ailure-Cause Analysis—Feedwater Heaters

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Project 1265-7
Final Report
April 1981

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nternational Energy Associates Limited
Vashington, D.C.

LECTRIC POWER RESEARCH INSTITUTE

Failure-Cause Analysis—
Feedwater Heaters

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Research Project 1265-7

Final Report, April 1981

Prepared by

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ABSTRACT

Feedwater heater (FWH) failures have had a significant adverse impact on availability and thermal efficiency in large fossil-fired power plants. The purpose of this study is to document the major causes of FWH failures and to make appropriate recommendations for improvement.

Data were gathered through a literature search; a questionnaire distributed to utilities with fossil units over 500 MWe; and visits to selected utilities, architect/engineers, and FWH vendors. Responses to the questionnaire revealed that problems had been experienced in approximately one-third of all the FWHs at 44 utilities. Major problem areas were tube vibration, flashing in the drains subcooler zone due to inadequate level control, tube inlet erosion, corrosion, steam impingement, and difficulty in plugging failed tubes.

The main conclusion from the study is that industry standards do not adequately address most of the major FWH problems that were reported. As a result, utilities do not have sufficient guidance to prepare purchase specifications so that these problems can be avoided. It is recommended that straightforward guidelines be developed to address each of these FWH problem areas.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

This final report under RP1265-7 is one of several surveys being conducted through the Fossil Plant Performance and Reliability Program to define more clearly the major generic equipment and/or operating problems responsible for utility power plant outages. This survey includes input from 57 U.S. utilities encompassing 175 generating units with an average size over 500 MW and 1635 feedwater heaters.

PROJECT OBJECTIVES

The main objective of this 16-month investigation was to determine the underlying causes of feedwater heater failures. Other objectives were to identify design changes to reduce failure frequency, to quantify the relative importance and contribution of each problem to feedwater heater reliability, and to identify those problems having solutions requiring developments in current technology.

PROJECT RESULTS

Data analysis resulting from this survey clearly demonstrates problems with feedwater heater systems and their components that contribute to the unavailability of generating units. Six major problem areas are tube vibration, flashing of drains in subcooler zone, steam impingement, tube inlet end erosion, corrosion, and plugging of failed tubes. The indicated causes and effects are discussed.

Recommendations are made to improve the reliability of existing feedwater heaters, and generic problems requiring future research and application of existing technologies are identified. It is also recommended that users place more emphasis on the initial procurement phase to specify those design features that improve reliability. Another recommendation is to encourage manufacturers to accelerate their efforts to improve the technology and correct critical problems by upgrading industry standards. Implementation of the recommendations included in this report by users and manufacturers can substantially improve the availability of feedwater heaters.

Further information regarding utility contacts and plants associated with this survey may be made available through EPRI.

Isidro A. Diaz-Tous, Project Manager
Coal Combustion Systems Division

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INTRODUCTION AND SUMMARY

GENERAL

Feedwater heater (FWH) performance plays a significant role in controlling steam power plant efficiency and availability. If a FWH fails and must be removed from service, the possible impacts include reduced thermal efficiency due to inadequate heating of the feedwater, overloading of the remaining FWHs, overloading of the turbine, and plant derating, especially if the system design requires the isolation of an entire string of FWHs to gain access to the failed FWH. The same is true even after the failed FWH has been restored to service if repairs cause reduced FWH efficiency (as with the plugging of a significant number of tubes). Continued operation of a FWH after its initial failure while waiting for a more opportune time for plant shutdown often leads to secondary failures that can rapidly cause extensive damage and can lead to premature FWH replacement. In many plants, safe isolation of a failed FWH cannot be achieved, thus aggravating the impact of FWH failures, as repair procedures would then require a unit outage.

The Electric Power Research Institute (EPRI) analyzed data available from the Edison Electric Institute (EEI) and issued a report (Special Report FP-422-SR) in June 1977, identifying the principal plant areas that contribute to plant non-availability. The EPRI analysis identified FWHs as having a moderately high outage impact on fossil-fired units with capacities exceeding 600 MWe. This information, combined with reports from EPRI workshops concerning the significant and sometimes serious availability problems that some utilities experience with FWHs, clearly cites the FWH as an important candidate for improvement in the context of the EPRI Fossil Plant Performance and Reliability Program.

STUDY APPROACH

The objective of this study is to address utility concerns about FWHs by (1) documenting the major causes of FWH failures, (2) identifying areas that need improvement, and (3) making appropriate recommendations. Special emphasis is given to those areas where standards and specifications need improvement and to those corrective efforts that appear to be prime candidates for further study under EPRI sponsorship. The information used in this study was obtained from three major efforts:

- Survey of operating plants. A questionnaire (described in Section 2) was distributed via the EEI Prime Movers Committee to utilities that operate fossil plants of capacities over 500 MWe. Forty-four utilities responded, providing information on a total of 411 problem FWHs in fossil units.
- Literature search. This effort consisted of a review of pertinent articles in industry periodicals and other related journals from 1965 to the present in order to gain background of FWH problems as reported in the literature. Appendix C is a summary of the literature search.
- Site visits and telephone interviews. As described in Section 2, selected utilities, architect/engineers (A/Es), and FWH vendors were visited. Visits were augmented by selected telephone interviews to obtain additional information on reported FWH failures and corrective measures.

The final phase of the study effort consisted of an analysis of the data. The principal conclusions and recommendations are summarized in the following section, Conclusions and Recommendations. Section 1 provides a functional description of closed FWHs. Section 2 summarizes the survey results. Sections 3 through 9 discuss specific FWH problem areas: tube vibration; level control and drains subcooler zone problems; tube inlet erosion; tube plugging; steam impingement; corrosion; and miscellaneous other problems, such as inadequate quality control, shellside weld leaks, and gasket failures.

CONCLUSIONS AND RECOMMENDATIONS

The major conclusions and recommendations of this study are summarized below. These findings are addressed in more detail in other sections of the report.

General Approach to FWH Procurement

In evaluating the data and the comments received during this study, the study team concluded that the FWH procurement process, itself, may be contributing to poor reliability by placing an inordinate emphasis on FWH acquisition cost, thereby discouraging vendors from developing design/manufacturing techniques that, although initially more costly, could be utilized to improve performance and to reduce overall life cycle costs.

Typically, a utility or its A/E drafts procurement specifications which include tube material selection and general operational performance requirements. The vendors respond with proposals that attempt to meet the stated requirements at a competitive cost. This process effectively minimizes initial costs, but it may be inadequate for obtaining quality, reliability, and minimum life cycle costs. With detailed technical guidance (especially in the critical, more specific recommendations that follow) and with a formal statement in the procurement process to the effect that reliability factors will carry equal weight as initial cost factors in the selection process, utilities would be in a better position to procure more reliable FWHs. During the interviews, it was noted that several utilities are free to choose a vendor other than the low bidder. However, even in those cases it appeared that inadequate technical information was available to ensure that a reliable product was purchased.

Recommendation: Guidance for purchase specifications for high-, intermediate-, and low-pressure FWHs should be developed. Some specific problem areas that should be addressed in these specifications are discussed below. In addition, a more conservative approach to design should be used by vendors and users.

Level Control and Drains Subcooler Zone Problems.

Survey results indicate that significant damage can occur to carbon steel tubes in the drains subcooler zone if the proper water level is not maintained or if the drains subcooler inlet area is improperly designed. Contributing causes include poor design of the level control system, poor maintenance of the level control system, recommended normal water levels that are too low, and deficiencies in the quality of the welds and the design of the joints in the drains subcooler zone. Industry standards do not address these areas, nor do most utility purchase specifications. Also, the level control system is designed and purchased separately from the FWH itself, although it should be an integral part of the design. As a result, the damaging effects of inadequate level control on the FWH are not always recognized. (See Section 4.)

Recommendations: Develop straightforward guidelines in the following areas:

- Determining the correct water level and range for horizontal FWHs with integral drains subcoolers (e.g., number of tube rows, if any, that should be covered; inches of submergence for the drains subcooler inlet nozzle).
- Stating the maximum velocity and minimum flow area for the drains subcooler inlet.
- Explaining the need for anti-vortex devices in the drains subcooler inlet.

- Designing the drain level control system, including response time, operating range, alarm levels, and trip setpoints. Both transient and steady state conditions should be considered in the design. To develop such guidelines, it may be necessary to obtain data from an instrumented FWH and to correlate the data with dynamic computer simulations.

- Designing the joints in the drains subcooler envelope to prevent cracking and leakage of steam into the drains subcooler zone.

- Establishing the thickness of the drains subcooler endplate.

- Comparing the advantages and disadvantages of alternative drains subcooler designs (e.g., fully submerged integral drains subcooler, separate drains subcooler, integral drains subcooler with only the inlet nozzle submerged) in terms of performance and longevity.

- Designing the overall system to integrate FWH operation with the remainder of the system (i.e., drain valve location, pipe sizes, emergency dump line location, etc.).

Tube Vibration

A review of industry standards shows inadequacies with respect to the issue of tube vibration. Methods for designing FWHs and specific guidance on writing purchase specifications to minimize vibration are not included in the standards. As a result, the treatment of vibration in purchase specifications varies widely, and many do not adequately specify overload conditions so that the FWH can be designed properly to avoid vibration. (See Section 3.)

Recommendations:

- Develop a data bank on FWH tube vibration parameters. This data bank should include information such as tube pitch, shell diameter, baffle arrangement, normal and abnormal shellside flows, clearance between tube OD and tube support plate, and tube wall thickness for FWHs with and without vibration problems. Also, the data bank should differentiate among various causes of vibration, such as excessive fluid flow, condensate slugging, cascaded drains, etc. The information could then be used to verify or modify existing vibration design methods, and could be useful in developing new standards on vibration.

- Examine ways to detect damaging tube vibration in an operating FWH. If instrumentation could be installed to detect tube vibration, a utility could ensure, at initial startup, that a FWH is free from vibration problems. Such a vibration checkout could be included in the FWH acceptance tests.

- Develop guidelines for addressing vibration in utility purchase specifications. The guidelines should recommend the abnormal flow conditions to be used for vibration design, the need for a desuperheater bypass line, tube-to-baffle plate clearance, analytical design methods to be used by vendors, margins of conservatism, etc.

Tube Plugging Procedures

The utility personnel providing input to this study exhibited a widespread lack of confidence in the tube plugging methods available, including those recommended by vendors. While part of this problem may be due to shortcomings in training, poor maintenance conditions, or simply failure to follow the procedures, the need to identify or to develop practical, technically sound plugging methods is an urgent requirement for improved FWH performance. (See Section 6.)

Recommendations:

- Develop comprehensive plugging procedures for each generic method of tube plugging in use today, based on proven engineering practices and demonstrated performance. For basic methods used in the past (e.g., tapered plugs, welded plugs), much of the effort would entail identification and review of the most successful procedures now in use and the experimental or operational performance data that provide confidence in those procedures. Some testing would be required to determine applicability to different metals, suitability under various operating conditions, the limitations of the procedures, etc. The objective would be to provide, as models or standards, the best possible procedures and their known limitations and guidance to ensure success of the repair. This information is needed for authoritative reference by utilities and vendors.

- Provide guidance for the utilities that would assist them in addressing tube plugging in their FWH procurement specifications. This could be an extension of the effort recommended above. The need to specify channel designs that permit safe and easy access should be included.

- Make available to the utility industry procedures and equipment for testing individual tubes adjacent to a failed tube to limit unnecessary "insurance" plugging.

- Initiate R&D efforts to develop and make available the more promising new and special purpose plugging techniques such as, explosive plugging "flower" plugs, etc. (See Section 6 and Appendix D.)

Tube-to-Tubesheet Connections

Industry standards do not provide adequate guidance to assist the utilities in specifying the preferred techniques for sealing tubes to tubesheets during FWH construction (e.g., Is tube expansion desirable in addition to welding, and if so, what are the special precautions and the preferred sequence of fabrication?). (See Section 7.)

Recommendation: Provide guidance to the utilities regarding the best proven practices for tube-to-tubesheet welding and expansion, to assist them in preparing procurement specifications and in evaluating proposals.

Tube Inlet Erosion

The literature review and discussions with several FWH vendors indicated that the problem of tube inlet erosion is well understood. It is not recommended that further study in the area of FWH tube inlet erosion be pursued. However, it is recommended that this problem be formally recognized and addressed in the HEI standards for closed FWHs. Standards should address channel and tubesheet geometry and designs (1) to minimize turbulence and (2) to allow for corrective measures such as tube inserts and flow distributors.

Corrosion

All materials used for FWH application are susceptible, in varying degrees, to some form of corrosion. Industry standards that are often relied upon by utilities when preparing purchase specifications do not adequately address corrosion-related problems and remedies.

Recommendations:

- Initiate a program to compile data on the causes of corrosion in materials used in FWHs. The ultimate objective of this program would be to provide the utilities with guidelines for determining the compatibility of specific ranges of chemistry and plant operating conditions with the materials selected for FWHs.

- Conduct a study to investigate the suitability of some proposed, highly corrosive-resistant materials for FWH application.

Steam Impingement

Steam impingement refers to shellside tube damage caused by the impact of extraction steam or drains flowing at the tubes from an inlet nozzle. The literature review and survey results indicated that there are at least four causes of steam impingement damage in FWHs:

1. An impingement plate breaks loose.
2. Inadequate design of the impingement plate.
3. Wet steam conditions in the desuperheater zone of the FWH.
4. Dry steam entering the moist condensing zone at an excessive velocity.

Industry standards do not address these problems in sufficient detail.

Recommendations: It is recommended that guidelines be developed in the following areas to assist utilities in dealing with FWH steam impingement problems:

- Impingement plate design. Guidelines on impingement plate thickness, geometry, materials, and methods of attachment are needed for use in preparing FWH purchase specifications or modifying impingement plates in existing FWHs.

- Steam impingement parameters. Guidelines are needed that provide limiting values of the relevant parameters (e.g., steam quality, velocity, water droplet size, angle of impingement, kinetic energy) associated with steam impingement damage, especially in areas where an impingement plate provides no protection (e.g., the entrance to the condensing zone).

Such guidelines would help predict the likelihood of steam impingement damage for a given FWH design under various operating conditions. The need for external modifications (such as a desuperheater zone bypass), operating procedure modifications, or an improved FWH design could then be determined.

New Concept Possibilities

As a result of the general evaluation of the accumulated data, several ideas for new approaches to FWH problems evolved. Two possibilities emerged that were not specifically addressed in the literature or the utility surveys; they are not verified as workable concepts, but are mentioned briefly here as possible candidates for further EPRI study in the FWH design improvement area. Both ideas are based on the observation that most failed FWHs are eventually replaced because the number of plugged tubes precludes efficient operation of the FWH. If individual tubes could be repaired or replaced at the site, most FWHs could continue in service for an extended period.

Recommendations:

- Conduct a study on the feasibility of inplace tube repair methods, so that tubes could be repaired in place, rather than plugged, after failure.

- Investigate the advantages and disadvantages of a closed FWH that uses straight tubes and a floating rear tubesheet, for both low- and high-pressure applications. Such a design could allow for onsite replacement of individual failed tubes and could improve maintainability, which is not feasible in U-tubed FWHs. Straight-tubed FWHs have been used in the past, but U-tubed FWHs gained favor apparently because of improved reliability.

- Conduct a survey of foreign FWH design practices to search out new, innovative concepts that could be used in the U.S.

Section 1

GENERAL DESCRIPTION OF CLOSED FWHs

1.1 GENERAL

All modern, large steam power plants use a process of regenerative feedwater heating to increase the overall cycle efficiency of the plant and to minimize induced thermal stresses in the boiler. Figures 1-1A and 1-1B are diagrams of a typical plant utilizing three sets of feedwater heaters (FWHs) -- low-pressure, intermediate-pressure, and high-pressure.

The low-pressure (LP) FWHs begin the process by heating the subcooled condensate. LP FWHs are of the closed type, using low-pressure turbine extraction steam for heating. In newer plants, they are often placed at the turbine exhaust throat within the condenser.

The intermediate-pressure (IP) and high-pressure (HP) FWHs are located at the discharge of the feed-booster and the boiler feed pumps, respectively. They are always of the closed type and are similar in basic design and function.

Some plants also have a deaerating FWH, which is an open-type heater that serves to remove dissolved oxygen, as well as to heat the feedwater. Deaerating FWHs are not within the scope of this study.

1.2 CLOSED FWHs

Most IP and HP FWHs are of the 3-zone (desuperheating, condensing, and drain subcooling zones) design. LP heaters are typically of the 3-zone or 2-zone (condensing and subcooling zones) design. (See Figures 1-2 and 1-3.) The major parts of the FWH are discussed below:

- Channel: The FWH channel provides for the feedwater inlet and outlet nozzles. There are four basic channel configurations. (See Figure 1-4.) Channels are designed to minimize the effects of erosion on the tubesheet and to provide convenient access for tubesheet plugging and other related maintenance.

