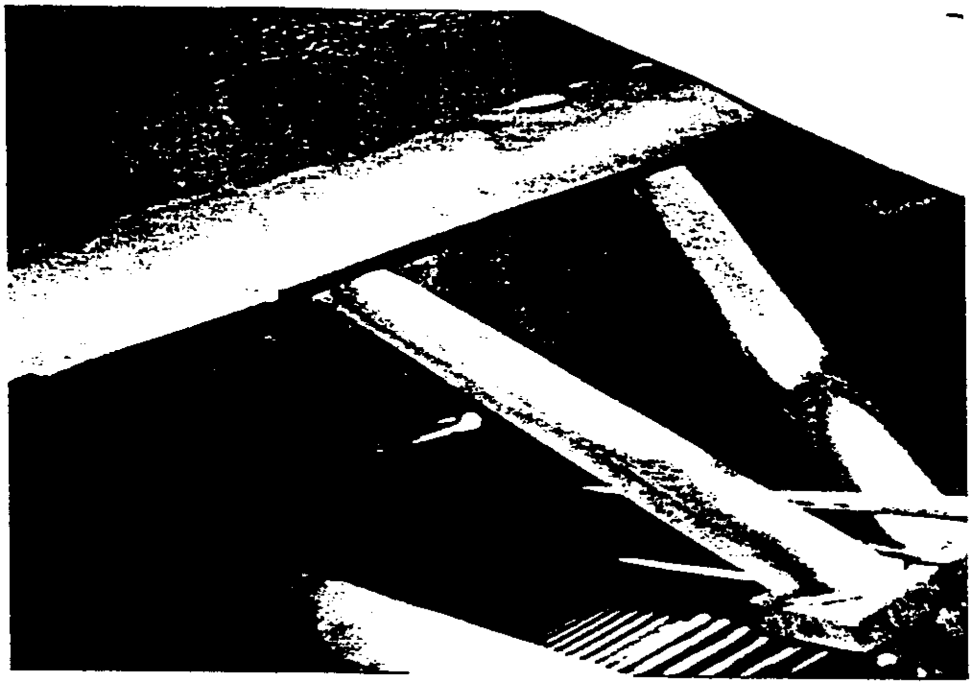

Figure 1. Shell Support Bracing Condition

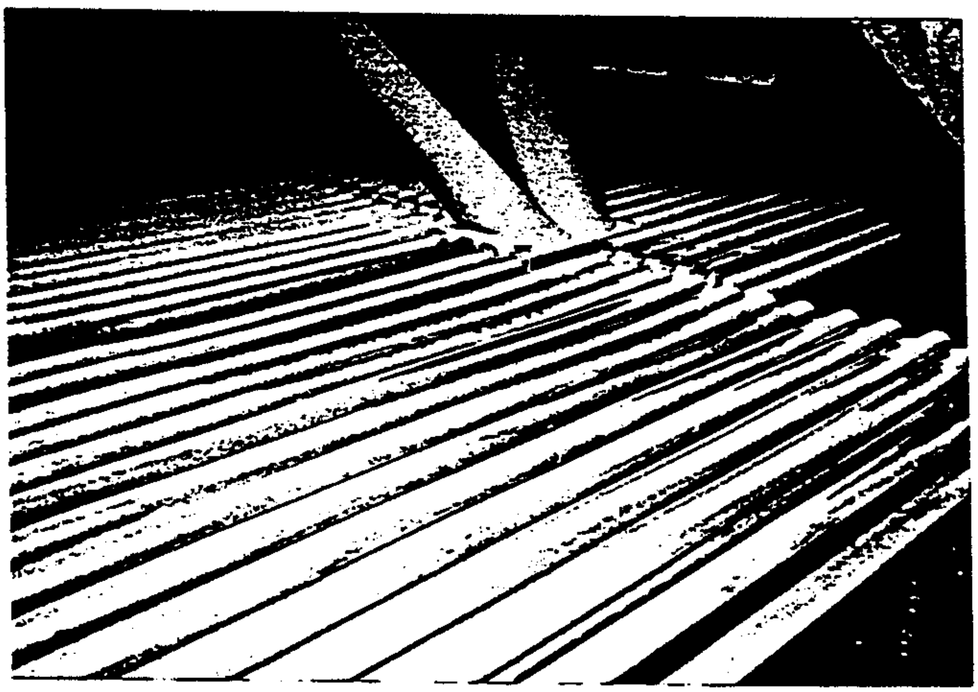

Figure 2. Steam Impingement