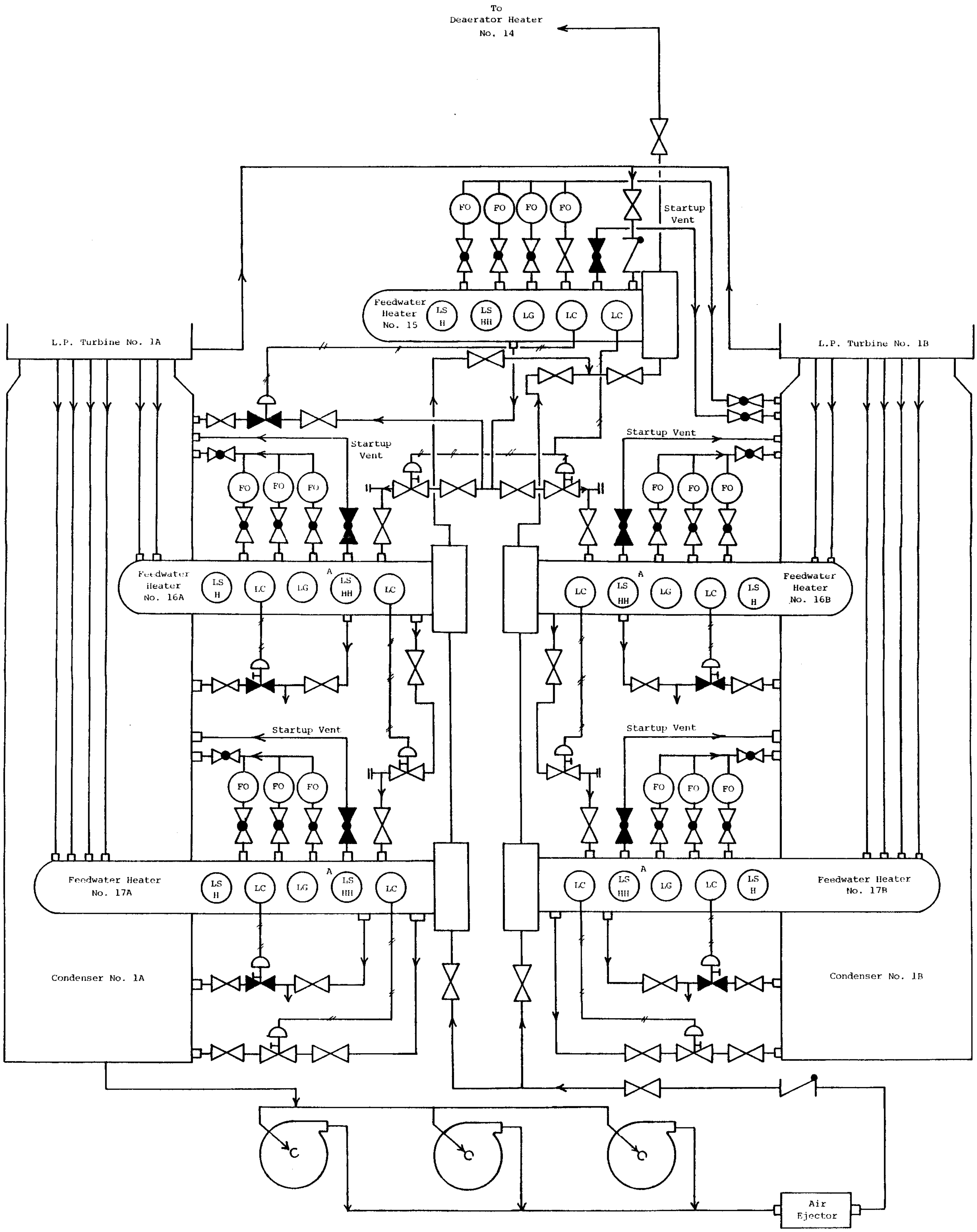


Figure 1-1A. Typical Arrangement of Feedwater Heaters in a Fossil Unit

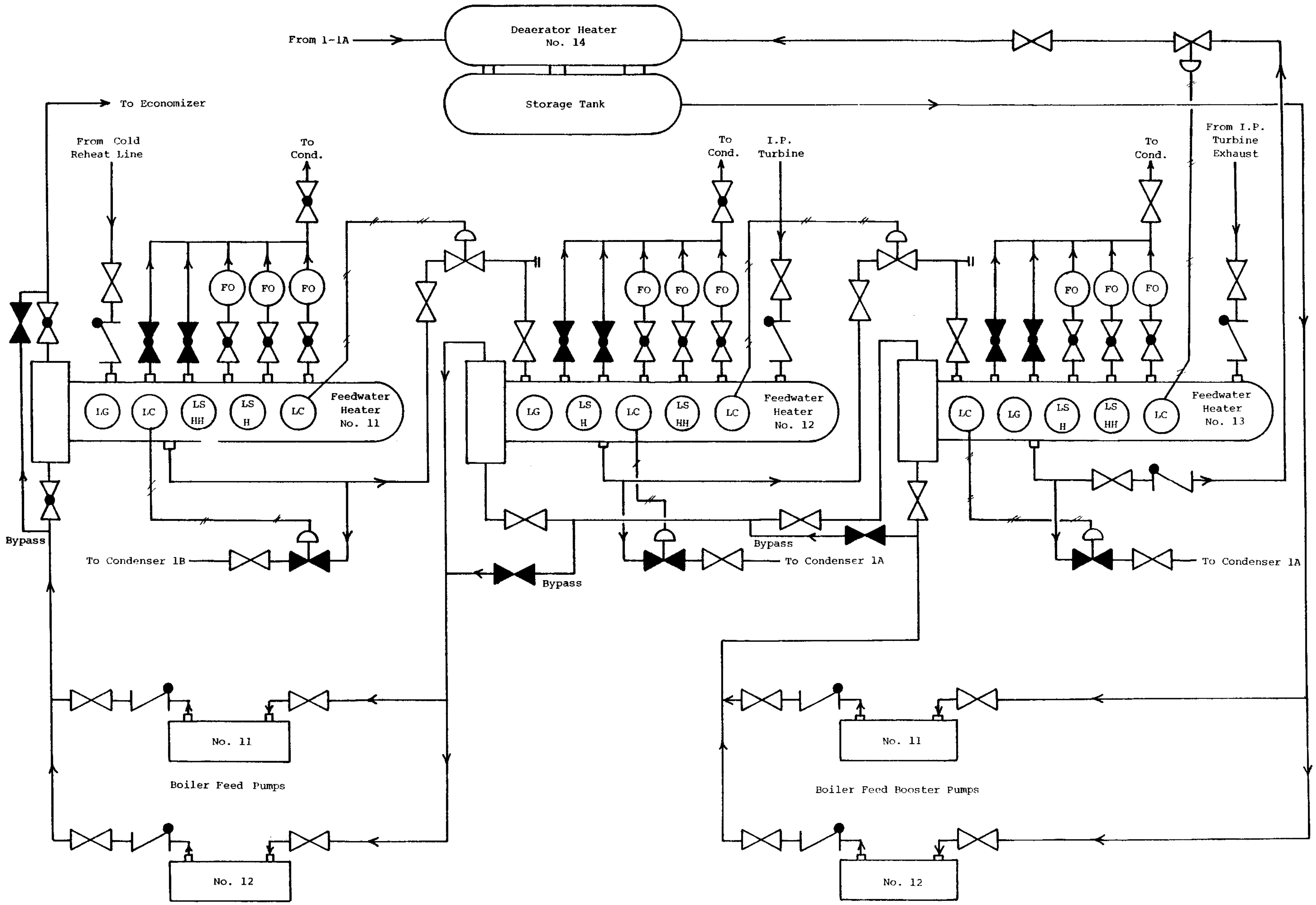


Figure 1-1B. (Continued from Figure 1-1A.

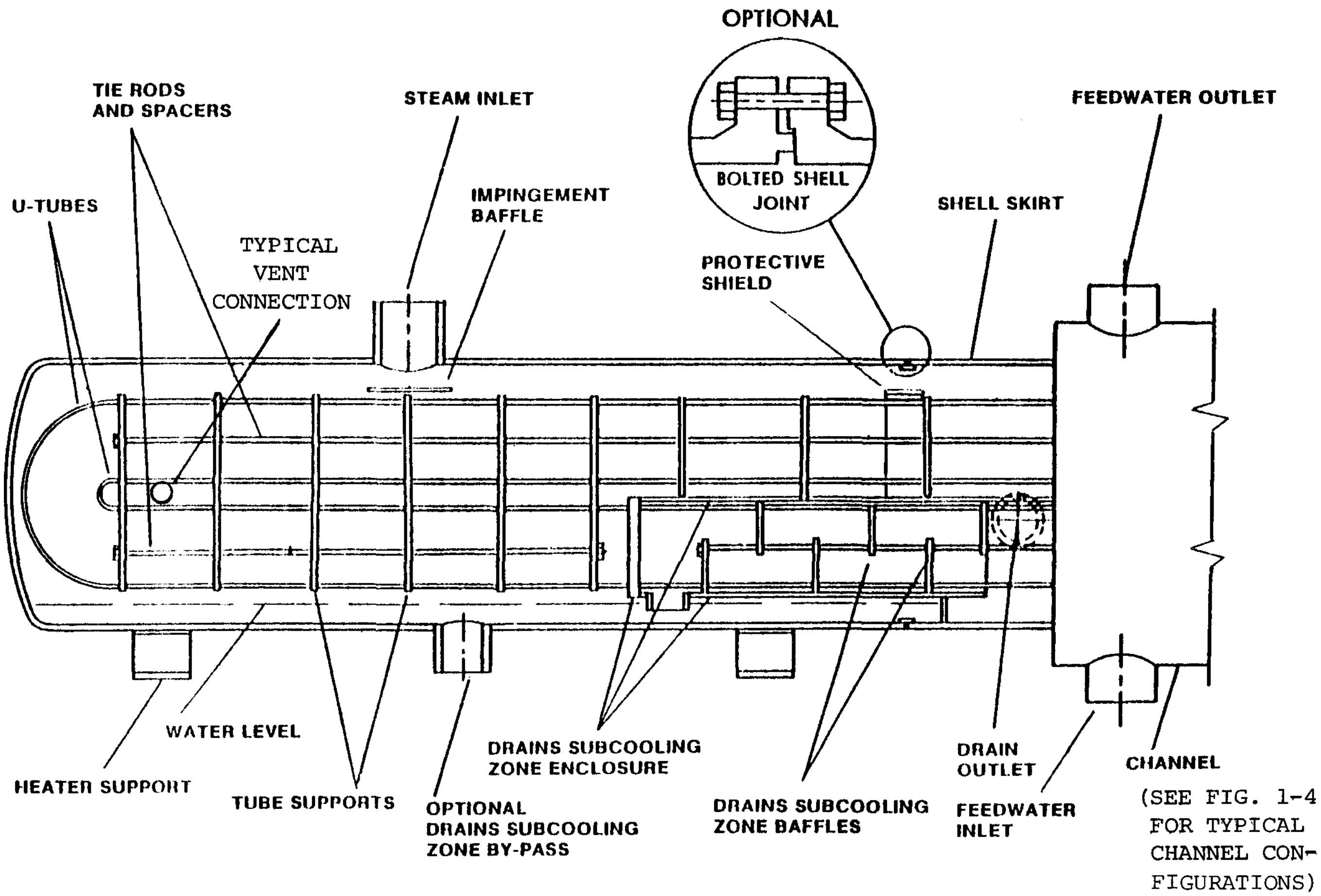


Figure 1-2. Typical 2-Zone Feedwater Heater (Condensing and Subcooling Zones)

Source: <u>HEI Standards For Closed Feedwater Heaters</u>, Third Edition.

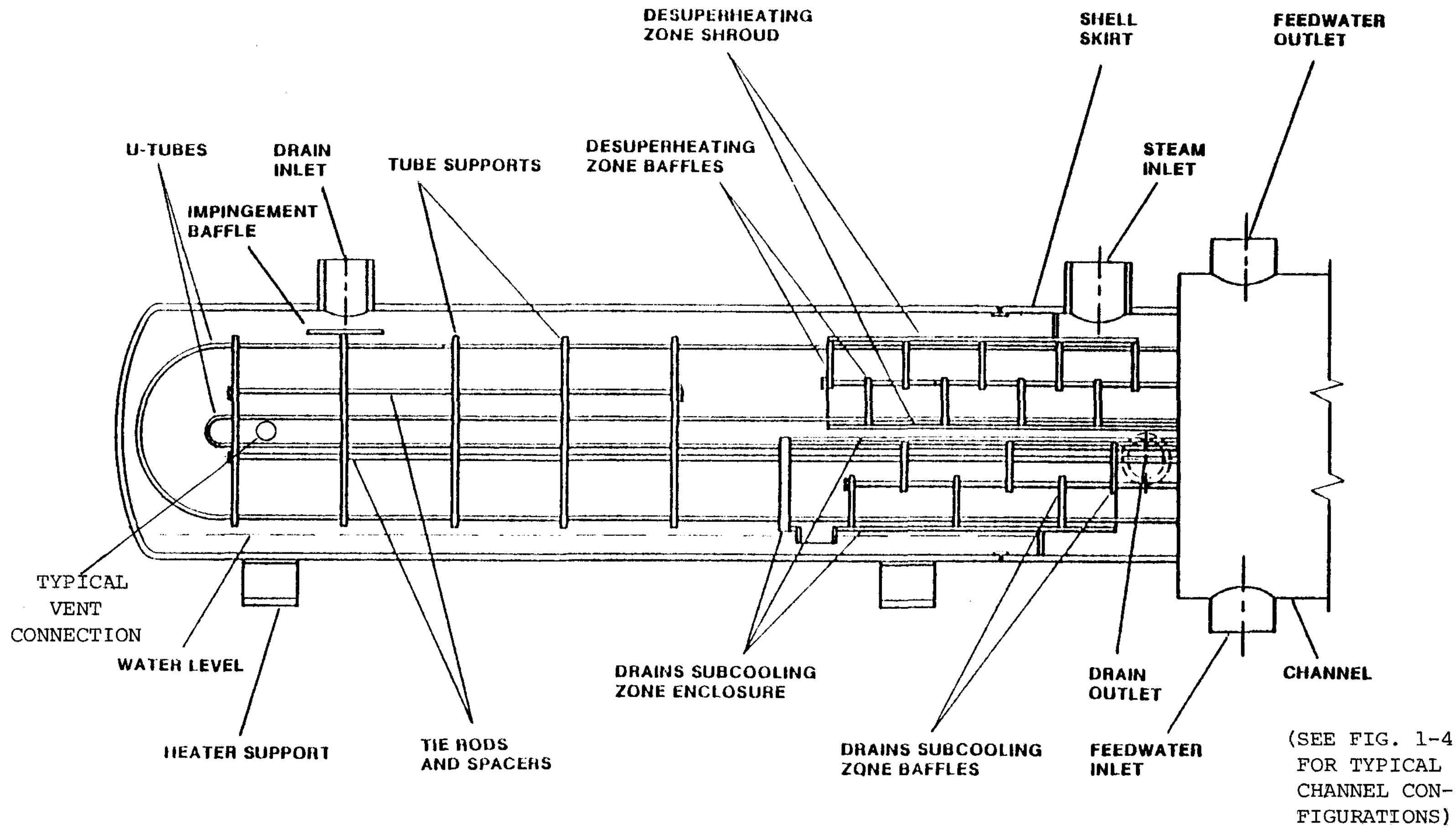


Figure 1-3. Typical 3-Zone Feedwater Heater (Desuperheating, Condensing, and Subcooling Zones)

Source: HEI Standards For Closed Feedwater Heaters, Third Edition.

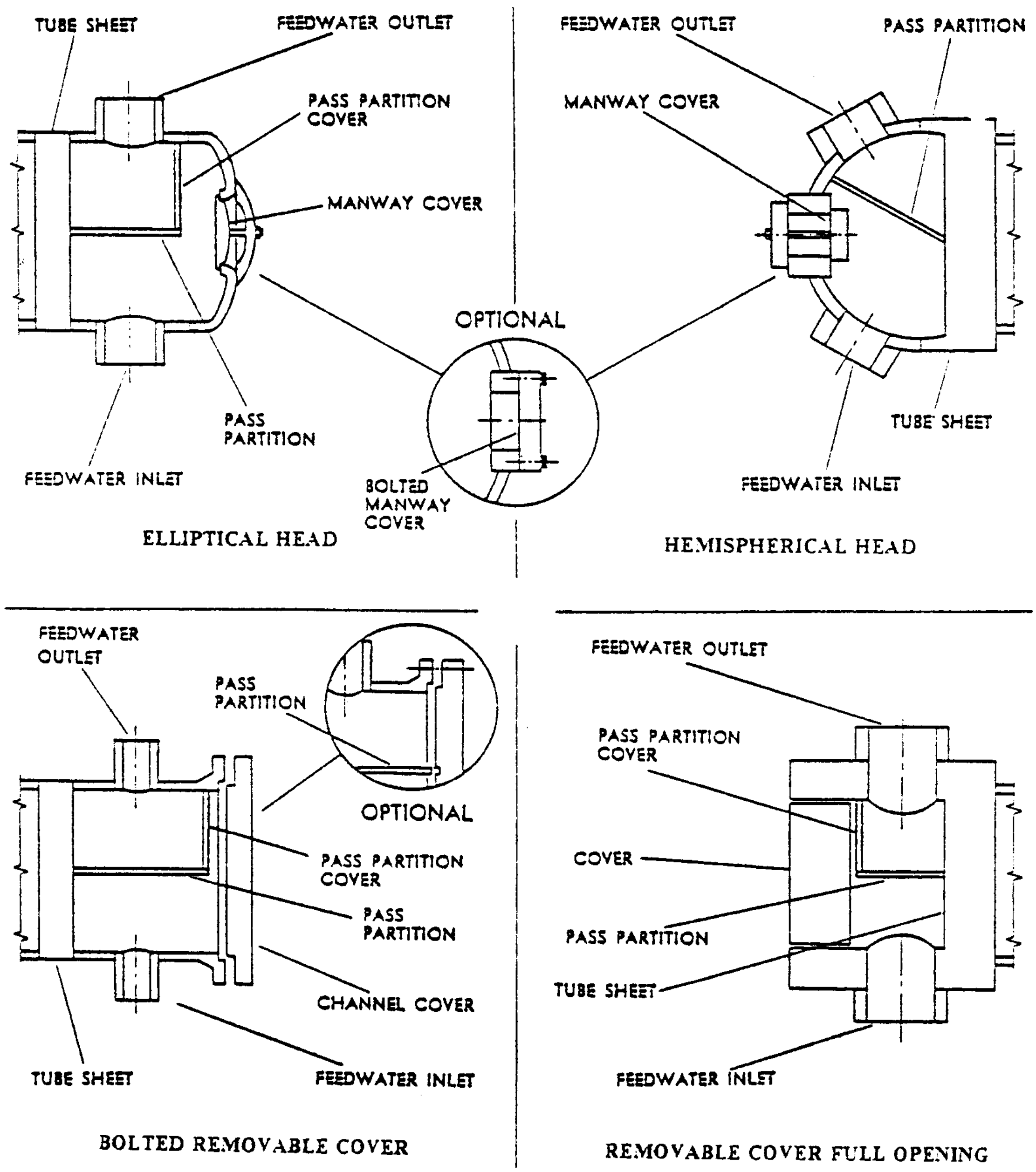


Figure 1-4. Typical Channel Configurations

Source: HEI Standards For Closed Feedwater Heaters, Third Edition.

- Desuperheating Zone: This is an enclosed portion at the outlet end of the tube bundle. Its purpose is to maximize the outlet feedwater temperature by transferring heat from the incoming superheated extraction steam. An impingment plate is installed below the steam inlet nozzle to prevent impingement damage to the tubes.

- Condensing Zone: This is the largest zone in the FWH. Steam exiting the desuperheating zone is condensed as it traverses through the condensing zone. Also, any drains from higher pressure FHWs flow into the condensing zone through the drain inlet nozzle. An impingement plate is installed below this nozzle to protect the tubes from these flashing drains. The condensing zone is vented continuously to remove non-condensibles. The vent system typically consists of one or more perforated vent pipes installed along the length of the tube bundle. Noncondensibles collect in these pipes and then pass through shell vent connections to the deaerator or the main condenser. An orifice, installed in the vent discharge, is sized to result in a flow rate equal to 0.5% of the steam flow entering the FWH.

- Drain Subcooling Zone: This zone is an enclosed portion of the inlet end of the tube bundle. Its purpose is to maximize heat transfer from the shellside condensate to the incoming feedwater before the condensate exits. The condensate should be cooled sufficiently to prevent flashing as the condensate leaves the FWH shell through the drain outlet nozzle and approaches the level control valve.

Section 2

SUMMARY OF FWH SURVEY RESULTS

In November 1979, EPRI and EEI (Edison Electric Institute) distributed a questionnaire to selected utilities throughout the U.S. in a joint effort to gather information on FWH problems. The questionnaire (shown in Figure 2-1) requested data on FWH failures in fossil units of 500 MWe capacity or greater. Smaller units were excluded from the survey to limit the scope of the study to manageable proportions and to concentrate on problems that occur in newer units.

A total of 57 utilities responded to the questionnaire. Of these, 43 reported FWH failures in fossil units, 3 reported that they had no 500 MWe units, and 1 reported no FWH failures in its single 500 MWe unit. The remaining 10 utilities had no 500 MWe fossil units, but submitted data on their 500 MWe nuclear units. In addition, 9 of the utilities that reported on their 500 MWe fossil units also submitted data on their 500 MWe nuclear units.

After a review of the questionnaire responses, a study team visited 8 utilities to gather additional information on problems at fossil units. The utilities that were visited had experienced most of the major types of problems reported in the questionnaires. Also, three of the major FWH vendors and a major A/E firm were visited and asked for their views on the causes of FWH failures. Finally, follow-up telephone interviews were conducted with most of the utilities that were not visited. These conversations helped to clarify and to augment the data supplied in the questionnaires. Additional information on nuclear units was not sought because they are outside the scope of this study, although it is recognized that FWH problems in nuclear and fossil units are similar in many ways.

Table 2-1 summarizes the survey results for the fossil units. Appendix A contains the detailed set of data for each problem FWH. Appendix B presents data on FWHs in the nuclear units for which questionnaire responses were received. Some general conclusions derived from the data for the fossil units are:

- A significant number (33%) of all the FWHs at the 44 utilities surveyed experienced problems.

FIGURE 2-1

EPRI SURVEY
FEEDWATER HEATER QUESTIONNAIRE
(SHELL AND TUBE HEATERS ONLY)

INSTRUCTIONS:
1) Complete Section A for each generation unit >500 MWe
2) Complete Section B for each heater which has had problems.
3) Include prints of: condensate, feedwater, and extraction steam P&IDs and of the unit design heat balance.
4) Return completed questionnaire to:

Ron Jacobstein
International Energy Associates Limited
600 New Hampshire Avenue, N. W. Suite 600
Washington, D.C. 20037

Section A: PLANT Date:______________

1. Person to contact for further information:
Person's Name ______________ Title ______________ Phone ______________

2. Unit Information
Utility ______________ Station ______________ Unit # ______ Unit Rating ________MWe Boiler Steam Pressure ______________psig

3. Base Loaded ___yes ___no

3.1 When unit is on line, estimate the percentage of time it operates in the following load ranges:

Load percentage	<25%	25-50%	50-75%	75-90%	>90%
Time percentage	________	________	________	________	________

4. Heaters

4.1 Low Pressure Heaters:

Number of strings __1__2__3; Number of heaters per string __;
Bypassable ___yes ___no

4.2 High Pressure Heaters:

Number of strings __1__2__3; Number of heaters per string __;
Bypassable ___yes ___no

SECTION B: PROBLEM HEATERS

If possible, provide a copy of or reference to problem reports/analysis.

5. Basic Data for Heater (for problem heaters only)

5.1 Heater #__. Heater arrangement: ___horizontal ___vertical channel up ___vertical channel down, condenser exhaust neck ___yes ___no, ___U-Tube
Other (describe)______________________________

FIGURE 2-1 (cont.)

5.2 Shell Side (design at 100%)

Bleed steam inlet pressure ___psig, temperature __°F, flow ___#/hr
Drains: __cascade back, __pump back, __pump forward; temperature ___°F
flow ___#/hr
Normal drain destination______________________________
High level destination______________________________
Vent flow rate ___#/hr, destination______________________________
Does shell receive drains ___yes ___no, from where ______________
Desuperheating zone ___yes ___no, drain cooler zone ___yes ___no
Shell diameter (I.D.) ____inches

5.3 Tube Side (design at 100%)

Inlet pressure ___psig, temperature ___°F, flow ___#/hr.
Outlet pressure___psig, temperature ___°F, flow ___#/hr.
Tube material______________________________
Flow velocity in tubes (if known) ___ft/sec. Tube to tube sheet joints:
Welded ___yes ___no, expanded ___yes ___no
Tube sheet material ______________________. Overlay material__________
Tube outside diameter ___in., wall thickness ___in.