Protection Rack Condition

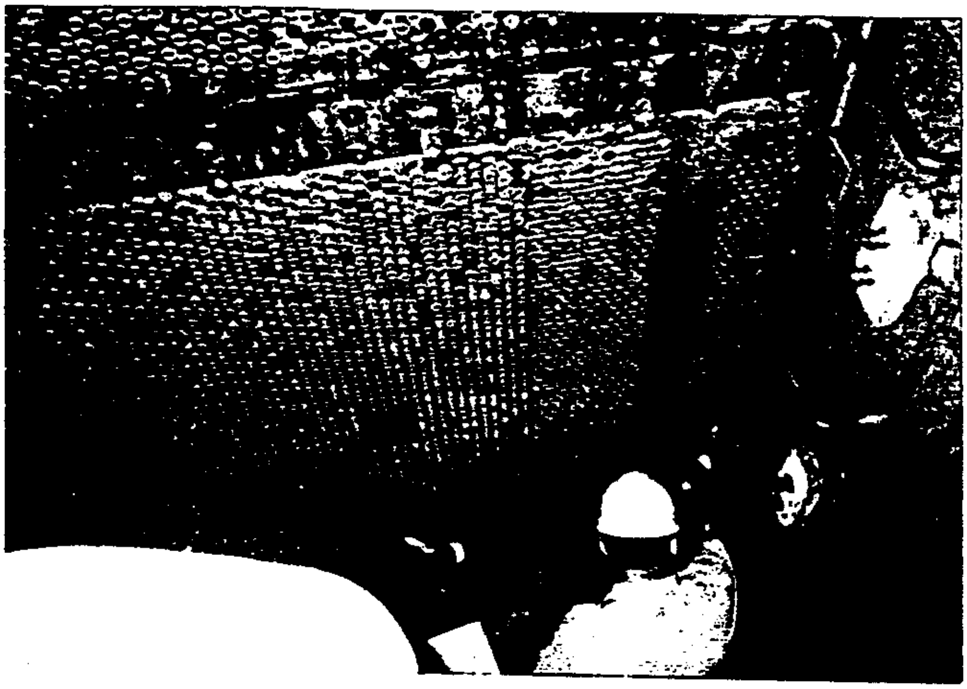

Figure 3. Waterbox: Inserts and Tube Plug Condition

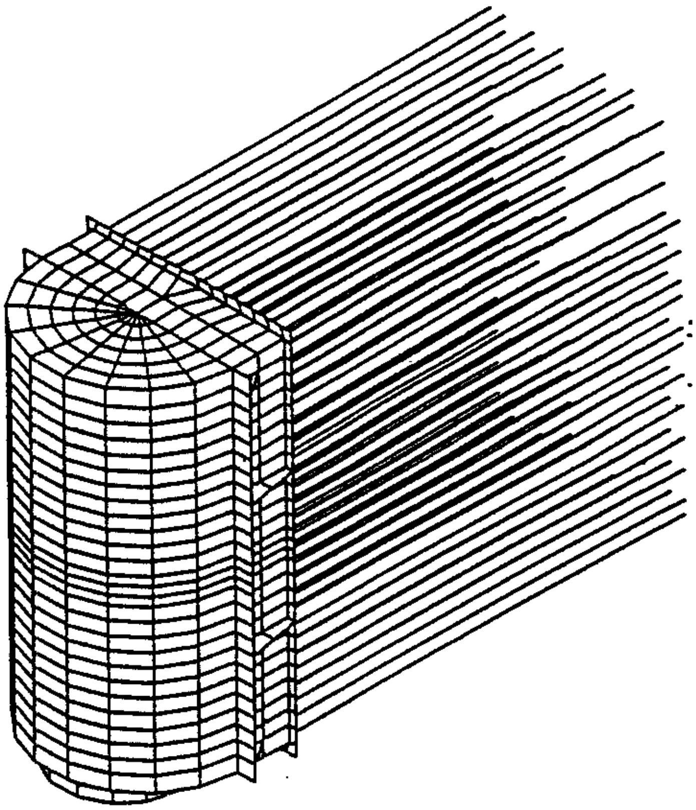