5.4 Chemistry: Briefly describe water treatment:______________________
____
____

6. General History

6.1 Is this the original heater ___yes ___no, tube bundle ___yes ___no
Is this problem _________chronic ____________one-time
In-service years of heater operation before problem became apparent ____
Total years in service ________

6.2 Heater Loading (prior to problem)

Percentage of operating time at: ___overload ___design rating
___part load (<90%) ___bypassed; layup practice______________________
____
____

6.3 Maintenance: Do isolation valves close tightly to permit maintenance
while on line? _____yes _____no. Other maintenance problems____________
____

7. General Problem Description

7.1 Performance (i.e., thermal capacity, vents, drains, pressure drop)
____
____
____

7.2 Structural Failure (i.e., baffling, shrouding, tube fatigue/fretting/
erosion, external supports)______________________________________
____
____

FIGURE 2-1 (cont.)

7.3 Leakage (i.e., tube, tube-to-sheet joints, shell, channel head joints)

____
____
____

8. Cause of Problem: Check and describe
___design ___installation ___operation ___maintenance
___instrumentation and controls ___other

____
____
____

9. Effects of Problem: Check and describe (where appropriate)
___unit derating ___unit forced outage ___reduced heat rate
___overload of other heaters ___excessive maintenance ___other

____
____
____

Other equipment affected as a result of the problem (e.g., eroded piping)

____

10. Corrective Actions: Check and describe (where appropriate)
___heater replacement____
___tube bundle replacement____
tube plugging, technique______________________________% plugged ________
___minor/major in-place repair (describe) ____________________________

Table 2-1

SUMMARY OF SURVEY RESULTS FOR FOSSIL UNITS

Problem	No. of Utilities	No. of Units	No. of HP FWHs*	No. of LP FWHs*	No. of IP FWHs*	Tube Material: CS	Tube Material: SS	Tube Material: Cu Alloy	Tube Material: Monel	No. of FWHs or Bundles Replaced
1. Steam impingement	17	24	21	25	6	40	0	4	8	27
2. Tube inlet erosion	6	9	25	4	0	29	0	0	0	15
3. Drains subcooler flashing/level control problems	18	30	62	40	5	49	46	8	4	43
4. Tube vibration	9	20	17	9	15	21	3	9	8	27
5. Tube plugging problems	8	12	26	4	8	24	0	6	8	9
6. Corrosion	13	22	30	13	6	35	0	9	5	21
7. Unknown	23	52	74	51	5	92	6	21	11	42
8. Failure of internal non-tube component	6	7	16	0	0	13	0	2	1	2
9. Head or shell leak	10	14	28	8	0	27	2	7	0	12
10. Tube-to-tubesheet joint failure	5	9	27	1	0	28	0	0	0	14

*Individual FWHs often experienced more than one type of problem.

Table 2-1 (cont.)

Problem	No. of Utilities	No. of Units	No. of HP FWHs*	No. of LP FWHs*	No. of IP FWHs*	Tube Material CS	SS	Cu Alloy	Monel	No. of FWHs or Bundles Replaced
11. Foreign material impingement	3	3	1	2	0	3	0	0	0	1
12. Tube manufacturing defect	1	1	1	0	0	0	0	1	0	1

TOTALS

No. of utilities responding with fossil units 44
No. of fossil units 144
No. of FWHs 1250
No. of problem FWHs 411

- A significant number (36%) of the problem FWHs required replacement of the tube bundle or the entire FWH.

- Sixty-six percent of the problem FWHs had carbon steel tubes. Eighty-five percent of the FWHs requiring FWH or tube bundle replacement had carbon steel tubes. It cannot be determined whether this simply reflects the percentage of all FWHs with carbon steel tubes, because data on the FWHs without problems was not compiled. However, it was learned that many of the utilities switched to stainless steel tubes when replacing a carbon steel tubed FWH or tube bundle.

- The average time period that a problem FWH had been in service before detection of the first failure was 3.7 years, well below the design life. This points out that FWH problems are generally not the result of the expected deterioration that comes with age.

- Tube-to-shell leakage was the predominant mode of FWH failure. Most of the leaks occurred in the desuperheating or drains subcooling zones of the FWH, while the condensing zones were relatively free of leaks.

- The difference in the number of high-pressure FWH problems vs. low- or intermediate-pressure FWH problems is not significant.

Table 2-1 indicates which problem areas are the most serious, in terms of the prevalence of the problem and the number of FWHs or tube bundles requiring replacement. The most serious problem areas are:

- Tube vibration;
- Drains subcooler flashing and level control;
- Tube plugging;
- Corrosion;
- Tube inlet erosion; and
- Steam impingement.

A separate section in this report is devoted to each of these problem areas. Head and shell leakage also appears to be a relatively serious problem according to Table 2-1. However, many FWHs experienced more than one type of problem, and in the case of FWHs with head or shell leaks that required FWH or tube bundle replacement, it was usually some other problem that was responsible for the major damage. Also, tube-to-tubesheet joint problems are not as serious as is indicated in Table 2-1, because all except two of the FWH or bundle replacements caused by this occurred at just two utilities. At one of these utilities, a new type of tube-to-tubesheet joint (no longer used in the U.S.) was being tried. FWHs that failed for unknown reasons comprise the largest single problem area, reflecting the difficulty of diagnosing failures in a closed FWH.

Section 3

TUBE VIBRATION

3.1 PROBLEMS AND SOLUTIONS REPORTED*

Nine utilities reported tube vibration problems in a total of 41 FWHs. In every case except one, the damage occurred in the desuperheating zone of a horizontal FWH. Table 3-1 presents pertinent data on these FWHs.

Several means were used to conclude that vibration was the cause of damage in these FWHs. In some cases, the shell was pulled, or cut open, allowing visual examination of the tube bundle. Individual tubes were removed for visual examination as well. Circumferential wear of the tubes at baffle locations and/or flattening and longitudinal cracks at tube midspan locations indicated vibration damage. When the tubes could not be visually inspected, the location of the damage was often determined by probing the ID of individual tubes. Probalog or boroscope methods were sometimes used, or simpler methods such as pressurizing the shell and inserting a plunger inside individual tubes until airflow was detected. If tube failures existed at baffle or at midspan locations, vibration was assumed to be the cause. Finally, steam velocity and/or unsupported tube lengths were sometimes calculated. If the calculated values exceeded certain "critical" values, it was concluded that vibration damage had occurred.

Unfortunately, it is not easy to diagnose vibration problems. Other problems, such as corrosion or wet steam impingement, can result in desuperheater tube failures. When one tube fails, the cutting action of the leaking water can damage adjacent tubes, especially in high-pressure FWHs. This makes it difficult to determine the location and cause of the original failure. Many cases of wet steam impingement damage were reported with no real supporting evidence. It is possible that some of these cases actually involved vibration damage.

*Conditions and solutions as reported by utility respondees. The solutions or causal relationships are not necessarily endorsed by EPRI or the authors.

Table 3-1

FWHs THAT EXPERIENCED DAMAGE FROM TUBE VIBRATION

			FWH			EXTRACTION STEAM INLET CONDITIONS AT 100% LOAD			TUBES			
UTILITY	PLANT	UNIT	DESIG-NATION	TYPE	VENDOR	PRESSURE (psia)	TEMPERA-TURE (^{o}F)	FLOW (lb/hr)	MATERIAL	THICKNESS	OD	PITCH
33	1	1	3	IP	West.	202	692	289273	Carbon Steel	.050"	5/8"	13/16"
33	1	2	2	IP	West.	277.3	789.6	186076	Carbon Steel	.050"	5/8"	13/16"
33	1	2	3	IP	West	160.1	642.3	175928	Carbon Steel	.050"	5/8"	13/16"
28	1	1	4	IP	West.	178.9	711.8	225104	90-10 Cu-Ni	18 BWG	5/8"	13/16"
28	1	1	5	IP	West.	329.3	877.4	209322	Monel	18 BWG	5/8"	13/16"
28	1	1	6	HP	West.	579.8	642.6	226896	Monel	17 BWG	5/8"	13/16"
28	1	2	4	IP	West.	178.9	711.8	225104	90-10 Cu-Ni	18 BWG	5/8"	13/16"
28	1	2	5	IP	West.	329.3	877.4	209322	Monel	18 BWG	5/8"	13/16"
28	1	2	6	HP	West.	579.8	642.6	226896	Monel	17 BWG	5/8"	13/16"
7	1	1	1	HP	West.	238.4	865	151218	Carbon Steel	.085"	3/4"	N/A
7	1	1	2	HP	West.	472.7	595	188253	Carbon Steel	.085"	3/4"	N/A
7	1	1	3	HP	West.	864.4	740	232523	Carbon Steel	.085"	3/4"	N/A
7	1	1	4	LP	West.	38.4	460	107232	Carbon Steel	.050"	3/4"	N/A
7	1	1	5	LP	West.	86.2	620	102363	Carbon Steel	.050"	3/4"	N/A
7	2	2	2	HP	West.	514.2	618	158838	Carbon Steel	.075"	3/4"	N/A
7	2	2	1	HP	West.	215.3	810	77178	Carbon Steel	.075"	3/4"	N/A
7	2	1	3	HP	West.	912	760	213196	Carbon Steel	.085"	3/4"	N/A

NOTE:
1. All FWHs are horizontal.
2. All FWHs except one have three zones. FWH 4 at Utility 13 has condensing and drains subcooling zones only.
3. HP = high pressure LP = low Pressure
   IP = intermediate pressure N/A = information not available

Table 3-1 (cont)

			FWH			EXTRACTION STEAM INLET CONDITIONS AT 100% LOAD			TUBES			
UTILITY	PLANT	UNIT	DESIG-NATION	TYPE	VENDOR	PRESSURE (psia)	TEMPERA-TURE (°F)	FLOW (lb/hr)	MATERIAL	THICKNESS	OD	PITCH
7	2	1	1	HP	West.	252	860	132169	Carbon Steel	.085"	3/4"	N/A
7	2	1	5	LP	West.	95.4	620	113237	Carbon Steel	.050"	3/4"	N/A
3	3	1	7	LP	NA	339.7	764	213000	Carbon Steel	.049"	3/4"	N/A
3	3	1	6	LP	NA	126.7	NA	156754	Stainless Steel	.035"	5/8"	N/A
3	4	1	7	LP	Yuba	339.7	764	235180	Stainless Steel	.035"	5/8"	N/A
3	4	1	6	LP	Struthers-Wells	126.7	NA	156754	Stainless Steel	.035"	5/8"	N/A
13	2	1	4	LP	NA	77.7	478	187000	Carbon Steel	.05"	3/4"	N/A
13	2	1	5	LP	NA	186.7	681	232000	Carbon Steel	.05"	3/4"	N/A
17	2	1	7	HP	Struthers-Wells	586.7	627	341000	Cufenloy 30	17 BWG	5/8"	N/A
34	1	1	7A	HP	Foster-Wheeler	632	894	103000	Carbon Steel	.122"	3/4"	N/A
34	1	1	7B	HP	Foster-Wheeler	632	894	103000	Carbon Steel	.122"	3/4"	N/A
34	1	1	6A	HP	Foster-Wheeler	365	750	93000	Carbon Steel	.122"	3/4"	N/A
34	1	1	6B	HP	Foster-Wheeler	365	750	93000	Carbon Steel	.122"	3/4"	N/A
34	1	1	8B	HP	Foster-Wheeler	1120	682	186000	Carbon Steel	N/A	N/A	N/A
29	1	1	1	HP	West.	679.7	603	439919	Monel	17 BWG	5/8"	N/A
29	1	1	2	IP	West.	282.7	812	239170	Monel	18 BWG	3/4"	N/A
29	1	1	2	HP	West.	679.7	683	439919	Monel	17 BWG	5/8"	N/A
29	1	2	2	IP	West.	282.7	812	239170	Monel	18 BWG	3/4"	N/A
29	2	1	3	IP	SWECO	162.7	718	190969	90-10 Cu-Ni	18 BWG	3/4"	N/A
29	2	2	3	IP	SWECO	162.7	718	190969	90-10 Cu-Ni	18 BWG	3/4"	N/A
29	2	3	3	IP	SWECO	162.7	718	190969	90-10 Cu-Ni	18 BWG	3/4"	N/A
29	2	4	3	IP	SWECO	162.7	718	190969	90-10 Cu-Ni	18 BWG	3/4"	N/A
41	2	1	3	IP	SWECO	188.7	716	232000	90-10 Cu-Ni	18 BWG	5/8"	N/A
41	2	2	3	IP	SWECO	188.7	716	232000	90-10 Cu-Ni	18 BWG	5/8"	N/A

The cause of the damaging tube vibration was generally reported as excessive steam velocity or poor baffle design, although one utility reported the cause as wet steam. The exact reason for the excessive velocity or poor baffle design usually remained unclear. It could have been attributed to inadequate design by the vendor, or operation of the FWH with a steam flow higher than specified. Most vendors claim that FWHs can be designed to avoid vibration damage, provided that the customer completely specified all of the overload conditions at which the FWH will be operated. However, this claim has yet to be proven.

Each reported vibration problem was solved either by modifying the existing FWH or by purchasing a redesigned replacement FWH. In one modification, a bypass line was installed from the extraction steam inlet to the condensing zone, thereby allowing some steam to bypass the desuperheater, which reduced the desuperheater steam velocity. Another modification was to add baffles in the desuperheating zone in order to reduce unsupported tube lengths. A brief summary of the vibration problems experienced by the nine utilities follows:

- Utility 3

  Plant 3: Tube vibration in the desuperheater zone was blamed for two low-pressure FWH failures. The tube failures began 2-3 years after plant startup. Wet steam was considered to be the cause of the vibration, and tube-to-tube contact was noted. The tube bundle of one low-pressure FWH was replaced, and the other low-pressure FWH was replaced with a new unit.

  Plant 4: Two low-pressure FWH failures, also attributed to tube vibration due to wet steam, occurred at this plant. The FWHs, manufactured by Struthers-Wells approximately twenty years ago, were not analyzed for vibration in the original design. As an interim measure, a desuperheater bypass and additional bundle support bars were installed. Both FWHs were eventually replaced.

- Utility 7

  Plants 1 and 2: This utility concluded that desuperheater zone, flow-induced vibration was responsible for the damage in five of its Westinghouse FWHs at Unit 1 of Plant 1. However, the basis for this conclusion is not clear. The vendor claimed that the damage resulted from low water level in some cases, and wet steam in others. All five FWHs were replaced in less than five years from initial operation, with stainless steel tubes used in all replacements.

  At Unit 1 of Plant 2, three FWHs were replaced after less than eight years of operation, and at Unit 2, two FWHs were replaced after less than twelve years. All were Westinghouse FWHs. The utility blamed tube vibration for all failures. In one FWH, steam velocities of 130 fps (39.6 m/sec) were calculated, and failures at tube support locations were noted.

- Utility 13

Plant 2: Tube vibration was indicated by damage at tube support locations in the desuperheater zones of two low-pressure FWHs. The cause was believed to be high steam velocity. As an interim measure, the inlet nozzle was enlarged. Both FWHs eventually required replacement.

- Utility 17

Plant 2: A Struthers-Wells high-pressure FWH suffered tube vibration damage as evidenced by the classic symptoms in three rows in the desuperheater zone: circumferential wear and longitudinal flattening at the support locations with cracks at tube midspan locations. The FWH was placed in service in 1974, and a vibration analysis done by the vendor indicated that no vibration damage should occur. The vendor has expressed concern about a 90° bend in the steam inlet nozzle, which he believes may have introduced excessive turbulence. Under warranty, the FWH was modified by replacing the original eight horizontal-cut baffles with 14 vertical-cut baffles. A similar modification was done on the identical FWH in Unit 2.

- Utility 28

Plant 1: Within the first several years of operation, all of the Westinghouse intermediate-pressure FWHs at this two-unit plant experienced vibration problems, as evidenced by tube wear at baffle locations in the desuperheater zone. All four tube bundles were replaced under warranty. In addition, desuperheater bypasses were installed to direct steam to the condensing zone, thereby reducing velocities in the desuperheater zone. The improved reliability compensated for the resulting 4% loss in FWH efficiency. A bypass line between the steam inlet nozzle and the condensing zone was also added to the high-pressure FWHs in each plant to prevent vibration in the high-pressure FWH due to overloading when an intermediate-pressure FWH is bypassed.

Utility 29

Plant 1: The Westinghouse high-pressure FWH #1 and intermediate-pressure FWH #2 at each of two units at this plant were damaged by desuperheater tube vibration caused by high steam velocity. The problem was resolved by installing a desuperheater bypass line from the extraction steam inlet to the condensing zone. The branch connection for the bypass line was approximately six feet (1.8 meters) from the steam nozzle in the shell.

Plant 2: A Southwestern Engineering Company intermediate-pressure FWH #3 at this four-unit plant experienced desuperheater tube vibration due to high velocity. The problem was resolved by baffle plate modifications.

- Utility 33

Plant 1: Vibration damage occurred in all three intermediate-pressure FWHs of this two-unit plant, as evidenced by tube wear at the baffle locations. These FWHs were built by Westinghouse.

The high-pressure FWHs were also built by Westinghouse, but it was not determined why they did not experience the same problem. Tube leaks from the vibration damage were a chronic problem since startup in 1968. A vibration analysis on one intermediate-pressure FWH showed desuperheater steam velocity to be greater than 280 ft/sec (85.34 m/sec), which exceeds the critical velocity for vibration. The percentage of tubes plugged reached 14% and 15% in the two intermediate-pressure FWHs at Unit 2, and 24% in the one intermediate-pressure FWH at Unit 1. In an attempt to extend the life of one of the Unit 2 intermediate-pressure FWHs, the desuperheater was partially bypassed. All of the intermediate-pressure FWHs are to be replaced.

The original FWH specifications, written by the A/E, were general with respect to designing against vibration. They required a design that could operate at 5% excess flows and "baffles designed so that no vibration is transmitted to the tubes."

The utility believes that vendor designs have improved since 1968 and that vibration can be avoided. The specifications for the replacement FWHs require:

- No vibration with steam and feedwater flows 10% greater than design conditions;
- Stainless steel tubes, intended to provide more resistance to wear;
- Critical velocity in the desuperheater that is 30% greater than actual velocity ("critical velocity" was not defined);
- Chamferred baffle and tube support plate holes, intended to prevent wear between the plates and the tubes;
- Tube-to-support hole clearance that is sufficient to prevent binding, yet small enough to eliminate whirling and fretting due to excess motion; and
- 7% excess number of tubes.

- Utility 34

Plant 1: Five Foster-Wheeler high-pressure FWHs at this plant had required replacment after less than five years of service because of tube-to-tubesheet weld failures. These FWHs had internal bore welds, in which the tube is butt-welded to a spigot on the backside of the tubesheet. Calculations showed that vibration may have been the significant contributor to the weld failures. Results of the calculations are shown in Table 3-2.

The utility concluded that mass velocities in the desuperheater zones significantly exceeded the unpublished industry standard of 80 lbs/ft^2 -sec (390.6 kg/m^2 -sec). It was also concluded that unsupported tube spans in the desuperheater exceeded HEI standards.

Table 3-2

VIBRATION CALCULATIONS BY UTILITY 34

	FWH Number					
	26		27		28	
Desuperheater	100% Load	150% Load	100% Load	150% Load	100% Load	150% Load
Mass Velocity (lbs/ft^2-sec)/(ks/m^2-sec)	48.2/235.3	72.3/353.0	131/639.6	197/961.83	128/625.0	192/937.4
Lineal Velocity (ft/sec)/(m/sec)	83/25.3	125/38.1	160/48.8	240/73.2	66/20.1	99/30.2
Unsupported Tube Span (in)/(cm)	53/134.6		52/132.1		44/111.8	
Drains Subcooler						
Mass Velocity (lbs/ft^2-sec)/(ks/m^2-sec)	204/996.0	306/1494.0	203/991.1	307/1498.9	191/932.5	287/1401.2
Lineal Velocity (ft/sec)/(m/sec)	388/118.3	5.8/1.76	4/1.22	6/1.83	4/1.22	6/1.83
Unsupported Tube Span (in)/(cm)	48/121.9		47/119.4		10/25.4	

- Utility 41

 Plant 2: Eddy current tests indicated tube OD wear at tube support locations in the desuperheating zone of the IP #3 FWHs at each unit of this two-unit plant. Based on the location of the tube damage, it was concluded that vibration was the cause. A vibration analysis done by the vendor indicated that there was virtually no chance of tube failure by vibration. However, the analysis was based on design conditions and may not have reflected the actual conditions in the desuperheater zone during operation.

3.2 TUBE VIBRATION PROBLEMS AS DISCUSSED IN THE LITERATURE

Much has been written on the subject of vibration in shell and tube heat exchangers. The following subsections, based on References 1-8, present the major findings in the literature and discuss their relevance to FWHs.

Vibration in shell and tube heat exchangers is a natural phenomenon caused by the interaction of elastic tubes with the fluctuating forces imposed by the flowing shellside fluid. Tube vibration becomes a problem when its intensity reaches a point where damage to the tubes or tube joints occurs by fretting, fatigue, etc.