Figure 4. Finite Element Analysis: Waterbox, Tubesheet, and Tubes-Mesh Model

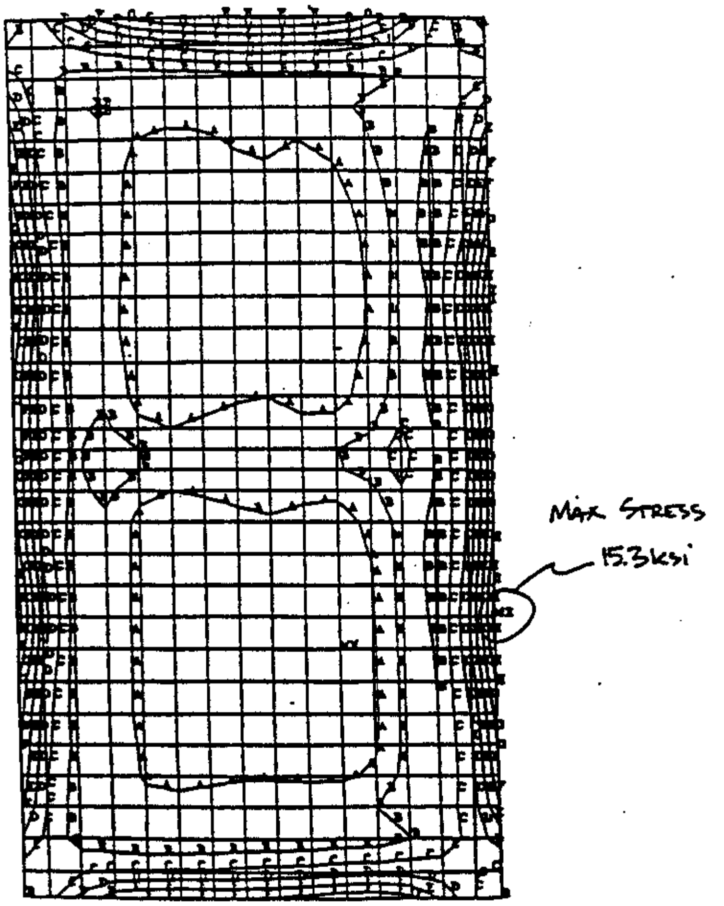

Figure 5. Finite Element