Tubes can vibrate only at discrete frequencies that depend on the tube geometry, tube material, and fluid densities. The lowest frequency is called the natural frequency. The forces imposed on the tube by shellside fluid flow fluctuate at certain frequencies which are dependent on the flow rate. The fluctuating forces will often cause the tube to vibrate, but damage results only if the amplitude of the tube vibration is sufficient to cause (1) stresses in the tube or tube joint that exceed the endurance limit for fatigue failure; (2) collision between adjacent tubes; or (3) fretting wear between the tube and tube support plate. The amplitude of tube vibration is the product of the static deflection and the magnification factor (C_{MF}). The static deflection is the non-vibrating tube displacement caused by the lift and drag forces due to fluid flow over the tube. The value of C_{MF} depends on the ratio of the flow frequency to the tube natural frequency and on the level of system damping. A plot of C_{MF} versus frequency ratios for various levels of system damping is shown in Figure 3-1. Damping in a FWH is influenced by factors such as tube-to-baffle clearance, fluid density, etc. Note that when the frequency ratio is near unity (resonance), large amplitude vibration can occur.

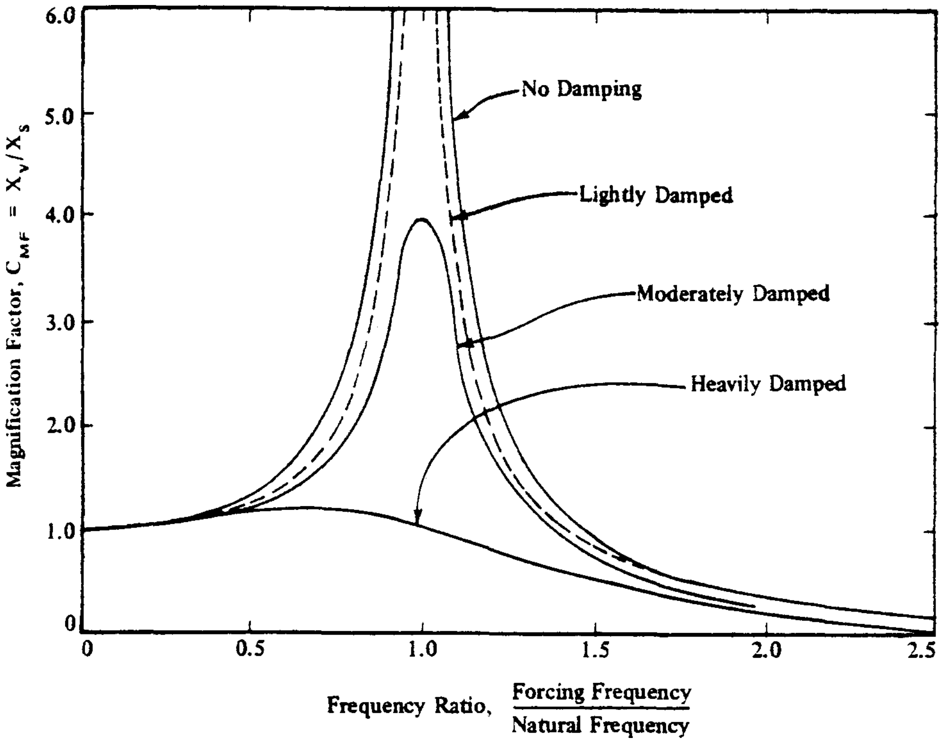


Figure 3-1. Magnification Factor for Calculating Forced Vibration Amplitude From Static Deflection.

Source: Flow-Induced Tube Vibrations in Shell-and-Tube Heat Exchangers, J. M. Chenoweth, Heat Transfer Research, Inc., February 1977.

3.2.1 Vibration Theories and Correlations

A number of investigators have developed theories and correlations to describe the fluctuating forces (also called the excitation mechanisms) imposed on tubes by flowing fluids and to predict when damaging tube vibration will occur. Most of these theories are based on idealized laboratory experiments and have yet to be adequately verified by data from actual real heat exchangers in service. However, the theories and correlations are used widely in heat exchanger design; each is described briefly below.

3.2.1.1 Vortex Shedding. Vortex shedding is an excitation mechanism that has been observed during crossflow (i.e., the fluid flows perpendicularly to the tube axis). During crossflow with a single tube, alternating vortices may be shed from the back of the tube. Vortex shedding occurs when the Reynolds number (Re) is between 100 and 5×10^5 or is greater than 2×10^6 (1), where:

$$Re = \frac{\rho V d}{\mu}$$

ρ = mass density of fluid

μ = viscosity of fluid

V = free stream flow velocity

d = outside diameter of cylinder

The alternating vortices create alternating drag forces (F_D) and lift forces (F_L) on the tube, where:

$F_D = 1/2\ C_D\ \rho A V^2$

$F_L = 1/2\ D_L\ \rho A V^2$

C_D = drag coefficient

C_L = lift coefficient

ρ = mass density of fluid

V = free stream fluid velocity

C_D is a combination of a constant coefficient and an oscillatory coefficient. In the high Reynolds number regime, a nearly constant value of $C_D = 1.1$ is observed, with the oscillatory coefficient in the range of 0.1-0.2. Values of C_L are difficult to assign because of the wide scatter in experimental data. The lift force is completely oscillatory, and a conservative value of C_L lies in the range of 1.5-2.0 (7). Thus, the oscillating lift forces are about 10 times higher than the oscillating drag forces. Since oscillating forces cause tube vibration, the lift direction is of primary importance with respect to vibration.

The frequency at which the vortices are shed from a tube is defined in terms of the Strouhal number (Sl), where:

$Sl = f_{vs}\ d/V$

f_{vs} = vortex shedding frequency

d = tube diameter

V = free stream velocity (crossflow)

For a single tube, Sl remains nearly constant at a value of 0.21 in the Reynolds number range from 300 to about 2×10^5, and at a value of 0.27 for a Reynolds number beyond 3.5×10^6 (7).

For an array of tubes, vortex shedding is not as well understood. The magnitude and frequency of the lift and drag forces are different than for a single tube because of the interaction between adjacent tubes. Also, the effect of tube motion on the vortex shedding frequency is not completely understood. Some investigators have questioned whether vortex shedding can even occur deep within tube bundles. Vortex shedding is still considered to be a potential problem for tubes on the periphery of the bundle, but is not considered to be the dominating influence within the bundle.

Chen (1) performed experimental investigations to determine Strouhal numbers for tube bundles with various geometries. His results are used widely as a design method to prevent tube vibration in heat exchangers. The Chen method consists of predicting the vortex shedding frequency using the following equation:

$$f_{vs} = \frac{(Sl)V_c}{d}$$

where

Sl = Strouhal number
V_c = crossflow velocity
d = tube diameter

The value of Sl is determined using the curves in Figure 3-2. The heat exchanger is designed such that the natural frequency of the tubes is higher than the vortex shedding frequency for the maximum expected crossflow. This prevents occurence of a resonance condition, in which the vortex shedding frequency equals the tube natural frequency, resulting in damage from high amplitude vibrations.

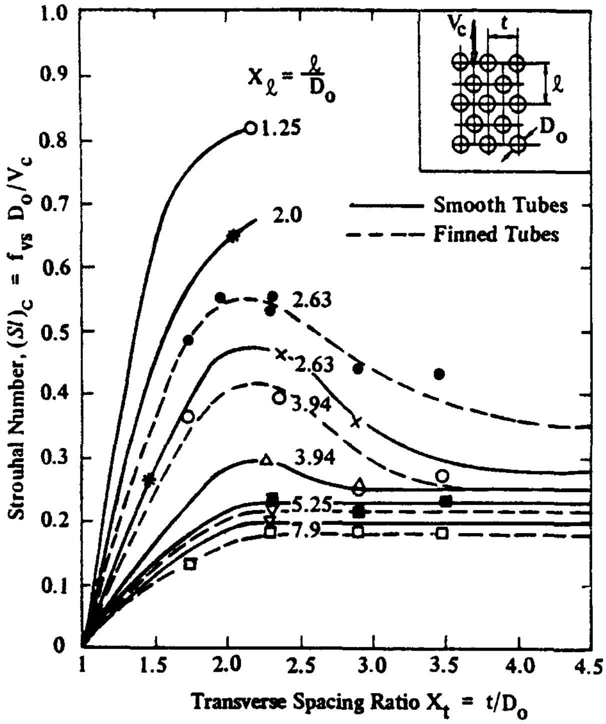


Figure 3-2. Strouhal Numbers for Staggered Tube Banks.

Source: <u>Flow-Induced Tube Vibrations in Shell-and-Tube Heat Exchangers</u>, J.M. Chenoweth, Heat Transfer Research, Inc., February 1977.

3.2.1.2 <u>Turbulent Buffeting</u>. Turbulent buffeting is an excitation mechanism caused by fluctuating forces imposed on the tubes due to extremely turbulent shellside flows. The forces on the tubes are not at a single frequency as would be predicted by the vortex shedding theory, but rather lie within a wide range of frequencies around a dominant frequency that increases with crossflow velocity. Owen (1) developed the following empirical relation to predict the dominant frequency:

$$tb = \frac{V_c d}{lt} \left[3.05 \left(1 - \frac{d}{t}\right)^2 + 0.28 \right]$$

where

f_{tb} = dominant turbulent buffeting frequency, Hz

V_c = crossflow velocity, in/sec (m/sec)

l = longitudinal tube pitch, in (m/sec)

t = transverse tube pitch, in (m/sec)

d = tube OD, in (m)

By designing the heat exchanger such that the tube natural frequency is sufficiently higher than f_{tb}, resonance is avoided.

3.2.1.3 Fluidelastic Whirling. Fluidelastic whirling is an excitation mechanism proposed by Connors (2). The momentary displacement of one tube in an array from its normal equilibrium position alters the flow field, thereby upsetting the force balance on neighboring tubes and causing them also to change their positions in a vibratory manner. If during vibration the energy extracted from the flowing fluid by the tubes exceeds the energy dissipated by damping, fluidelastic vibration will occur. The vibration is self-excited, and, once initiated, will grow in amplitude until adjacent tubes make contact and damage results. The tubes exhibit a whirling, orbital motion during fluidelastic whirling.

Connors (2) proposed a method for designing against fluidelastic whirling. A critical velocity for the initiation of fluidelastic whirling is determined by the following equation:

$$V_{crit} = f_n \beta d \sqrt{\frac{m\delta}{\rho_s d^2}}$$

where

V_{crit} = critical velocity, in/sec (m/sec)

f_n = tube natural frequency in the n^{th} mode, Hz

β = threshold instability constant, dimensionless

d = tube outside diameter, in (m)

m = mass of the tube per unit length including the added mass of fluid inside and outside the tube, lb-sec^2/in^2 (kg-sec^2/m^2)

δ = logarithmic decrement, dimensionless

ρ_s = shellside fluid density lb-sec^2/in^4

An effective crossflow velocity is calculated as follows:

$$\rho_s V_{eff}^2 = \frac{\sum_{j=1}^{n} \rho_{sj} \left[V_j \phi_{jn} \right]^2 \Delta Z_j}{\rho_s \sum_{j=1}^{n} \left[\phi_{jn} \right]^2 \Delta Z_j}$$

where

ϕ_{jn} = normalized displacement of the j^{th} lumped mass in the n^{th} mode of vibration

ρ_{sj} = shellside fluid density at the j^{th} lumped mass, $lb\text{-}sec^2/in^4$ ($kg\text{-}sec^2/m^4$)

V_j = flow velocity in the gap between adjacent tubes in the same transverse row applicable to the j^{th} lumped mass, in/sec (m/sec)

ΔZ_j = incremental length used in the finite element model, in (m)

The effective velocity accounts for the fact that the shellside fluid imparts more energy where the tube displacement is greatest. To prevent fluidelastic whirling, the heat exchanger is designed such that $V_{eff}/V_{crit} < 1$ for each mode of tube vibration. The mode shapes and frequencies are calculated by a finite element computer code, and typically no more than the first five modes are considered.

Hartlen (1) experimentally determined values of β as shown in Figure 3-3. However, exact values of β cannot yet be predicted for each tube type, layout angle, and tube pitch. Moreover, values of the log decrement depend on the mechanical properties of the tube material, geometry of the bundle, and viscosity of the shellside fluid; and these values are difficult to predict. Measured values range from 0.17 to 0.001.

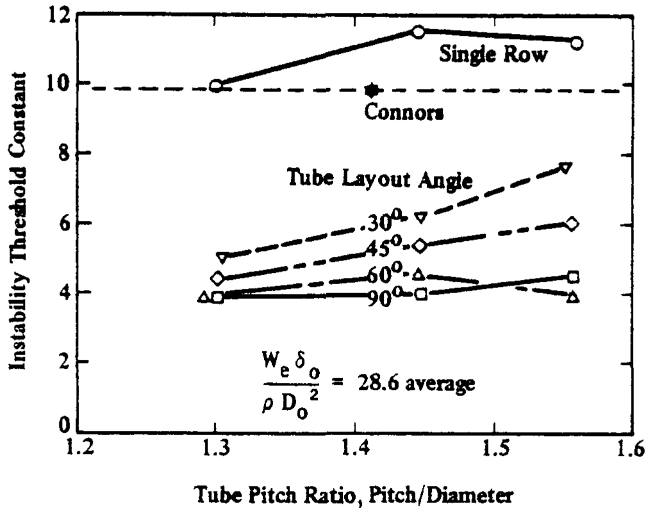


Figure 3-3. Hartlen Experimentally Determined Instability Threshold Constants

Source: Flow-Induced Tube Vibrations in Shell-and-Tube Heat Exchangers, J. M. Chenoweth, Heat Transfer Research, Inc., Feb. 1977.)

3.2.1.4 Tube Vibration Induced by Parallel Flow. Flow parallel to a tube can produce turbulent eddies, which can cause vibration. The Chen-Weber method (1) for predicting tube vibration induced by flow parallel to tubes uses a critical velocity given by:

$$V_{cp} = f_n L \sqrt{\frac{W_e}{W_s\left[\left(\frac{0.002L}{D_o}\right) + 1\right]}}$$

where

V_{cp} = critical parallel flow velocity, in/sec (m/sec)

f_n = tube natural frequency, Hz

L = tube span length, in (m)

W_e = effective weight of tube per unit length including the fluid in the tube and the shellside fluid displaced by the tube, lb/in (kg/m)

W_s = weight per unit length of the shellside fluid displaced by the tube, lb/in (kg/m)

D_o = tube OD, in (m)

The critical parallel flow velocity is then used to predict a dimensionless midspan amplitude:

$$Y_p = \frac{2\left(\frac{V_p}{V_{cp}}\right)^2}{\left[1 - \left(\frac{V_p}{V_{cp}}\right)^2\right]} = \frac{x_p}{d_h}$$

where

V_p = velocity parallel to tubes, in/sec (m/sec)
x_p = actual midspan deflection, in (m)
d_h = hydraulic diameter for flow parallel to tubes, in (m)

$$= 4\left(\frac{0.867P^2}{2} - \frac{\pi D_o^2}{8}\right) \bigg/ \pi D_o$$ for triangular layouts (30° and 60°)

$$= 4\left(P^2 - \frac{\pi D_o^2}{8}\right) \bigg/ \pi D_o$$ for square layouts (45° and 90°)

P = tube layout pitch, in (m)

Chen and Weber found that there is no significant vibration produced by parallel flow when Y_p is less than 0.0075.

3.2.1.5 Gregorig Method. Gregorig (1) developed a plot of Strouhal number vs. Reynolds number (using the tube natural frequency rather than the vortex shedding frequency to define Sl), which shows regions where vibration would be expected (see Figure 3-4). More data is needed to test the location of the boundaries between vibration and no vibration.

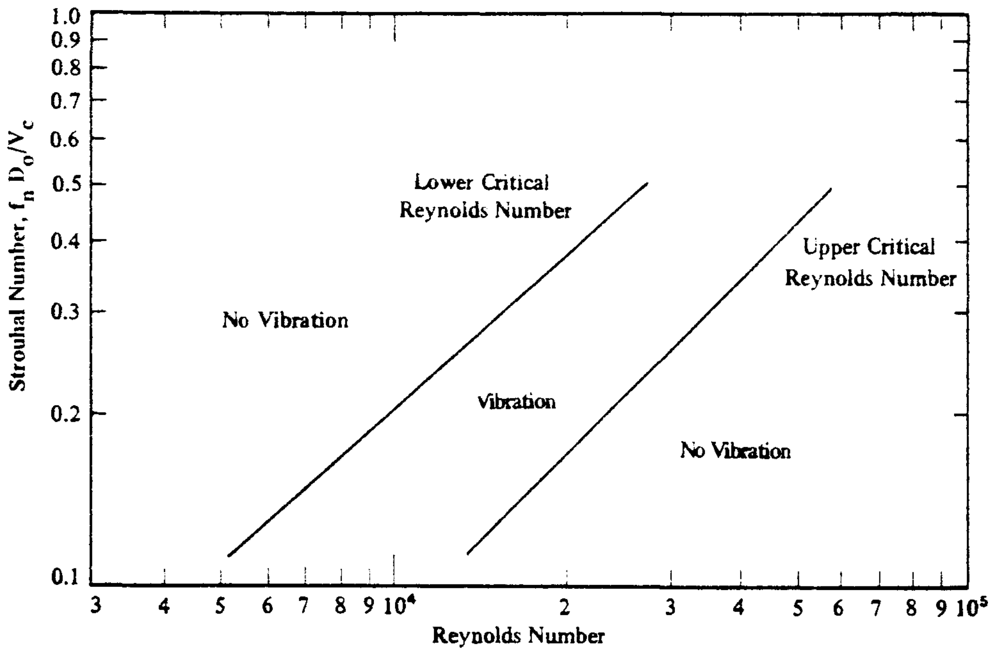


Figure 3-4. Vibration Map Proposed by Gregorig et al.

Source: Flow-Induced Tube Vibrations in Shell-and-Tube Heat Exchangers, J. M. Chenoweth, Heat Transfer Research, Inc., February 1977.

3.2.1.6 Thorngren Damage Numbers. Thorngren (1) proposed two dimensionless numbers, called "damage numbers," to predict tube damage from cutting at the baffles and collision between adjacent tubes:

$$N_{BD} = \frac{D_o \rho_s V_c^2 L^2}{F_B S_m g_c A_m B_t}$$

and

$$N_{CD} = \frac{0.625 D_o \rho_s V_c^2 L^4}{F_B^4 g_c A_m \left(D_o^2 + D_i^2\right) C_t E}$$

where

F_B = tube-to-baffles clearance factor, dimensionless
= 1.00 for 1/32 inch clearance (0.079 cm)
= 1.25 for 1/64 inch clearance (0.040 cm)
S_m = fatigue stress, lb/in^2 (kg/m^2)

= E/2400 for carbon steel or low alloy

= E/1000 for stainless steel or non-ferrous

A_m = tube wall metal cross-sectional area, in^2 (m^2)

C_t = minimum gap between adjacent tubes, in (m)

E = modulus of elasticity, lb/in^2 (kg/m^2)

D_i = tube ID, in (m)

D_o = tube OD, in (m)

ρ_s = shellside fluid density, lb/in^3 (kg/m^3)

V_c = crossflow velocity, in/sec (m/sec)

L = tube span length, in (m)

g_c = gravitational constant, 386.4 in/sec^2 (9.81 m/sec^2)

B_t = baffle thickness, in (m)

Thorngren indicated that if either of these damage numbers was equal to or greater than 1.0, tube damage would be probable. These numbers are based on the static deflection of the tube, and do not account for the amplitude magnification that could occur when the vibration frequency is close to resonance.

3.2.1.7 Brothman Method. Brothman (4) proposed a method for predicting flow-induced vibration problems that involves summing the tube displacements resulting from various types of excitation mechanisms to obtain a worst-case peak midspan deflection. The Brothman method attempts to determine the cumulative effect of all possible excitation mechanisms in a heat exchanger. These include flow-induced mechanisms (vortex shedding, turbulent buffeting, fluctuating axial drag, fluid-elastic whirling, acoustical coupling), hydraulically coupled mechanisms (disturbances from pumps and level control valve "hunting"), and mechanically coupled excitations (noise energy fed into the heat exchanger through supports and piping). The analysis involves establishing natural frequencies; estimating damping; computing lift, drag, and longitudinal forces that are developed by shell flow; calculating the displacement amplification factors; and determining the cumulative displacement response. Peak tube stresses and cyclical wear rates at tube support locations can then be computed.

3.2.1.8 Taylor Method. Taylor (1) proposed a dimensionless failure criterion that is used as a multiplier to equations for predicting tube-to-tube collision damage failure, bending stress failure, and tube fretting failure at the baffles.

The multiplier is:

$$F_c = \frac{2\pi C}{\delta}$$

where

F_c = failure criterion multiplier

C = lift coefficient, dimensionless

δ = log decrement, dimensionless

For predicting tube-to-tube collision damage, the midspan amplitude must be greater than half the gap between adjacent tubes. For bending stress failure, the calculated stress must exceed the endurance limit as defined by the stress that will just cause failure at 108 cycles. For failure due to fretting at the baffles, the maximum stress due to impacting the baffle edge must exceed the endurance limit for the tube material.

3.2.1.9 <u>Jet Switching</u>. When closely spaced tubes are displaced in an alternating fashion, jet pairs that are emitted from adjacent tube gaps can switch back and forth, causing fluctuating forces on the tubes. However, it is believed that this jet switching is of secondary importance to fluidelastic whirling (7).

3.2.1.10 <u>Sebald Method</u>. In a paper submitted at the EPRI Feedwater Heater Workshop (3), J.F. Sebald presented a method of vibration analysis for FWHs that is similar to one that has been used successfully for steam surface condensers. In this method, the tube loadings due to lift and drag are calculated using the following equations:

$$W_L = C_L \rho A \frac{V^2}{2g}$$

and

$$W_D = C_D \rho A \frac{V^2}{2g}$$

where

W_L = lift force, lbs/lineal inch of tube (kg/m)
W_D = drag force, lbs/lineal inch of tube (kg/m)
ρ = fluid density, lb/ft^3 (kg/m^3)
V = fluid velocity, ft/sec (m/sec)
A = area per lineal inch of tube, ft^2 (m^2)
C_L = lift coefficient
C_D = drag coefficient
g = gravitational constant, ft/sec^2 (m/sec^2)

Tube deflection as a result of these loadings is then calculated using standard beam equations to determine if midspan tube contact will occur. In the example described in his paper, Sebald used a value of 1.15 for C_D. For C_L he used values of 1.0 and 2.19 to cover the range that exists in available data. In addition to checking for midspan collision, Sebald recommends that flow velocities be checked to ensure that they do not match the critical Strouhal velocity.

3.2.1.11 Comparison of Vibration Prediction Methods. At least two investigations have been conducted to compare various vibration prediction methods with data from operating heat exchangers. However, none of these heat exchangers was a FWH. In one investigation (1), Chenoweth examined the TEMA and the HTRI vibration data banks, which together contain data on 67 heat exchangers. Each of the vibration methods that was considered has more than one value to use as the criterion for predicting vibration. Chenoweth found that the more conservative value leads to a higher number of cases of vibration being correctly predicted. However, this more conservative value also leads to overprediction of vibration for cases where none was reported. The methods that were considered were the Connors method for fluid-elastic whirling, the Chen method for vortex shedding, the Owen method for turbulent buffeting, and the Thorngren method using baffle damage numbers. Also, using a limiting value of ρV^2 as a criterion was considered as another method (similar to the approach used in Section 3.3.1). Chenoweth found that for both vibration data banks, nearly perfect predictions of cases with vibration are made by:

- The Connors method, using a value of 0.0033 for the logarithmic damping decrement;
- The Chen method, using a vortex shedding to tube natural frequency ratio of 0.5;

- The Owen method, using a turbulent buffeting to tube natural frequency ratio of 0.5; and

- The Thorngren method, using a baffle damage number of 0.1.

However, by using these conservative values, many cases with no vibration are incorrectly predicted to have vibration. The method using a limiting value of ρV^2 was generally unreliable.

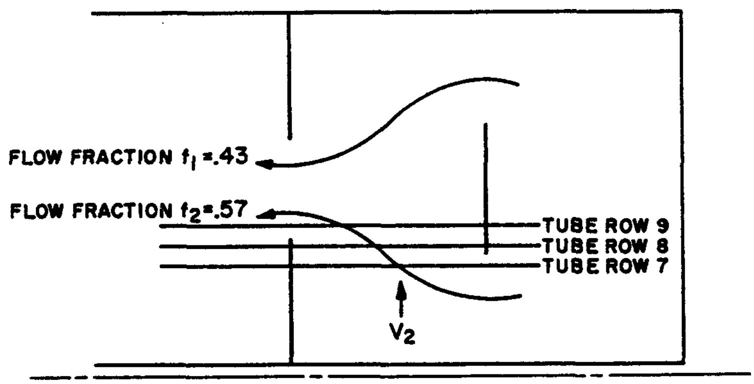
Erskine and Waddington (8) conducted an investigation to compare various vibration prediction methods with data from nineteen chemical plant heat exchangers that experienced failures due to vibration. Additional heat exchangers that did not fail were included for comparison. It was found that resonant vibration, as predicted by the Chen or Owen methods, was not a likely cause of the failures. The Connors method was considered to be a promising approach, but hard to apply because of the difficulty in predicting a correct damping value.

Almost all of the heat exchanger failures involved baffle damage, rather than collision damage, so the Thorngren baffle damage number (N_{BD}) was considered. This method was unreliable if a critical value of 1.0 was used for N_{BD}. However, if the critical value of N_{BD} is varied proportionally with log ($\rho/\sqrt{\mu}$), it was found that fairly accurate predictions could be made for cases with and without vibration damage. (Note: ρ is fluid density, and μ is fluid viscosity.)

3.2.2 Application to FWHs

It is not always certain which of the vibration excitation mechanisms described above will be present in a specific shell and tube heat exchanger. However, designers of FWHs generally agree that (1) fluidelastic whirling in the desuperheater and drains subcooler zones and (2) vortex shedding in the drains subcooler zone are of concern. Therefore, the Connors method (fluidelastic whirling) and the Chen method (vortex shedding) are commonly used in design to avoid FWH vibration problems.

Prediction of these vibration problems can only be as good as the prediction of crossflow velocity. The magnitude of the crossflow velocity is difficult to determine because of the complex flow pattern in the desuperheater and drains subcooler zones, especially near nozzles, impingement plates, and tube supports. One method for arriving at the crossflow velocity is to divide the volumetric flow rate by the net free area (perpendicular to the flow) located halfway between overlapping baffle tips (see Figure 3-5). If the baffles are arranged such that more than one flowstream exists, the flow for each is proportioned according to the net free flow area for that stream where the baffle splits the streams. This simple method does not account for leakage and bypass streams, which often have considerably higher velocities than the main crossflow stream. More sophisticated methods, such as the stream analysis method (1), are required to predict velocities more accurately.



$$V_2 = \frac{12M\ (f_2)\ \nu_2}{A_8}$$

where

M = desuperheater mass flow rate, lbs/sec

f_2 = flow stream flow fraction, decimal fraction

A_8 = net free area at tube row 8, ft^2

V_2 = gap crossflow velocity for flow stream f_2 in flow zone 2, in/sec

ν_2 = steam specific volume at zone 2, ft^3/lb

Figure 3-4. Typical Cross-Sectional Gap Velocity Determination

Source: Feedwater Heater Desuperheater Vibration Analysis, H. Wightman, Struthers-Wells Corporation, n.d.

Obviously, prediction of crossflow velocity also depends on the total mass flow that is used. Often, the FWH is designed only for normal operation. During abnormal operation, considerably higher shellside flows can exist, leading to higher velocities and damaging tube vibration. One common example of abnormal operation is the bypassing of a FWH, so that the next downstream FWH receives colder feedwater and, therefore, extracts more steam. A conservative rule of thumb is that this downstream FWH will extract the same amount of steam as both FWHs would extract during normal operation. Another example of abnormal operation is the bypassing of one string in a two-string FWH arrangement, and doubling feedwater flow through the remaining string. In this case, the extraction steam flow would approximately double. In general, design for abnormal conditions is left to the vendor. Obviously, to have the same crossflow velocity at twice the flows would require twice the shell area, which is impractical. Therefore, vendors typically design closer to the critical velocity when designing for abnormal flows. For example, one vendor uses the criterion that V_{eff}/V_{crit} must be less than .95 for abnormal flows. Another approach to designing against tube vibration during abnormal operation is to incorporate desuperheater zone bypasses and drains subcooler zone bypasses into the piping system.

Prediction of tube natural frequency is more certain. The natural frequency of the tube depends on the method by which the ends are fixed, the type of intermediate supports, the tube cross-sectional geometry, the number of spans, the materials, and the length of the spans. Current methods of prediction are considered adequate, but the effects of roller expanding and operating conditions on the axial loads, which also affect natural frequency, are not completely known (1).

Since all tubes in the FWH do not have the same number of supports and since their span lengths differ, many different tube natural frequencies can exist. A rigorous approach to predicting the frequencies requires solving the differential equation for each span. A simpler approach assumes spans of equal lengths (1), with:

$$f_n = 0.04944\ C_n \sqrt{\frac{EIg_c}{W_e L^4}}$$

where

f_n = frequency for the n^{th} mode, Hz

C_n = frequency constant for the N^{th} mode

I = sectional moment of inertia, in^4 (m^4)

$$= \pi \left(D_o^4 - D_i^4 \right) / 64$$

g_c = gravitational constant; 386.04 in/sec^2 (9.81 m/sec^2)

E = modulus of elasticity of tube material, lb/in^2 (kg/m^2)

L = length of span, in (m)

W_e = effective weight per unit length, lb/in (kg/m)

$= W_m + W_t + W_s$

W_m = weight per unit length of tube itself, lb/in (kg/m)

W_t = weight per unit length of tube for tubeside fluid, lb/in (kg/m)

W_s = virtual weight per unit length of tube for the shellside fluid displaced by the tube, lb/in (kg/m)

$= k\rho_s \, (\pi/4) \, D_o^2$

k = experimentally determined hydrodynamic inertia coefficient (values range from 1.3 to 2.0, depending on tube pitch-to-diameter ratio)

ρ_s = shellside fluid density, lb/in^3 (kg/m^3)

D_i = tube ID, in (m)

D_o = tube OD, in (m)

The frequency constant, C_n, depends upon the way the ends of the tube are fastened, the number of spans, and the type of intermediate supports. Normal baffle clearances result in the tube holes acting like simple supports. Tube-to-baffle clearance would have to be reduced to a pressed fit before any appreciable change in natural frequency would occur. The frequency can be adjusted for axial stress by applying the following formula:

$$\left(f_n\right)_s = f_n \sqrt{1 + \frac{P_a L^2}{EI\pi^2}}$$

where

$\left(f_n\right)_s$ = stressed frequency, Hz

P_a = axial load, compressive (-) or tensile (+), lb (kg)

L = length of span, in (m)

E = modulus of elasticity of tube material, lb/in^2 (kg/m^2)

I = sectional moment of inertia, in^4 (m^4)

The length of the unsupported span is the most influential factor in determining natural frequency, and the current trend in heat exchanger design is to limit span lengths to 80% of the TEMA standards.

3.2.3 Solutions to Vibration Problems

There are three approaches the designer can use if he anticipates vibration problems:

- Increase the tube natural frequency;
- Reduce the flow velocity; and
- Increase damping.

Tube natural frequency can be increased by adding extra baffles and reducing the span length; but care must be exercised since extra baffles may increase velocities. Velocities can be reduced by increasing the shellside diameter, increasing tube pitch, creating bypass lanes in the direction of the flow, enlarging inlet/outlet nozzle diameters, or changing the tube field layout angle. Damping can be increased by reducing the tube-to-baffle clearance, at the possible expense of increased fretting.

3.3 VIBRATION PROBLEMS AS ADDRESSED IN INDUSTRY STANDARDS

The problem of vibration is discussed in both the Standards for Closed Feedwater Heaters (HEI) and the Standards of the Tubular Exchanger Manufacturers Association (TEMA); but neither standard provides specific guidance for designing against vibration. It is suggested that the reason is that vibration mechanisms are not yet well enough understood to establish strict industry standards. The standards do give criteria on certain aspects of the design that can effect vibration, such as baffle spacing, baffle thickness, inlet velocity, etc., and these are discussed below. It must be recognized that none of these design criteria are specifically intended to prevent vibration.

3.3.1 Shellside Inlet/Outlet Velocities

HEI states that nozzles should be sized such that:

- Condensate drain outlet velocity does not exceed 4 fps (1.22 m/sec) for subcooled drains; 4 fps (1.22 m/sec) for saturated drains when the water level in the FWH is controlled, and 2 fps (0.61 m/sec) when not controlled;
- G^2/ρ does not exceed 4000 and G does not exceed 250 for flashing drain inlets,

  G = mass velocity, lb/ft^2-sec

  ρ = density, lb/ft^3;

- G^2/ρ does not exceed 1000, and lineal velocity does not exceed 150 fps (45.72 m/sec) for steam entering the drain inlet from the flash tank;

- Lineal velocity does not exceed 4 fps (1.22 m/sec) for liquid entering the drain inlet from the flash tank; and

- Lineal velocity does not exceed $250/(\text{psia})^{0.09}$ fps for dry or saturated steam in the steam inlet nozzle or in the steam distribution dome. Also, the distance between the nozzle penetration point and the impingement plate must not be less than one-fourth of the nozzle diameter.

TEMA states that ρV^2 must not exceed 4000 for shell or bundle entrance or exit areas, where ρ is density (lb/ft^3) and V is velocity (fps). (Note: $\rho V^2 = G^2/\rho$.)

Neither standard addresses the velocity of steam entering the drains subcooler zone or in the gaps between tubes.

3.3.2 Tube Layout

HEI states that tubes should be arranged in a triangular pitch with a minimum center-to-center spacing equal to:

tube OD + 3/16"

or

tube OD x 1.25

whichever is greater.

TEMA states that the minimum spacing should be (1.25 x tube OD) for R exchangers. In C exchangers, this could be reduced to (1.20 x tube OD) for tubes of 5/8" (1.58 cm) diameter or smaller that are only rolled into the tubesheet. (TEMA standards cover three classes of heat exchanges: R, C, and B. FWHs would probably fall within class R or C.)

3.3.3 Tube-to-Baffle Clearance

HEI recommends a tube-to-baffle clearance of 1/64" (0.397 mm), except that 1/32" (0.794 mm) can be used in the drains subcooler zone.

TEMA recommends a tube-to-baffle clearance of 1/32" (0.794 mm) for tubes with an unsupported span less than 36" (91.34 cm) or with an OD greater than 1-1/4" (31.75 mm), and a clearance of 1/64" (0.397 mm) for all other cases. When "pulsating conditions" exist, the clearance may be tighter. The maximum over tolerance on baffle holes should be 0.010" (0.254 mm).

3.3.4 Unsupported Tube Lengths

HEI recommends a maximum unsupported straight tube length of 48" (121.92 cm) for 5/8" OD, 54" (137.16 cm) for 3/4" OD, 57" (144.78 cm) for 7/8" OD, and 60" (152.4 cm) for 1" OD. A vibration analysis may necessitate shorter lengths in specific zones.

TEMA gives maximum unsupported tube lengths as a function of tube material, temperature, and tube OD, as shown in Table 3-3.

Table 3-3

MAXIMUM UNSUPPORTED STRAIGHT TUBE LENGTH
(all dimensions in inches)

Tube O.D. Inches	Maximum Unsupported Span—Inches	
	Tube Materials and Temperature Limits (°F)	
	Carbon & High Alloy Steel (750) Low Alloy Steel (850) Nickel-Copper (600) Nickel (850) Nickel-Chromium-Iron (1000)	Aluminum & Aluminum Alloys Copper & Copper Alloys at Code Maximum Allowable Temperature
1/4	26	22
3/8	35	30
1/2	44	38
5/8	52	45
3/4	60	52
1	74	64
1 1/4	88	76
1 1/2	100	87
2	125	110

Note: Above the metal temperature limits shown, maximum spans shall be reduced in direct proportion to the fourth root of the ratio of elastic modulus at temperature to elastic modulus at tabulated limit temperature. In the case of circumferentially finned tubes, the tube O.D. shall be the diameter at the root of the fins and the corresponding tabulated or interpolated span shall be reduced in direct proportion to the fourth root of the ratio of the weight per unit length of the tube, if stripped of fins to that of the actual finned tube.

Source: Standards Of Tubular Exchanger Manufacturers Association, Sixth Edition, 1978.

3.3.5 Baffle Thickness

HEI recommends 3/8" (9.525 mm) for baffle and support plant thicknesses in desuperheating and condensing zones for shell diameters less than 18" (45.72 cm), and 5/8" (15.88 mm) for larger shell diameters. The minimum thickness in subcooling zones for all FWHs should be 1/4" (6.35 mm) for spacings less than 18" (45.72 cm), and 3/8" (9.525 mm) for spacings greater than 18" (45.72 cm).

TEMA provides recommended baffle and support plate thickness as a function of shell diameter and unsupported tube length, as shown in Table 3-4. For larger shell diameters, the recommended thickness is part of the "Recommended Good Practice" rather than the standard itself.

Table 3-4

BAFFLE OR SUPPORT PLATE THICKNESS
(all dimensions in inches)

Nominal Shell I.D.	Plate Thickness					
	Distance between adjacent full diameter baffles, supports or the unsupported tube length between other type baffles.					
	12 and Under	Over 12 to 24 Inc.	Over 24 to 36 Inc.	Over 36 to 48 Inc.	Over 48 to 60 Inc.	Over 60
6 - 14	1/16	1/8	3/16	1/4	3/8	3/8
15 - 28	1/8	3/16	1/4	3/8	3/8	1/2
29 - 38	3/16	1/4	5/16	3/8	1/2	5/8
39 - 60	—	1/4	3/8	1/2	5/8	5/8

Note: The thickness of the baffle or support plates for U-tube bundles shall be based on the unsupported tube length in the straight section of the bundle. The U-bend length shall not be considered in determining the unsupported tube length for required plate thickness.

Nominal Shell I.D.	Plate Thickness				
	Distance between adjacent full diameter baffles, supports or the unsupported tube length between other type baffles.				
	24 and under	Over 24 to 36 Inc.	Over 36 to 48 Inc.	Over 48 to 60 Inc.	Over 60
61 - 100	⅜	½	⅝	¾	¾

Source: Standards Of Tubular Exchanger Manufacturers Association, Sixth Edition, 1978.

3.3.6 General Standards For Vibration

HEI states that flow passages for the distribution of fluid into the tube bundle should be designed to minimize tube vibration.

TEMA points out that existing predictive correlations for vibration are inadequate. Vulnerability to vibration depends on flow rate, tube and baffle materials, unsupported tube spans, tube field layout, shell diameter, and inlet/outlet configuration. The manufacturer will not necessarily attempt to analyze for vibration unless specifically requested to do so by the customer, and then only if specific information is supplied. In the "Recommended Good Practice" section, it is pointed out that the recommended maximum tube spans do not consider vibration. If analysis indicates that vibration will occur, design features such as tube pitch, shellside piping, or baffle configuration can be modified.

A recommended method for calculating tube natural frequency is also provided. For straight tubes on multiple equal spans:

$$f_n = \frac{3.36C}{l^2} \sqrt{\frac{EI}{W}}$$

where

f_n = tube natural frequency

C = mode constant (see Table 3-5)

l = span length, in

E = modulus of elasticity, psi

I = moment of inertia, in

$W = W_t + W_{fi} + MW_{fo}$

W_t = weight of empty tube, lb/ft

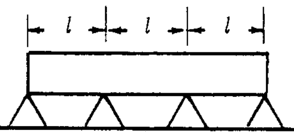
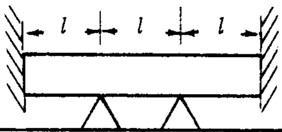
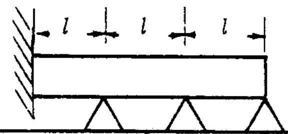
W_{fu} = weight of fluid inside tube, lb/ft

W_{fo} = weight of fluid displaced by tubes, lb/ft

M = added mass coefficient (see Table 3-6)

Table 3-5

MODE CONSTANT C FOR CALCULATING TUBE NATURAL FREQUENCY

No. of Spans	Extreme Ends Supported 		Extreme Ends Clamped 		Extreme Ends Clamped-Supported 	
	1st Mode	2nd Mode	1st Mode	2nd Mode	1st Mode	2nd Mode
1	31.73	126.94	72.36	198.34	49.59	160.66
2	31.73	49.59	49.59	72.36	37.02	63.99
3	31.73	40.52	40.52	59.56	34.32	49.59
4	31.73	37.02	37.02	49.59	33.02	42.70
5	31.73	34.99	34.99	44.19	33.02	39.10
6	31.73	34.32	34.32	40.52	32.37	37.02
7	31.73	33.67	33.67	38.40	32.37	35.66
8	31.73	33.02	33.02	37.02	32.37	34.99
9	31.73	33.02	33.02	35.66	31.73	34.32
10	31.73	33.02	33.02	34.99	31.73	33.67

Source: Standards Of Tubular Exchanger Manufacturers Association, Sixth Edition, 1978.

Formulas are also given to account for axial stress, to calculate frequencies for straight tubes with unequal spans, and to calculate frequencies for U-tubes.