Analysis: Tubesheet Stress Pattern

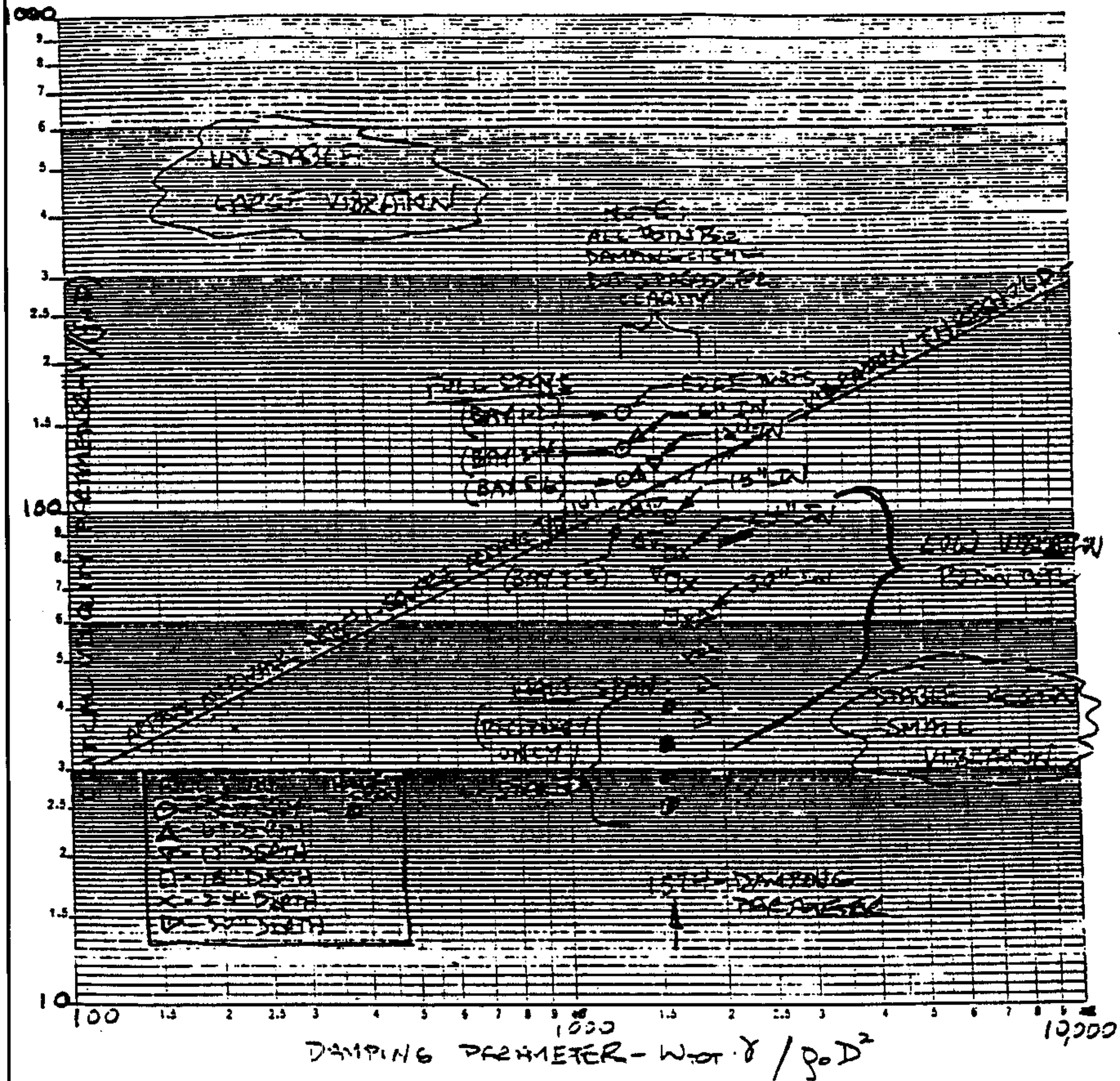

Figure 6. Fluid-Elastic Tube Vibration Criteria

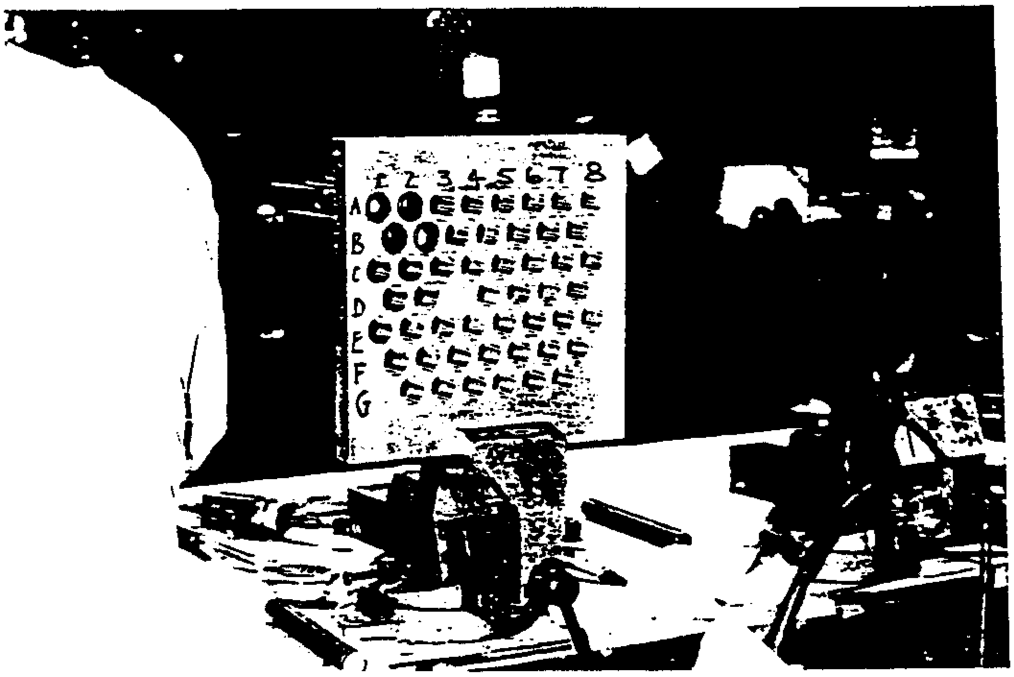

Figure 7. Tube Pullout Test

Figure 8. Tube Pullout Test

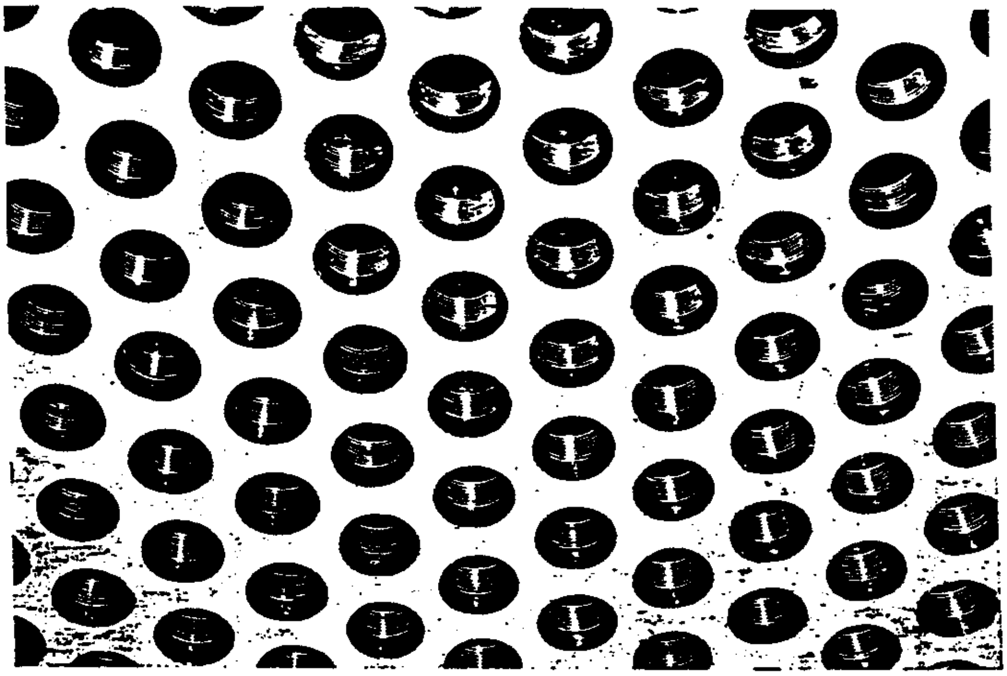

Figure 9. Tube Sheet Grooves