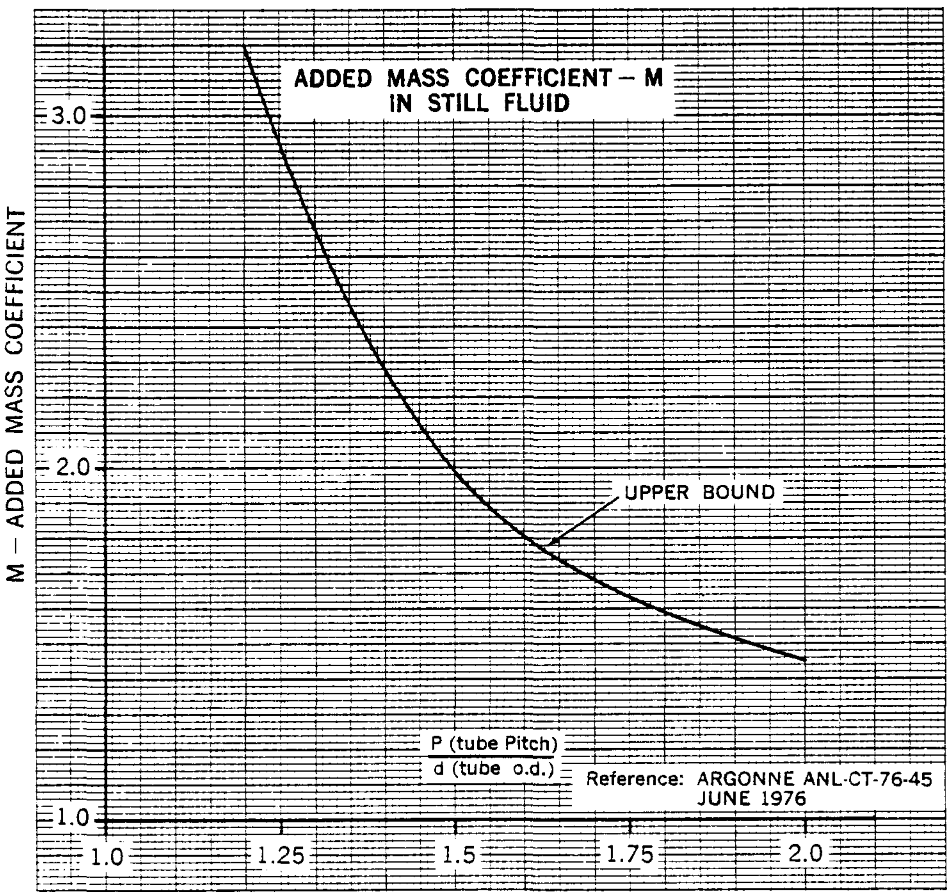
No particular method of vibration analysis is endorsed; however, various mechanisms of tube vibration are listed. They are:

- Vortex shedding frequency matches tube natural frequency;
- Turbulent pressure fluctuations;
- Axial flow-induced vibration;
- Fluidelastic whirling; and
- Acoustic resonance.

3.4 VIBRATION PROBLEMS AS ADDRESSED IN PURCHASE SPECIFICATIONS

The problem of vibration is addressed by utilities in FWH purchase specifications in a variety of ways. A review of several purchase specifications revealed the following typical approaches. (Note: The reader should be cautioned that the following examples from utility purchase specifications are not endorsed by EPRI or by the authors of this report.)

- Nothing is mentioned about designing against vibration other than by reference to the HEI standard.



Notes: (1) The natural frequency of a low finned tube can be approximated conservatively by using the actual weight of the tube for W_t, the actual inside diameter for d_i and the root diameter for d_o in the calculation of moment of inertia, I.

(2) Increasing baffle thickness and reducing hole clearance within practical limits have no major effect on the natural frequency of a tube. However, damping is increased by these factors and impacting of the tube at the baffle is reduced.

Figure 3-6. Added Mass Coefficient M For Calculating Tube Natural Frequency

Source: Standards Of Tubular Exchanger Manufacturers Association, Sixth Edition, 1978.

- "The feedwater heater shall operate satisfactorily during abnormal conditions." "Satisfactorily" may mean no excessive pressure drop, no water hammer, no excessive wear, etc.; but vibration is not mentioned.

- "The feedwater heater shall operate without vibration under normal and abnormal conditions," where "abnormal" is either undefined or is defined in one of the following ways:

  - The upstream FWH is out of service, in the case of a specified FWH used in a single-string arrangement. Full feedwater flow bypasses the upstream FWH, causing the specified FWH to extract more steam.

  - Full feedwater flow through one FWH in a double-string arrangement, with the twin FWH out of service.

  - Unspecified changes in generating load or an unspecified number of FWHs out of service.

  - A specific percentage of normal feedwater and/or extraction steam flow. Typical values of this are 105%, 110%, 125%, 150%, and 200%.

- Specific design features are required, which are intended to reduce the potential for vibration problems. Some examples are:

  - Holes in the baffles and in the tube support plate must be chamferred;

  - Clearance between the tube OD and the tube support hole must be tighter than specified in the HEI standard (e.g., 0.010" + 0.0002" [0.254 mm + 0.005 mm], rather than 1/64" [0.397 mm]); and

  - Unsupported tube lengths must be less than the maximum specified in the HEI standard (much less than 48" [121.9 cm]).

- The vendor is requested to supply a vibration analysis showing the "critical velocities and the actual velocities in the shellside of the desuperheater and drains subcooler zones. The specification may also state that the critical velocity must be a certain amount (e.g., 30%) higher than the actual velocity.

- Shellside velocities must be less than specified values. One utility specifies 150 ft/sec (45.72 m/sec) lineal velocity (no pressure is referenced) and 50 lb/ft^2-sec (244 kg/m^2-sec) mass velocity as maximum values into and within the desuperheater zone; 3 ft/sec (.91 m/sec) maximum velocity entering the drains subcooler suction line; and 4 ft/sec (1.22 m/sec) maximum velocity within the drains subcooler zone. These values are for overload conditions.

No standard approach exists for specifying against vibration. Manufacturers use analytical methods in designing the FWHs against vibration, using the purchaser specifications to select the steam and drain flow rates for the analysis. A common complaint by vendors is that all abnormal flow rates that may be experienced during

FWH operation are not always defined in the purchase specifications. As a result, the FWH is often under-designed from the standpoint of vibration.

Some utilities avoid specifying conservatively high abnormal flow rates because they assume that the FWH would then be designed to meet all criteria (e.g., pressure drop, thermal performance, tubeside velocity) at that flow rate, resulting in excessively expensive FWH. However, there is no reason that a utility cannot specify one flow rate for vibration design and a lower flow rate for other design criteria.

3.5 CONCLUSIONS AND RECOMMENDATIONS

The results of the utility survey show that Westinghouse FWHs were responsible for a large portion of the vibration problems. This might simply reflect the Westinghouse share of the FWH market. Alternatively, it might indicate a poor design, but all failures were not investigated in enough depth to determine that other causes, such as operation with FWH flows beyond specified limits, were not the cause. An industry representative stated that Westinghouse did not begin using the Connors method of vibration analysis until the late-1960s. Many of these failed Westinghouse FWHs might have been designed earlier. With the exception of the Westinghouse FWHs, no obvious correlation in terms of the reported data (e.g., FWH type, tube material, tube OD) is apparent in the data. This is not surprising, since important vibration parameters such as unsupported tube spans and steam velocities were not reported in most cases.

A review of industry standards has shown that they are inadequate with respect to tube vibration problems. Methods to design against vibrations, and specific guidance for purchase specifications to avoid vibration, are not included in the standards. As a result, the treatment of tube vibration in purchase specifications varies widely among utilities. In the opinion of several vendors, many utilities do not adequately specify overload conditions so that the FWH can be designed properly to avoid vibration.

Vendors use analytical methods to design against vibration. Discussions of these methods are available in the literature, and results of vibration analyses are usually available to customers upon request. However, key constants used in the analysis may be proprietary, so it is not always possible for the customer to check the results independently. Vendors are confident that their analytical methods are adequate to prevent vibration problems (provided that the customer does not subject the FWH to flows in excess of those specified). The vendors may be correct, but the amount of published data on FWHs in the field is insufficient to support this contention. Thus, the customer must rely solely on the vendor to ensure that the FWH will be adequately designed to prevent vibration.

The following recommendations for EPRI are intended to provide utilities with more confidence that their FWHs will be free from tube vibration problems:

- Develop a data bank on FWH tube vibration parameters. In the past, other data banks (HTRI, TEMA) have been developed to analyze flow-induced vibration, but they did not specifically address FWHs. The proposed data bank should include information such as tube pitch, shell diameter, baffle arrangement, normal and abnormal shellside flows, clearance between tube OD and tube support plate, tube wall thickness, and vibration analysis method used for FWHs with and without vibration problems. Also, the data bank should differentiate among various sources of vibration, such as fluid flow, condensate slugging, cascaded drains, etc. Some of these data are already available from the survey conducted for this study. The information would be used to verify or modify existing vibration design methods. HEI intends to address vibration in the next edition of the Standard on Closed Feedwater Heaters. The data bank could be useful in developing new standards on vibration.

- Examine ways to extrusively detect damaging tube vibration in an operating FWH. If reliable instrumentation could be installed to detect tube vibration, a utility could ensure, at initial startup, that a FWH is free from vibration problems. Such a checkout could be included in the FWH acceptance tests.

- Develop guidelines for addressing vibration in utility purchase specifications. The guidelines should recommend the abnormal flows to be used for vibration design, the need for a desuperheater bypass line, tube-to-baffle plate clearance, analytical design methods to be used by the vendor (calculation of critical crossflow velocity conducive to vibration), margins of conservatism, etc. Depending on its timing and completeness, the next edition of the HEI Standard on Closed Feedwater Heaters might eliminate the need for such a guideline.

Section 4

LEVEL CONTROL AND DRAINS SUBCOOLER ZONE PROBLEMS

4.1 PROBLEMS AND SOLUTIONS AS REPORTED*

Eighteen utilities reported problems involving drain level control or damage to the shellside of the drains subcooler zone. Since poor level control often causes drains subcooler zone damage, these two problems are discussed together.

Table 4-1 summarizes the problems reported. Some are minor and have not resulted in FWH damage. For example, Utility 1 reported difficulty in venting and draining low-pressure feedwater heaters (FWHs) prior to startup. Until the extraction valve is opened, there is insufficient head to force water out of the FWH shell. Several other utilities mentioned this problem in discussions, but failed to report it on their questionnaires. Poor venting and draining are operational nuisances, but they do not usually result in FWH damage.

Utilities 13, 21, and 42 reported problems in obtaining adequate drainage capacity, which caused high water levels or frequent cycling of the emergency dump valves. In the case of Utility 21, the problem was caused by tube leaks that caused the drainage capacity to be exceeded. In the other two cases, the problems were caused by undersized drain valves. According to utility responses, inadequate drain capacity never resulted in FWH damage. A level control problem will cause FWH damage only if it results in a too low water level. The main concern with a high water level is the possibility of water induction into the turbine.

Several utilities reported problems with the level control system that did not result in tube damage. The accumulation of crud in the floats and the Yarway remote liquid level indicators caused malfunctioning of level control systems of four high-pressure FWHs at Utility 21. At Utility 37, crud deposits caused the emergency drain regulator to repeatedly stick partially open, resulting in a fluctuating water level. Routine maintenance solved both problems. All of the high-pressure FWH level control systems at one unit of Utility 31 malfunctioned as a

*Conditions and solutions as reported by utility respondees. The solutions or causal relationships are not necessarily endorsed by EPRI or the authors.

Table 4-1

FWHs THAT EXPERIENCED CONTROL OR DRAINS SUBCOOLER ZONE PROBLEMS

UTILITY	PLANT	FWHs	FWH ARRANGEMENT	TUBE MATERIAL	VENDOR	PROBLEM DESCRIPTION
1	3	LP3, LP4	Horizontal	Carbon Steel	YUBA	20% of tubes plugged; leaks may be due to improper level control
1	1	LP1, LP2, LP3, LP4	Horizontal	Carton Steel	NA	Difficult to drain FWHs prior to opening extraction valve
16	1	HP2	NA	Carbon Steel	NA	Low level caused flashing in drains sub-cooler zone
21	2	HP: F1, F2, G1, G2	Horizontal	70-30 Cu-Ni	NA	Dirty floats and Yarways cause poor level control
21	3	LP: A1, A2,	Horizontal	Admiralty	NA	Excessive drains due to tube leaks caused high level trips
2	1	HP: 5A, 5B 6A, 6B	Horizontal	Carbon Steel	Foster Wheeler	Damaging shellside velocities in drains subcooler zone; FWHs may need replacement
2	2	HP: 15A, 15B, 25A, 25B, 35A, 35B	Horizontal	Carbon Steel	SWECO	Shellside erosion in drains subcooler zone; FWH replacements required
6	1	HP	Horizontal	Carbon Steel	NA	Leaks in drains subcooler; may be due to low level; FWH replaced
36	1	LP: 3S, 4S	Horizontal	Carbon Steel	NA	Shellside erosion in drains subcooler zone; FWHs replaced

NOTES: LP = low pressure
IP = intermediate pressure
HP = high pressure
NA = information not available

Table 4-1 (Cont.)

UTILITY	PLANT	FWHs	FWH ARRANGEMENT	TUBE MATERIAL	VENDOR	PROBLEM DESCRIPTION
3	1	HP: 7E	Horizontal	Carbon Steel	Foster Wheeler	Erosion from flashing at inlet to drains subcooler zone
3	1	LP: 3E, 3W	Horizontal	Carbon Steel	Worthington	Tube erosion at entrance to drains subcooler zone
13	1	LP 2B	Horizontal	Stainless Steel	NA	Drain valve too small
14	1	IP 41	Horizontal	Carbon Steel	Struthers Wells	Drains subcooler inlet too small, causing high velocity; FWH replaced
14	1	HP: 3A1, 3B1, 3A3, 3B3	Vertical Channel Down	Carbon Steel	Foster Wheeler	Level control problems caused drains subcooler zone damage; FWH replaced
31	1	All 6 HP FWHs at one unit	Horizontal	Carbon	YUBA	Steam leaks ruined electronics in level controllers
27	1	All HP FWHs at 2 units	Horizontal	Carbon Steel	Foster Wheeler	Shellside erosion in drains subcooler zone; level controller did not work, requiring manual level control; FWHs replaced
11	5	LP 1A, 1B LP 2,3,4 HP 6,7 at all 5 units	1A,1B Horizontal 2,3,4 Vertical 6,7 Horizontal	Stainless Steel	YUBA	Level controllers unacceptable for cyclic operation
37	1	HP 1F	Horizontal	Carbon Steel	NA	Emergency drain regulator malfunction
42	3	HP 1A, 1B 2A, 2B	Vertical Channel Down	Monel	NA	Drain control valve undersized
19	1	IP 2, LP 4	Horizontal	Carbon Steel	Westinghouse	Flashing in drains subcooler zone; FWHs replaced

Table 4-1 (Cont.)

UTILITY	PLANT	FWHs	FWH ARRANGEMENT	TUBE MATERIAL	VENDOR	PROBLEM DESCRIPTION
30	1	6A, 6B at 2 units	Horizontal	Carbon Steel	NA	Recommended water level does not provide design approach
35	1	LP 5	Vertical Channel Up	Carbon Steel	Westinghouse	Flashing at water level
44	1	4A, 4B	Horizontal	Carbon Steel	NA	Flashing at drains subcooler inlet causing erosion at shellside of tubes

result of steam leaking into the electronic controls. The problem was resolved by relocating the electronic control module and by using a control system that had fewer pipe connections and, therefore, fewer potential leak points. Utility 11 had to replace all of the FWH level control systems at a five-unit plant because the systems were unacceptable for cyclic operation. Finally, Utility 30 reported that the manufacturer's recommended water level was not providing the approach temperature specified in the design.

Although the reason for the absence of FWH damage in these cases was not determined, possible reasons are that (1) the problem was corrected before damage could result, (2) the malfunctions in the level control system did not result in FWH levels low enough to cause drains subcooler damage, and (3) the FWH tube material had adequate resistance to erosion damage. Regarding this last possibility, of 46 FWHs with level control problems and no resulting tube damage, 36 had tubes that were made of stainless steel, Monel, or copper-nickel, rather than carbon steel.

The remainder of the problems listed in Table 4-1 involve shellside damage of the tubes in the drains subcooler zone. The damage was apparently caused by steam flowing through the zone, resulting in corrosion-erosion or vibration of the carbon steel tubes. The drains subcooler zone is designed for subcooled water only. The presence of steam results in high velocities that are especially damaging to carbon steel tubes. The main reasons reported for the presence of steam were (1) flashing due to excessive velocities at the drains subcooler inlet, (2) flashing due to a low water level in the condensing zone, (3) steam entering the drains subcooler zone because the water level dropped below the drains subcooler inlet, and (4) steam entering through leakage paths other than the drains subcooler inlet. The second and third reasons involve low water levels, which were reportedly caused either by a faulty level control system that did not maintain the normal level or by maintaining a normal level that was too low. One utility representative recalled cases in which the operators had deliberately positioned the drain control valve fully open because they were overly concerned about the possibility of water induction into the turbine. This reduced the pressure drop across the valve, causing flashing in the drains subcooler. The level control system stabilized at this new valve position because the steam-water mixture in the drains subcooler caused the water level to swell to its normal level, and the higher velocity of the steam-water flow returned the pressure drop in the drain line to its normal value. This situation was easily corrected by throttling the drain control valve and by allowing the drain level control system to stabilize at its proper equilibrium point.

The fourth reason involves inleakage of steam through the drains subcooler end plate and through cracked weld seams where the shroud is attached to the tubesheet, endplate, and main shell. The causes are reported to be poor joint design and a lack of quality control during the weld process, e.g., insufficient weld penetration and inadequate fillet size. A fully submerged drains subcooler zone would preclude this problem.

Solutions to drains subcooler zone damage problems included plugging the leaking tubes, enlarging the drains subcooler inlet by widening the nozzle or by welding a "blister" onto the shell, raising the normal water level, modifying the level control system, removing the shroud (thereby eliminating the drains subcooler zone), as well as replacing the entire FWH or tube bundle. Utilities that replaced FWHs or tube bundles usually changed to stainless steel tubes to reduce the potential for erosion-corrosion damage. A novel solution that was recently used at one utility was the installation of a level control system that uses both level and approach temperature difference as inputs.

Two utilities furnished detailed accounts of drains subcooler zone damage. These accounts provide good examples of this particular problem. Utility 2 reported on a three-unit plant -- each unit having three pairs of horizontal high-pressure FWHs manufactured by Southwestern Engineering Company. The lowest point high-pressure FWHs in each plant experienced tube leaks in rows 1 through 6 of the drains subcooler zone. The cause was determined to be flashing in the drains subcooler inlet area. This problem was corrected by raising the normal water level 3-3/4" (9.53 cm) and by enlarging the drains subcooler zone inlet area. Subsequently, leaks began to occur in rows 18 to 23 of the drains subcooler zone. Since these rows are above the water level, inlet flashing was dismissed as a possible cause; but two other possible causes were considered. One was inadequate venting during startup. A review of plant procedures showed that the drains subcooler zone might not be completely vented of non-condensible gases during startup because a startup vent valve designed for that purpose may not have been left open long enough. In that case, the baffle arrangement in the drains subcooler zone could trap non-condensibles, leading to corrosion of the carbon steel tubes. A contributing factor may have been the cascaded vent arrangement used at the plant. Continuous vents are cascaded from higher point FWHs to lower point FWHs, rather than being independently returned to the condenser or the deaerator as recommended by the HEI standard.

A second possible cause was failure of the level control drain valve in the open position. The valve is designed to fail open on loss of air supply, and it was felt that this may have occurred several times. The result would be complete drainage of the drains subcooler zone, allowing steam to enter and damage the drains subcooler zone endplate as well as the tubes. An inspection of the Unit 1 FWHs showed that such damage to the endplate had, in fact, occurred. The damage was so severe that the utility decided to remove the drains subcooler shroud completely and to operate the FWHs without a drains subcooler zone until replacement FWHs could be procured. Replacement FWHs are also being considered for Units 2 and 3. The combined costs of (1) the increased heat rate due to removal of the shrouds, (2) derating the plant by 25 MW when a FWH string is isolated for tube leaks, and (3) plant downtime for tube plugging were estimated to be in excess of $1 million per year due to these FWH problems at Unit 1.

Utility 14 has a four-unit supercritical plant in which each unit has three pairs of vertical (channel-down) Foster Wheeler high-pressure FWHs. The lowest point high-pressure FWHs at Units 1 and 3 suffered extensive tube damage in the drains subcooler zone. The problem was attributed to level control problems. The level control system includes a surge tank to provide additional volume for the drains for high level conditions. At low level conditions, the surge tank is not used in the system. Since the extra capacitance of the surge tank exists on a rising level, but not on a falling level, the result is erratic water level control.

Compounding this problem is the location of the emergency dump valve, just before the inlet to the next lower FWH. When it opens, the normal dump valve is already fully open. The excess drains flow through the drains subcooler zone at increased velocity and then to the condenser through the emergency dump valve, until the FWH goes dry. This also causes the next lower FWH to blow back to the open condenser line through its drain inlet line. It was reported that for many years the dump valves were locked open so that the drains subcooler zone blew down continuously, because the system would not function properly otherwise. The result was extensive erosion-corrosion of the tubes in the drains subcooler zone, and subsequent FWH replacement. For the replacement FWHs, the surge tank will be removed and the level control system replaced. Also, the emergency dump valve will be relocated so that excess drains flow does not pass through the drains subcooler zone.

It was concluded by the utility that the other high-pressure FWHs in Units 1 and 3 were not failing because they operate at higher temperatures, causing the protective magnetite coating to form on the tubes more rapidly. Also, they have lower drains flows and lower temperature differentials between the shell and the feedwater than do the FWHs that failed. Finally, it was concluded that failures did not occur in Units 2 and 4 because those units are not cycled between low and high loads as often as Units 1 and 3.

4.2 DRAINS SUBCOOLER PROBLEMS AS DISCUSSED IN THE LITERATURE

The literature search identified two articles that deal specifically with problems experienced in the drains subcooler zone. In their investigation (9), Noe, Peterson, and Wyzalek discuss tests conducted by Worthington Corporation, in 1967, to gain a better understanding of the operation of the drains subcooler zone in a FWH. Pressure, temperature, and liquid level measurements were taken at three shell locations and six drains subcooler zone locations in an operating FWH. The FWH was a horizontal type with the drains subcooler zone inlet nozzle submerged in the condensate at the bottom of the condensing zone. Normal water level was maintained above the first row of tubes.