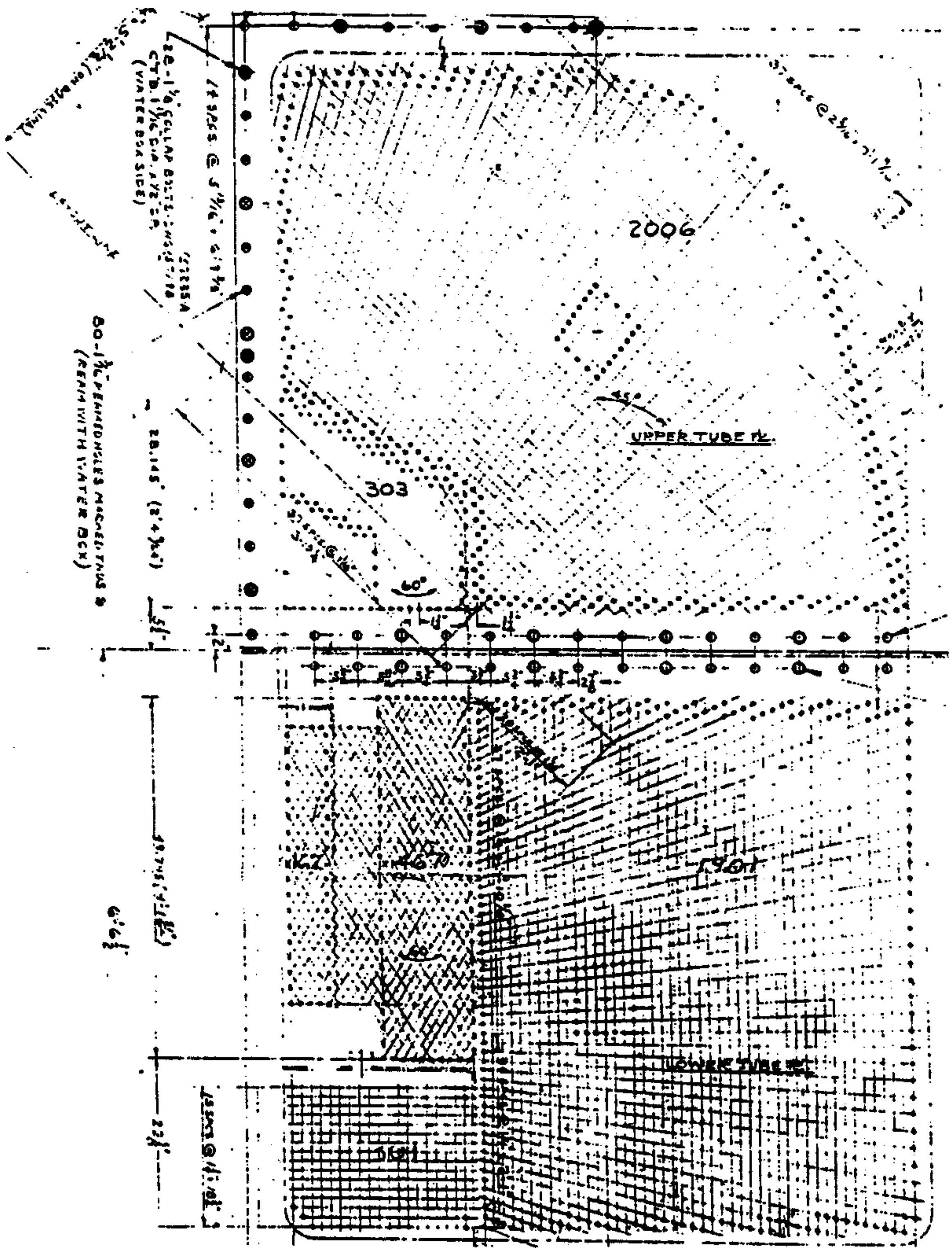

Figure 10. Tube Bundle Pattern

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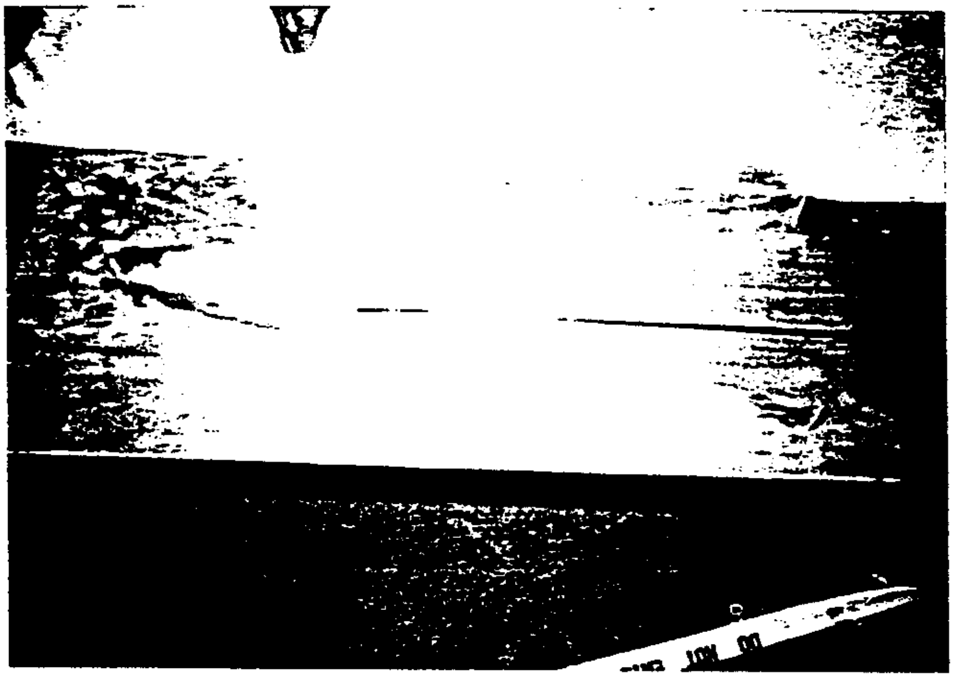

Figure 11. Stake Design Features

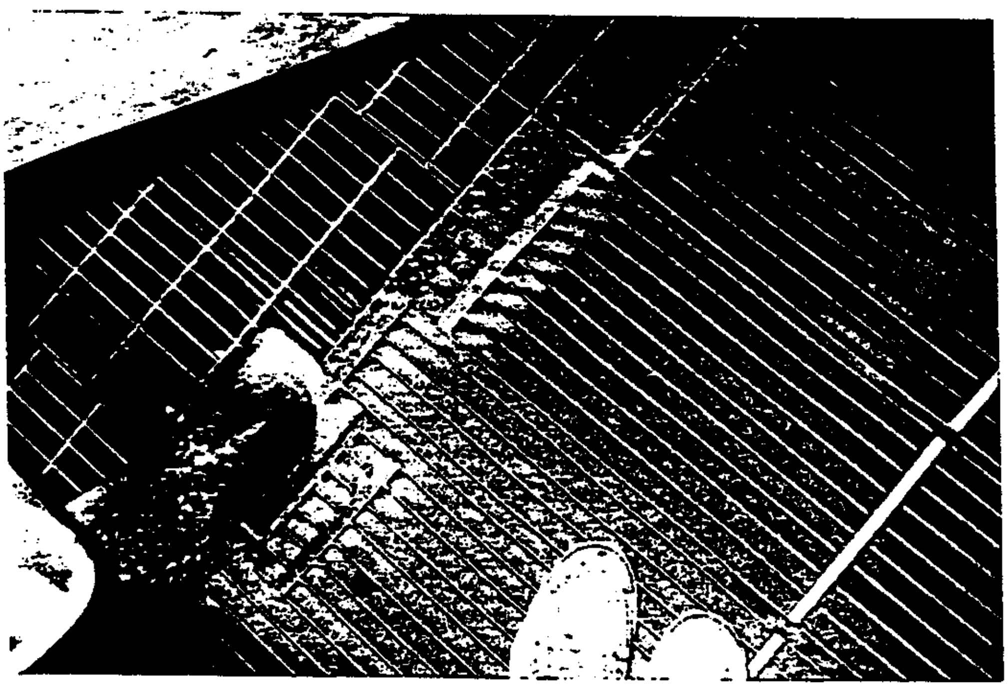

Figure 12. Steam Impingement Protection Racks
(and Personnel Walk Surface at Left)