Seventeen test runs were conducted with various shell liquid levels; two methods of liquid level control, manual and automatic; different drain outlet locations; and varied throttling of the gate valve at the lower FWH receiving the drains. Results indicated that flashing occurred in the drains subcooler zone when the water level in the shell was low (defined as 3" [7.62 cm] above the shell ID). The bottom of the lowest row of tubes was 2-3/4" (6.99 cm) above the shell ID. The flashing problem was aggravated when the level control valve was open wider than required to pass full flow. This reduced the pressure drop across the valve, which lowered the pressure in the drains subcooling zone, causing more flashing. It was also discovered that the shell liquid level had a definite slope, with the higher level at the U-tube end. This reveals the importance of locating level sensor connections near the drain subcooler inlet. The conclusion was that flashing can occur (1) when the liquid level is not maintained high enough in the condensing zone to afford precooling of the drains below the saturation temperature or (2) when automatic controls are not operated properly or monitored levels are not representative of that existing at the drains subcooler zone inlet nozzle. Flashing can cause high velocities in the drains subcooler zone and erosion-corrosion of carbon steel tubes.

In their investigation, Riegger and Wochele (10) present the Brown-Boveri philosophy with respect to drains subcooler zone design. Five different types of drains subcoolers can be manufactured (see Figure 4-1):

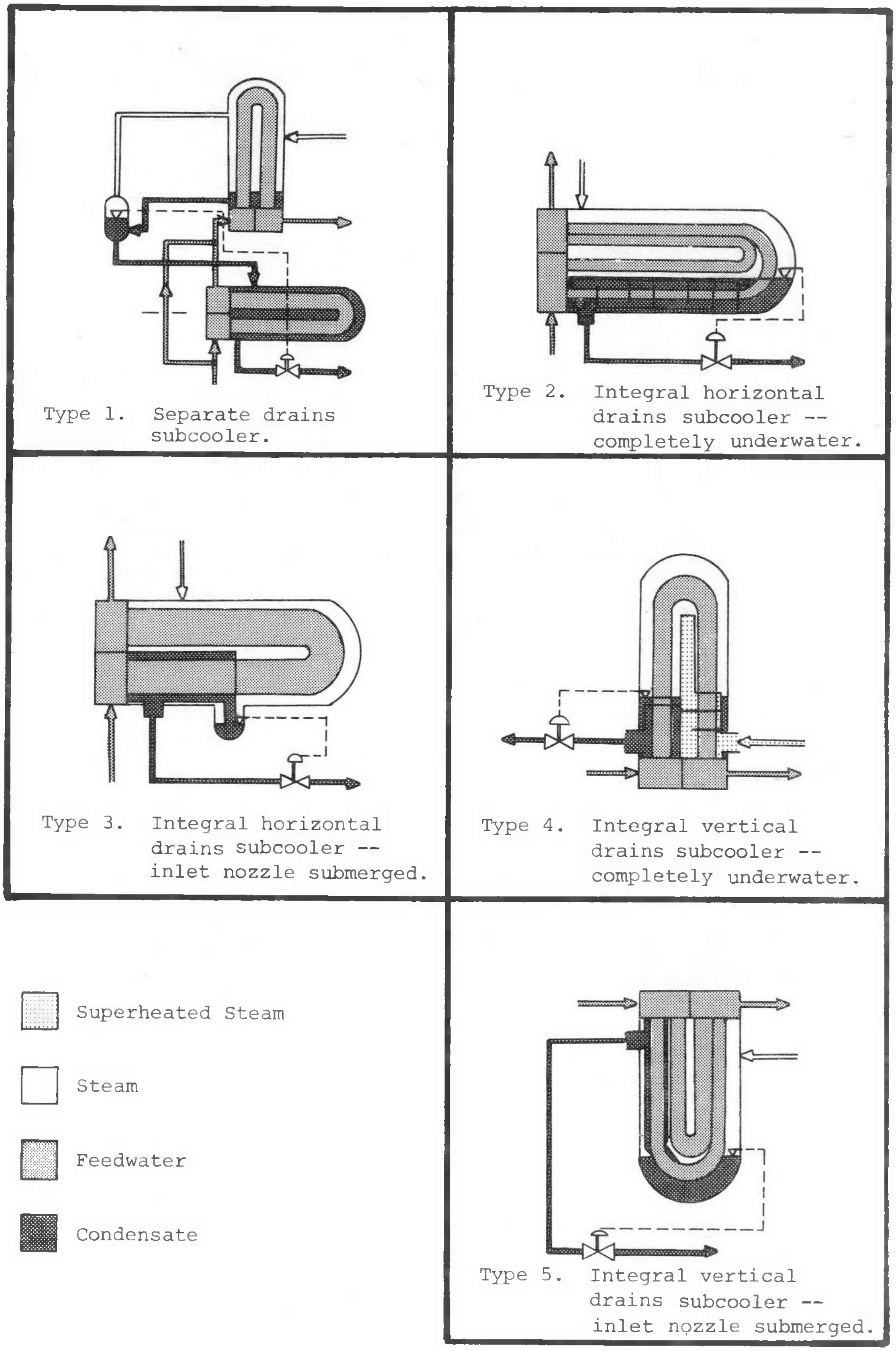


Figure 4-1. Five Types of Drains Subcoolers

Source: "Reliable Drain Coolers for Feedwater Heating," Brown-Boveri Review, H. Riegger and J. Wochele, August 1978.

1. Separate.

2. Integral in a horizontal FWH, with the drains subcooler completely underwater.

3. Integral in a horizontal FWH, with only the inlet nozzle submerged in water and the water level below the bundle.

4. Integral in a channel-down vertical FWH, with the drains subcooler completely underwater.

5. Integral in a channel-up vertical FWH, with only the inlet nozzle submerged in water at the bottom of the shell and the outlet nozzle near the top of the shell.

One problem that can occur in the drains subcooler is flashing, which leads to erosion-corrosion damage of carbon steel. Flashing is caused by (1) excessive velocity, resulting in pressure drops that exceed the subcooling ability of the drains subcooler; (2) internal elevation head losses that exceed the subcooling ability; (3) penetration of the condensate, through leakage paths inside the drains subcooler, into regions where the pressure is lower; (4) external leakage of condensate or steam into the drains subcooler (other than through the inlet nozzle); and (5) heat transfer from outside the drains subcooler. External leakage includes steam penetration through the endplate "ring gap" (i.e., the clearance between tube OD and the baffle or support hole).

Brown-Boveri solves the problem of velocity-induced flashing by calculations to ensure that the subcooling keeps pace with the pressure drop in all modes of operation. Internal leakage is controlled by installing baffles tightly to the shroud, using small ring gaps in the baffles, and ensuring low condensate pressure differentials. The problem of internal elevation head loss applies only to drains subcooler types 3 and 5, in which the drains subcooler is not completely submerged. The problem of steam penetration, which applies only to type 3, cannot be completely eliminated.

The separate drains subcooler (type 1) is the most reliable design, but has the highest capital cost. Types 2 and 4 (drains subcooler zone completely underwater) are also considered to be reliable designs. Type 3 can be made reliable with special design measures, but it is suitable only for high-pressure FWHs. Brown-Boveri does not believe the reliability of type 4 can be guaranteed if carbon steel tubes are used, because of potential elevation head loss and steam penetration problems. Type 4 is the most prevalent design used in the U.S. installations.

In his investigation (11), A. L. Cahn presents a general approach for sizing the piping system between the drains subcooler outlet and the lower-pressure FWH to which the drains flow. This problem involves the flow of a flashing steam-water mixture. As the subcooled drains leave the FWH, friction and static head losses reduce the pressure until the saturation point is reached somewhere in the piping system.

The specific volume of the steam-water mixture increases rapidly as steam is produced. Energy that becomes available as a result of the decrease in pressure results in an increase in the kinetic energy. This increased velocity further increases the rate of pressure drop. A critical downstream pressure will exist in the pipe, corresponding to the sonic velocity state for the conditions that exist. The Bosworth-Cahn equation was developed to calculate this critical end pressure:

$$P_c = \frac{(P_s)^{0.2}\ (W/A)^{0.9388}}{16.77}$$

where:

P_c = critical end pressure, psia
P_s = saturation pressure, psia
W = flow rate, lb/sec
A = pipe cross sectional area, ft^2

A general approach to sizing a drains system, using this equation, is provided in Cahn's report (11). The approach ensures that no flashing occurs upstream of the control valve and that the control valve is sized appropriately.

4.3 DRAINS SUBCOOLER PROBLEMS AS ADDRESSED IN INDUSTRY STANDARDS

Published industry standards say little about drains subcooler problems. The HEI standard recommends that a FWH be designed for an approach not closer than 10°F (5.6°C), that the pressure drop in the drains subcooler zone not exceed 5 psi (34,500 Pa), and that subcooled drains velocity not exceed 4 ft/sec (1.22 m/sec) in the drain outlet nozzle. The specific problem of flashing in the drains subcooler is not addressed. Also, it recommends that level sensor connections be located near the drains subcooler inlet and that independent connections be used for gauge glasses, level controls, and alarms.

Limited discussions about drains subcooler problems were held with several vendors. One vendor limits the drains subcooler inlet velocity to 2 ft/sec (0.61 m/sec) and installs an anti-vortex plate to avoid flashing from high velocities. Within the past several years, this vendor discovered flashing in the drains subcooler zone, a problem that could be attributed to the elevation head loss as the condensate rose into the inlet nozzle of the drains subcooler (horizontal FWHs). The problem was solved by raising the operating water level such that head loss was negligible before the condensate reached the first tube and started to subcool.

Another vendor reported that drains inlet nozzle velocities are kept below 1 ft/sec (0.3 m/sec), and a "division plate" in the nozzle is used to prevent vortices. A third vendor has used a "blister" design to solve drains subcooler inlet problems. The blister is welded to the bottom of the shell and serves as a collection pot for condensate drains. The drains subcooler inlet nozzle projects into the blister. The blister allows for an increased inlet area to reduce the velocities of the drains entering the drains subcooler zone.

4.4 DRAINS SUBCOOLER PROBLEMS AS ADDRESSED IN PURCHASE SPECIFICATIONS

Most of the purchase specifications that were reviewed did not comprehensively address the design of the drains subcooler zone to prevent level control and flashing problems. Some specifications did mention one or two aspects of the drains subcooler design. Examples include:

- The drains subcooler outlet nozzle should be located at the top of the drains subcooler zone;
- The drains subcooler endplate must be a minimum of 3 inches (7.62 cm) in thickness;
- A vibration analysis for the drains subcooler zone must be conducted;
- Adequate condensate storage capacity must be provided to permit level control without hunting; and
- Drains must be subcooled at least 5°F (2.8°C) before entering the drains subcooler zone.

One utility was an exception, in that it specified a relatively complete set of parameters related to drains subcooler design. Included were:

- Maximum drains subcooler entrance velocity;
- Maximum lineal velocity within tube rows in the drains subcooler;

- Minimum inlet flow area;
- Maximum unsupported tube span;
- Minimum drains subcooler endplate and shroud thicknesses;
- Maximum tube-to-hole clearance in the baffles and in the endplate; and
- Minimum submergence of downspout inlet at low water level.

The values specified for the above parameters were not disclosed for use in this study.

The drain level control system typically consists of level transmitters, a modulating drain valve, an emergency dump valve, high- and low-level alarms, gauge glass and/or a remote level indicator, and appropriate electrical and pneumatic connections. This system is usually supplied by the utility, rather than by the FWH vendor. Only one specification for a drain level control system was reviewed. It specified one level transmitter to operate both the normal drain valve and the emergency drain valve. A second level transmitter provides level indication in the control room, initiating an alarm at 2" (5.08 cm) above or below normal level, closing the extraction valve and the drains inlet valve at a level 12" (30.48 cm) above normal, and re-opening the extraction valve when the level drops to 6" (15.24 cm) above normal. A Yarway remote liquid level indicator is mounted locally at each FWH. The emergency drain valve is sized for 100% drain flow, and an alarm is initiated when that valve opens. Sufficient information was not available to determine whether this arrangement is typical at other utilities.

4.5 CONCLUSIONS AND RECOMMENDATIONS

Survey results indicate that significant damage can occur to carbon steel tubes in the drains subcooler zone if the water level is not maintained properly, if the drains subcooler inlet area is not designed properly, or if the shroud design results in cracked welds. These problems have long been recognized in the available literature. Low water level can cause flashing of saturated drains entering the drains subcooler zone, or it can allow steam from the condensing zone to enter. Improper inlet design usually allows insufficient flow area, resulting in high velocity and flashing. The importance of anti-vortex devices in the inlet area was not determined. In any case, high velocity wet steam rushes around the tubes, causing damage by erosion-corrosion and vibration.

These problems are attributed to poor design of the level control system, poor maintenance of the level control system, recommended normal operating water levels that are too low, improperly designed drains subcooler inlet, improperly designed shroud attachment joints, and inadequate quality control of welding. The use of stainless steel tubes would probably eliminate the tube erosion-corrosion consequences of these problems. However, vibration damage could still be possible, degradation of FWH performance from steam in the drains subcooler zone could still occur, and erosion-corrosion damage of other carbon steel components (e.g., endplate, baffles) could continue to be a problem.

Neither industry standards nor most utility purchase specifications address drains subcooler inlet design or recommended water levels. Also, the drain level control system is normally designed and purchased separately from the FWH itself. As a result, the damaging effects of poor level control on the FWH are not always recognized. In order to assist utilities in avoiding drains subcooler and level control problems in the future, it is recommended that EPRI develop straightforward guidelines (perhaps in cooperation with vendors as part of the next edition of the HEI standard) in the following areas:

- Determination of the correct water level and the range for horizontal FWHs with integral drains subcoolers (e.g., number of tube rows, if any, that should be covered; inches of submergence for the inlet nozzle);
- Advantages and disadvantages of alternative design concepts, such as a fully submerged drains subcooler zone or a separate drains subcooler;
- Maximum velocity and minimum flow area for the drains subcooler inlet;
- Need for anti-vortex devices at the drains subcooler inlet;
- Design of the level control system, including response time, operating range, alarm levels, and trip setpoints;
- Design of drains subcooler shroud joints and quality control of welds;
- Thickness of the drains subcooler endplate;
- General system design and arrangement to integrate FWH operation with the remainder of the system (i.e., drain valve location, pipe sizes, emergency dump line location, etc.).

Section 5

TUBE INLET EROSION

5.1 PROBLEMS AND SOLUTIONS AS REPORTED*

Tube inlet erosion is the gradual wastage of metal that occurs on the inside of the tube along the first several inches from the inlet end of the tube. Six utilities reported this problem in a total of 29 feedwater heaters (FWHs). Table 5-1 presents relevant data on these FWHs. The problem is apparent only in carbon steel tubes. Feedwater inlet temperatures ranged from 215°F (102°C) to 490°F (254°C) and, where reported, pH levels ranged from 9.0 to 9.8.

The most frequently applied solution was the installation of stainless steel sleeve inserts in the tube inlets to protect the tubes from the erosive turbulence of the feedwater. Inserts were expanded into the tubes explosively or mechanically. The joint between the tube wall and the end of the insert must be smooth and tight to minimize turbulence at the tip of the insert. Otherwise, the insert can shift the erosion area from the tube inlet to a point further inside the tube. This occurred in FWH No. 6 of Utility 13 in which 6-inch stainless steel inserts had been explosively expanded into the tubes. Tube erosion occurred at the downstream end of the inserts because they had not been expanded properly. Other approaches used were the installation of flow distributors in the inlet channel to reduce turbulence, and the replacement of carbon steel tubes with stainless steel tubes.

5.2 TUBE INLET EROSION AS DISCUSSED IN THE LITERATURE

An industry trend toward carbon steel tubed FWHs began in the early-1960s, and the problem of tube inlet erosion began to appear soon thereafter. Several investigations of this problem are reported in the literature from the mid-1960s. The following discussion presents the major conclusions of these investigations (9, 12 - 19).

*Conditions and solutions as reported by utility respondees. The solutions or causal relationships are not necessarily endorsed by EPRI or the authors.

Table 5-1
FWHs THAT EXPERIENCED TUBE INLET EROSION

Utility	Plant	Unit	FWH	FWH Arrangement	Tube Material	FWH Velocity (fps/mps)	FWH Inlet Temp (°F)/(°C)	Tube-to-Tubesheet Joint	Tubesheet Overlay	pH
11	4	1,2	3	VCD	CS:SA-179	8.1/2.47	215/102	Expanded only	None	N/A
			4	VCD	CS:SA-179	8.0/2.44	250/121	Expanded only	None	N/A
			6N,6S	VCD	CS:SA-210	8.0/2.44	358/181	Expanded only	None	N/A
			7N,7S	VCD	CS:SA-210	6.4/1.95	404/207	Expanded only	None	N/A
13	1	1	6	H	CS:A556-C2	8.0/2.44	376/191	Welded	Inconel	N/A
	1	1	7	H	CS:A556-C2	7.4/2.26	399/204	Welded	Inconel	N/A
30	1	1,2	6A,6B	H	CS:SA-210C	6.9 @/2.1 @ 60°F/15.6°C	379/193	Welded	CS	9.6-9.8
	1	2	8A	H	CS:SA-210C	N/A	491/255	Welded	CS	9.6-9.8
	2	2	6A	H	CS:SA-106C	7.3 @/2.23 @ 60°F/15.6°C	384/196	Welded	CS	9.6-9.8
	2	2	7A	H	CS:SA-106C	6.5 @/1.98 @ 60°F/15.6°C	438/226	Welded	CS	9.6-9.8
35	1	1	1	H	CS:A210C	7.4/2.26	490/254	Welded	Inconel	9.4-9.6
			2	H	CS:A210C	7.7/2.35	431/221	Welded	Inconel	9.4-9.6
			3	H	CS:A210C	8.0/2.44	385/196	Welded	Inconel	9.4-9.6
38	2	1	2	H	CS:A-106C	8.4/2.56	376/191	Welded	None	9.3-9.5
44	1	1	3A,3B	H	CS:A-210C	9.3/2.83	366.6/185	Welded	None	9.0-9.35
			3A,3B*	H	CS:A-210C	8.12/2.47	366.6/185	Welded	None	9.0-9.35

NOTES: VCD = vertical channel down
H = horizontal
N/A = information not available
CS = carbon steel

*Replacement FWHs.

Tube inlet erosion is a combined erosion-corrosion process in which tube leakage results from the physical loss of tube metal, weld metal, or both, in the first several inches from the tube inlet end. It is believed that the damage results from the continuous formation and removal of the protective oxide layer. The principal factors that influence the severity of the problem are pH, O_2 level, temperature and turbulence. Damage is most severe when the pH is less than 9.0, gradually decreasing as pH rises from 9.0 to 9.5, with tube inlet erosion essentially eliminated when pH is above 9.6.

In addition to its dependence on pH, tube inlet erosion will only occur when the inlet feedwater temperature lies below a certain value, although there is some disagreement in the literature as to the exact temperature -- three investigations (12, 13, 14) state 400°F (204°C), and one (9) states 450°F (232°C). The theory is that at higher temperatures, an erosion-resistant layer of Fe_3O_4 forms on the tube surfaces. The literature does not quantify to what extent those ranges of pH and temperature depend on the O_2 level.

Because of the relatively high degree of turbulence in the inlet channel, erosion is more severe at the tube inlets than in any other part of the feedwater side of the FWH. Laboratory investigations have shown that large turbulent vortices exist in the inlet channel, which cause pressure fluctuations at the tubesheet that extend 200 mm (7.87 in) into the tubes. The forces from these pressure fluctuations continuously remove the protective oxide layer, and leaks eventually develop. In addition to the pressure fluctuations caused by inlet channel turbulence, a vena contracta that forms 5 mm-15 mm (0.20 in-0.59 in) from the tube inlet end causes a low pressure zone and tiny vortices that also affect the oxide layer (12).

When pH and temperature are in the ranges such that tube inlet erosion can occur, the problem can only be mitigated by reducing or eliminating turbulence. Flow distributors of various designs have been shown to reduce inlet turbulence due to the large vortices and to reduce the pressure fluctuations, thereby significantly reducing inlet end erosion. However, they do not eliminate the erosion caused by the vena contracta in the tube inlet. This can only be eliminated by the use of tube inserts, or as suggested by Takahashi and Horiuchi (12), by the installation of a nozzle plate on the tubesheet face that gives each tube inlet a bell-mouth shape.

Takahashi and Horiuchi also suggest that there is a threshold feedwater velocity below which turbulence is not severe enough to cause tube inlet erosion. They noted that no inlet erosion occurred when the velocity in the tubes was below 1.6 meter/sec (5.25 ft/sec). However, reducing feedwater velocity (by designing the heater with more tubes or larger diameter tubes) is not recommended as a cost-effective method of combating tube inlet erosion. Sonnenmoser (15) states that tube inlet erosion can be eliminated, even at high feedwater velocities, as long as pH is maintained at usual levels (9.0-9.5), O_2 level is kept low (2 ppb to 7 ppb), and the channel and tube inlets are designed for smooth water flow.