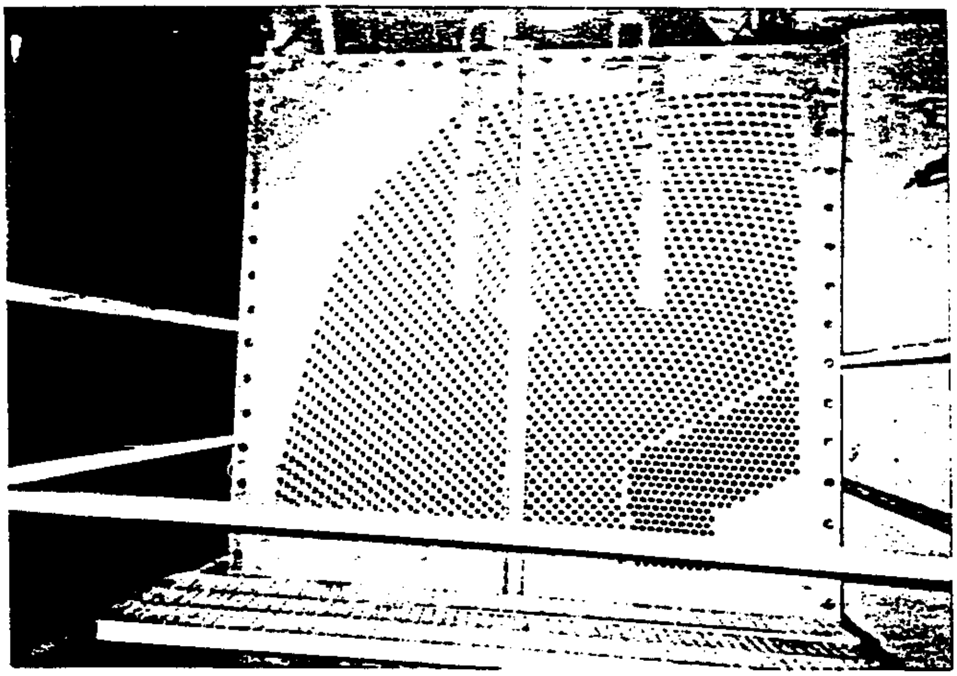

Figure 13. Tube Sheet Moving Into Place at Side

Figure 14. Pushing Tubes at Site

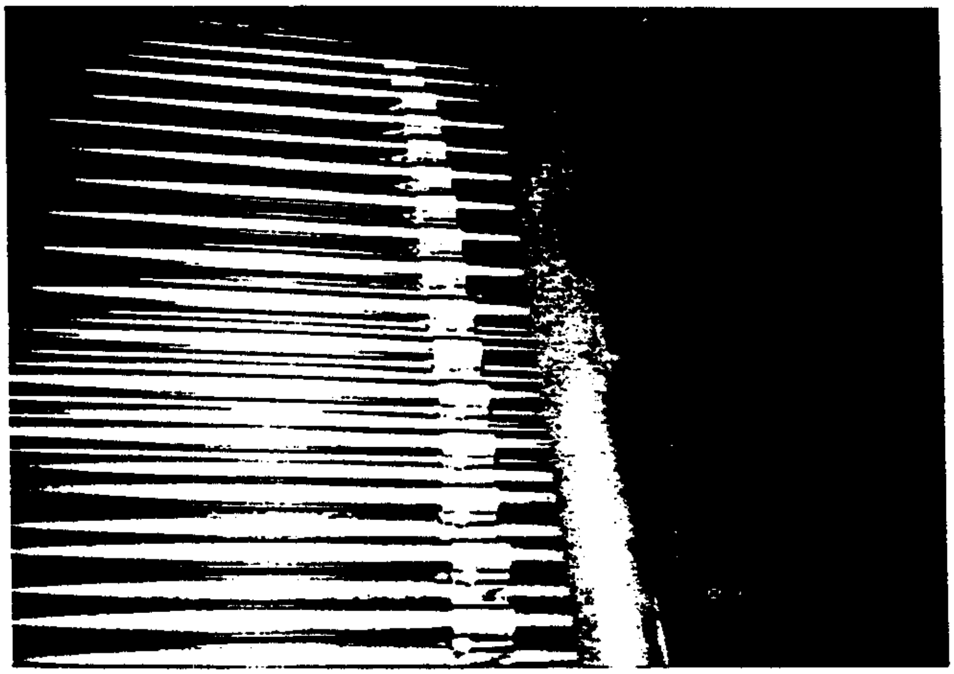

Figure 15. New Peripheral Titanium Tubes With Stakes Installed