Another investigation by Brundige (13) discusses tube-to-tubesheet joint design as it relates to tube inlet erosion. When an internal bore weld is used, the tubes are protected from inlet erosion because the inlet end of the tube is located at the back face of the tubesheet. Although the front of the tubesheet may be subject to erosion, leaks do not occur because the tube-to-tubesheet weld is protected from turblence by its location on the back of the tubesheet. This tube-to-tubesheet joint design is used in Europe, but generally not in the U.S.

5.3 TUBE INLET EROSION AS ADDRESSED IN INDUSTRY STANDARDS

The HEI standards for closed FWHs do not address the problem of tube inlet erosion. They do specify a maximum feedwater velocity of 8 ft/sec (2.44 m/sec) for carbon steel tubes, but this apparently is intended to limit erosion along the entire length of the tubes rather than specifically at the tube inlet. The TEMA standard makes a general statement that consideration should be given to the need for special devices to prevent erosion of the tube ends if an axial inlet nozzle is used or if liquid velocity in the tubes exceeds 10 ft/sec (3.05 m/sec).

Most vendors today, provide either a flow distributor or stainless steel inserts to minimize tube inlet erosion in carbon steel tubed FWHs. One vendor offers a distributor in the form of a flat, perforated plate that is installed parallel to the tubesheet face in the inlet channel. Another offers a diffuser basket (similar to a strainer) that extends into the channel from the inlet nozzle. A third vendor explosively expands stainless steel inserts in all carbon steel tubed FWHs.

5.4 TUBE INLET EROSION AS ADDRESSED IN PURCHASE SPECIFICATIONS

When carbon steel tubes are specified, utility purchase specifications typically include design requirements that address tube inlet erosion. Some examples of these requirements are:

- Water channels shall be designed to avoid erosion of internal parts;
- Tube entrances at the inlet to each pass shall be belled except where weld design will not permit;
- Water nozzles must be sized so that velocity is less than 10 ft/sec (3.05 m/sec) at 60°F (15.6°C) and design flow rate;
- Design feedwater velocity must be less than 6 ft/sec (1.83 m/sec) at 15% overload;
- The tubesheet face must have an Inconel overlay for erosion resistance;
- Stainless steel inerts must be installed in tubes at the inlet channel; and
- Stainless steel inserts must be installed in tubes at the inlet channel, and flow straighteners must be provided in the inlet channel.

5.5 CONCLUSIONS AND RECOMMENDATIONS

The literature review and discussions with several FWH vendors indicated that the problem of tube inlet erosion is well understood. By proper control of pH (preferably at 9.6), dissolved oxygen (less than 7 ppb), and turbulence (flow distributors or stainless steel inserts), the problem can be controlled. Results from our survey disagree somewhat with the conclusions in the literature. Cases of tube inlet erosion with a pH of 9.6 or a feedwater temperature greater than 450°F (237°C) or less than 300°F (149°C) were reported in the survey. The literature states that the problem should not occur under those conditions. Research to explain these minor anomalies probably would be of academic interest only, since stainless steel inserts and flow distributors appear to be effective solutions that have been adequately demonstrated. Therefore, it is not recommended that further R&D in the area of FWH tube inlet erosion be pursued. However, it is recommended that this problem be formally recognized and addressed in the HEI standards for closed FWHs. Standards should make reference to channel and tubesheet geometry and designs to minimize turbulence and to allow for corrective measures such as tube inserts and flow distributors.

Section 6

CORROSION

6.1 PROBLEMS AND SOLUTIONS REPORTED*

Thirteen utilities reported corrosion problems in 49 FWHs. (See Table 6-1.) In many cases, the information provided was insufficient to determine the actual cause of damage. Most of the corrosion failures were tube related, and the corrective action taken was tube plugging, tube bundle replacement, or FWH replacement. The following examples are typical of information received from the utilities, categorized according to tube material.

Table 6-1

CORROSION SURVEY RESULTS**

	TUBE MATERIAL			
TYPE OF CORROSION	CS	COPPER ALLOYS	MONEL	TOTAL
Uniform	25	--	4	29
Pitting	10	--	--	10
Stress	--	2	1	3
Exfoliation	--	3	--	3
Unknown	--	4	--	4

**The data in this table reflect only reported survey data. Other types of corrosion may be involved; however, they were not reported.

*Conditions and solutions as reported by utility respondees. The solutions or causal relationships are not necessarily endorsed by EPRI or the authors.

6.1.1 Carbon Steel Tubed FWHs

One carbon steel tubed FWH experienced tube corrosion under the pressure relief valve at the top of the FWH. The corrosion was the result of air entry during layup from a leaky relief valve gasket. The corrective action was replacement of the FWH.

The inspection of five low-pressure carbon steel tubed FWHs showed wall thinning and corrosion attack. Although hydrazine and oxygen controls needed improvement, the reporting utility does not believe that this should have caused such severe results in only 6-8 years of operation. During a tubeside inspection, a thick, brown-black deposit and several small, rusty barnacle-like formations with underlying pits containing black crystalline iron oxide were observed. The utility stated that these symptoms reflect probable oxygen attack. The outlet tube walls appeared thinner than the inlet tube walls. The conclusion drawn by the utility was that high dissolved oxygen levels were present at some time during the FWH's history; however, factors other than oxygen may have contributed to the tube corrosion, but these were not identified. Occasionally, excessively high hydrazine levels were also observed. Reportedly, the high concentration of hydrazine may have removed some of the natural protective oxide coating on the tubes, making them more susceptible to attack.

Eight low-pressure FWHs with carbon steel tubes using all volatile, low solids, continuous feed treatment experienced tube failures apparently caused by oxidation and pitting. A utility task force is currently investigating this problem, but no corrective action has been taken.

Two high-pressure carbon steel FWHs in service for 8 years experienced several corrosion problems, including shell cracking at the subcooler support plate attachments, failure of all outer tie rods and spacers, and excessive corrosion in all "noncooled" desuperheater components. The pH level was kept between 9.6 and 9.8, and ammonia and hydrazine treatments were used to maintain the water chemistry. The problems were determined to be related to a combination of desuperheater section design, operating temperature, pressure, and water chemistry. Corrective actions included plugging the leaking tubes with explosive plugs where possible, replacing cracked sections of the shells, adding two vents in each FWH, and replacing the failed tie rods. FWH replacement is being considered using an improved specification.

6.1.2 Copper-Nickel Tubed FWHs

Two high-pressure, copper-nickel tubed FWHs suffered extensive stress corrosion cracking. The root causes of the corrosion were determined to be high oxygen and ammonia concentrations. Failure to vent FWHs during startup also aggravated the problem by periodically exposing them to excessive oxygen levels. The corrosion process eventually led to copper deposits in the boiler and the high-pressure turbine. Corrective actions taken included replacing the tube bundles, installing a larger vent orifice, and changing the operating and preventive maintenance procedures. The revised procedures included changes in water chemistry, venting procedures, and nitrogen blanketing during shutdown.

One low-pressure FWH suffered from tube exfoliation, resulting in copper deposits in the high-pressure turbine. This particular tube material was CUFENLOY 30 (70/30 copper-nickel -- drawn stress relieved). The corrective action was to retube the FWH; however, modifications to resolve the exfoliation problem were not reported.

6.1.3 MONEL Tubed FWHs

Four MONEL tubed, high-pressure, vertical, channel-down FWHs developed tube leaks caused by general corrosion. The FWHs were in service for 11 years before the problems became apparent. Plant personnel suspect that the problems were due to poor venting and chemistry control and possibly to improper tube material. The corrective action will be FWH replacement with an alternative tube material. In the interim, several tubes have been plugged.

6.2 CORROSION PROBLEMS AS DISCUSSED IN THE LITERATURE

The following describe different types of corrosion found in FWHs and their effects on FWH materials, as discussed in the FWH literature. Table 6-2 summarizes tube material susceptibility to various forms of corrosion.

- Uniform corrosion is characterized by a uniform loss of metal and is most commonly found in carbon steel tubed FWHs. It also occurs in most non-ferrous metals and stainless steels, but to a lesser extent (20).

- Pitting is a localized form of corrosion where the destructive mechanism is by metal penetration. Once started, pits grow at an increasing rate. Low fluid velocities, stagnation, and surface deposits are all associated with the pitting process. Stainless steel alloys are highly susceptible to pitting corrosion in FWHs (20).

- Stress corrosion can generally be described as metal failure promoted by the interaction of stress, (residual, applied, or both),

Table 6-2

TUBE MATERIALS USED FOR FWHs AND HEAT EXCHANGERS

IN POWER PLANT APPLICATIONS

Tube Material	Alloy No.	ASME No.	Estimated Relative Susceptibility to Forms of Corrosion*: General Attack	Crevice	Pitting	Inter-granular	Leaching or Parting	Erosion Corrosion	Stress Corrosion
Copper-Based									
Arsenical Admiralty	443	SB-111 or SB-395	8	3	2	8	6	9	10
Arsenical Copper	142	SB-111 or SB-395	7	6	5	8	2	8	5
Copper-Nickel (90/10)	706	SB-111 or SB-395	7	3	4	8	4	7	4
Copper-Nickel (80/20)	710	SB-111 or SB-395	7	3	5	9	3	7	4
Copper-Nickel (70/30)	715	SB-111 or SB-395	6	3	5	9	3	7	4
Nickel-Based Alloys									
MONEL	400	SB-163	5	5	6	7	2	6	6
Ferrous Alloys									
Carbon Steel		SB-179 or SA-556	9	4	7	9	6	9	3
Stainless Steel Type 304		SA-249	4	8	10	9	3	4	3

*SUSCEPTIBILITY LEDGER
Scale of: 0-10
Where: 0-Immune
10-Extremely Susceptible

SOURCE: "Tube Material Selection for Feedwater Heaters and Heat Exchangers," Public Service Gas Company, Engineering Department, December 8, 1975.

time, material, and environment (oxygen, temperature, halides, caustic soda, etc.). The most common location for stress corrosion is at tube bends on both the water and steam sides of the tubes.

- Selective leaching, or parting, is a process whereby one element from an alloy is removed. The most common form of this corrosion is dezincification. Dezincification is often seen in brass alloys and is detected by the red or copper color (in lieu of the original yellow), concurrently with brittle, porous characteristics.

- Crevice corrosion is a localized attack that initiates in surface fissures or crevices. Crevice corrosion occurs in many environments and, once started, has a tendency to grow at an increasing rate. Stainless steel is particularly susceptible to this type of attack (20).

- Intergranular corrosion is a localized corrosion that appears to attack the grain boundaries with relatively little effect on the grain interiors themselves. This type of corrosion is found, for instance, in sensitized stainless steel and results in embrittlement, cracking, or disintegration of the alloy (20).

- Exfoliation is a general attack found on copper alloy tubes in FWHs, particularly in tubes of 70/30 copper-nickel. Exfoliation is characterized by leaf-like flaking of copper oxide from the tube wall. It appears to be a result of excessive oxygen levels on the shell side of the FWH.

- Erosion-corrosion is generally defined as the accelerated deterioration of metal caused by the relative movement between the fluid and the surface of the corroding metal (20).

6.2.1 Corrosion in FWH Materials

6.2.1.1 Carbon Steel. Corrosion of carbon steel in FWHs has been attributed to such factors as high dissolved oxygen, excessive surface deposits, temperature, low pH, excessive stress concentrations, and improper care (9). The following is a brief summary of these factors as discussed in the literature:

- Dissolved oxygen contributes to inlet-end wastage of carbon steel tubes. (See Section 5 for a discussion of tube inlet erosion in FWHs.) Oxygen on the shell side causes shell-side corrosion; however, no details were found in the FWH literature concerning this type of corrosion in carbon steel (9).

- Copper deposits have been found to be associated with tube-side pitting. The copper deposits from elsewhere in the system have been observed on tubesheet surfaces and on inside surfaces of tubes of high-pressure FWHs. Reportedly, a close examination of one such FWH revealed deposits of copper within pits; as copper concentrations increased on the steel surface, a corresponding increase in the severity of pitting was noted (9).

- Temperature and pH affect the formation of protective magnetite on the carbon steel surfaces. Magnetite usually becomes stable at 500°F (260°C), below which the degree of protection is dependent on pH and other environmental conditions (9).

- Stress Concentration corrosion has been observed in highly stressed areas in both FWH channels and on tube surfaces (9).

- Improper Care includes poor water chemistry control and layup practices where tubes were exposed to uncontrolled atmosphere without rapid drying (9).

6.2.1.2 Stainless Steel. Stainless steels have seen widespread use in FWH application in only the last 15 years. As a result, data on corrosion failure modes are somewhat limited. Tube failures in Type 304 stainless steel have been attributed to stress corrosion cracking, intergranular corrosion, pitting, and crevice corrosion (20). In the past several years, a number of new high-technology stainless steel alloys, both ferritic and austenitic, have become available and appear to be highly corrosion resistant. Some of these alloys are being tested and evaluated for future commercial applications (21).

6.2.1.3 Copper Alloys. Copper alloys have been used extensively for tubes in lower-pressure FWHs. Most of these alloys are quite resistant to corrosion; however, they are significantly affected by water chemistry. Several of the more common alloys in use today are discussed below.

- Copper-Nickel - The corrosion problems that have plagued copper-nickel tubes in FWHs are stress corrosion and exfoliation. Laboratory evidence indicates that exfoliation corrosion is most likely to occur in the presence of high-pressure steam and oxygen (22). It appears that 70/30 copper-nickel is the most susceptible to exfoliation and 90/10 the least. However, all copper-nickel alloys are susceptible to stress corrosion (20). No other form of corrosion for copper-nickel tubing was found reported in the literature.

- Arsenical Copper - This high copper alloy is considered by some investigators to be the least susceptible to stress corrosion cracking of the copper alloys. Most tubes of this material usually fail from erosion-corrosion and general attack; however, in general, it is considered to have only "fair" resistance to corrosion (20).

- MONEL - This copper-nickel alloy has fair to good corrosion resistance; however, it is not immune to stress corrosion or intergranular cracking. Specifically, stress corrosion cracking has been experienced inside tubes at bend areas that were not stress relieved after bending (23).

6.2.1.4 Other Materials. Several new corrosion resistant materials have been developed and are being considered for tube installation; however, none have any significant operating history in FWHs. These include:

- Titanium - Due to the high cost and low thermal conductivity of titanium (20), it has not been considered for use in FWHs until recently. With the increased use of titanium and the increased cost of other alloys used for heat exchangers, titanium is being considered as a feasible alternative for FWH application. It has desirable corrosion-resistant characteristics; however, an investigation conducted by the Public Service Electric and Gas Co. (20) specifies that titanium is "subject to pitting and can absorb hydrogen under certain conditions which can result in severe embrittlement and cracking." The description is vague and does not give the conditions and parameters that enhance these corrosion mechanisms.

- INCONEL 600 - Due to its high cost and low thermal conductivity, this alloy has also not been considered practical for FWH use. Operating experience with INCONEL 600 material in nuclear steam generators has been generally poor, and there have been scattered reports of intergranular stress corrosion cracking of INCONEL 600 in "very pure water" in experiments of one year duration (20). It should be noted that the operating conditions within a nuclear steam generator differ somewhat from those in a FWH.

- E-BRITE 26-1 - This ferritic stainless steel is claimed to have excellent resistance to pitting and to crevice, intergranular, and chloride stress corrosion attack. Operating experiences with E-BRITE 26-1 are limited to recent installations, and further observation is needed to determine how well E-BRITE 26-1 will perform in the FWH environment (20).

6.3 CORROSION PROBLEMS AS ADDRESSED IN INDUSTRY STANDARDS

The two standards reviewed are Standards for Closed Feedwater Heaters, Heat Exchange Institute Incorporated (HEI), third edition, 1979, and the Standards of Tubular Exchanger Manufacturers Association, (TEMA), sixth edition, 1978. Both of these standards are considered to be of limited value with regards to providing guidance on the issue of corrosion in FWHs. The former briefly discusses the corrosion protection methods required for FWH hydrostatic testing, storing, and shipping, and provides no guidance concerning FWH operation, water chemistry, or design requirements for minimizing corrosion. The latter lists corrosion allowances for various heat exchanger parts made of carbon steel. Again, there is no substantial information concerning the corrosion problems that exist in FWHs.

In summary, the two standards do not directly address corrosion, but, rather, discuss only some aspects of corrosion problems in FWHs. Thus, they provide only marginal guidance for the utilities in developing FWH purchase specifications as they relate to corrosion.

6.4 CORROSION PROBLEMS AS ADDRESSED IN PURCHASE SPECIFICATIONS

The purchase specifications reviewed have different requirements and varying levels of detail. Common to most, however, is that each utility specified basic corrosion-related design and manufacturing details:

- Tube material and the applicable manufacturing processes (e.g., heat treatment and minimum bending radius);
- Venting requirements to ensure adequate venting capability during startup and removal of noncondensible gases during operation;
- Cleaning requirements specifying chemistry limits and temperatures of solvents to be used after manufacturing to prevent chloride contamination, etc.;
- Hydrostatic testing details, indicating the fluid chemistry -- again, to avoid contamination by chlorides;
- Storage procedures e.g., nitrogen blanketing during storage and handling.

These items are the general types of parameters specified by the utilities. Although FWH operating parameters, such as temperature, flow, and pressure, are always included in the specifications, typically, the operating chemistry requirements are not provided for vendor review.

6.5 CONCLUSIONS AND RECOMMENDATIONS

The literature review indicated that all materials used for FWH application are susceptible, in varying degrees, to some forms of corrosion. As indicated by the survey results, 49 problem FWHs experienced severe corrosion, with most of the reported problem FWHs having carbon steel tubes. Even though the literature stated that some stainless steels were susceptible, no corrosion problems in stainless steel tubes were reported in the survey. Currently, there are efforts underway to develop new alloys with high corrosion resistance in FWH applications.

The TEMA and HEI industry standards referenced in this section are often relied upon by utilities for design criteria and guidance when preparing purchase specifications, but neither standard appears to adequately address corrosion-related problems and remedies.

In light of these conclusions, two programs should be considered for further study:

- A program to compile data on the causes of corrosion for the materials used in FWHs and the effects of different environments on these materials. The ultimate objective of this program would be to provide guidelines to the utilities on the compatibility of specific ranges of chemistry and plant operating conditions with the materials selected for FWH use.
- An R&D study to investigate the suitability of some proposed, highly corrosive-resistant materials, such as E-BRITE 26-1, for FWH application.

Efforts on some portions of these two proposed R&D programs have been attempted; however, the products of these efforts are not easily accessible, centrally located, or fully applicable to FWHs.

Section 7

STEAM IMPINGEMENT

7.1 PROBLEMS AND SOLUTIONS AS REPORTED*

Steam impingement damage refers to shellside tube damage caused by the impact of extraction steam or drains flowing at the tubes. Seventeen utilities reported this problem in a total of 52 feedwater heaters (FWHs). (See Table 7-1.) Only one utility reported a case of damage at a drains inlet nozzle. The others either reported damage at the extraction steam inlet or did not specify at which nozzle the damage occurred. A significant percentage of the damaged FWHs did not have desuperheating zones. A stainless steel impingement plate normally installed over the tubes at the inlet nozzles is intended to protect the tubes from steam impingement damage.

A variety of reasons were given to explain the causes of tube damage. The most common was faulty impingement plate design. Utilities 1, 24, 36, and 44 stated simply that the plate design was inadequate, but did not supply design details. Utilities 13, 38, and 41 reported that the impingement plate was undersized. In the case of Utility 41, the problem was discovered in six Westinghouse intermediate-pressure FWHs that were still under warranty. Westinghouse cut an opening in the shell of each FWH and modified the plates. Two utilities reported temperature-related design problems. Utility 5 stated that "the temperature design did not meet specifications." Utility 36 said that the design did not allow for thermal expansion, both in the drains impingement plate and in the extraction steam impingement plate, and that this resulted in cracked welds. To correct this problem, Utility 36 installed holding bars to keep the drains impingement plate in place in the event that the attachment welds should fail, and installed an additional extraction steam impingement plate with elongated holes at the support section to allow for thermal expansion. Utilities 11, 31, and 40 had FWHs in which the impingement plate became loose, physically damaging the tubes and allowing steam impingement damage. These utilities claimed that the vendor's method of attaching the plate was inadequate, but they did not provide details.

*Conditions and solutions as reported by utility respondees. The solutions or causal relationships are not necessarily endorsed by EPRI or the authors.

Table 7-1

FWHs THAT EXPERIENCED STEAM IMPINGEMENT DAMAGE

UTILITY	PLANT	UNIT	FWH	TYPE/ ORIENTATION	HAS DESUPERHEATER ZONE?	TUBE MATERIAL	REPORTED CAUSE OF DAMAGE
1	4	1	3,4	LP/H	No	CS:A-179	Inadequate design of impingement plate
3	2	1	1E, 1W, 2E, 2W, 3E, 3B	LP/H	No	CS:A-179	Moisture in steam
5	1	1	2A, 2B	LP/H	Yes	CS:A-179	Temperature design of impingement plate did not meet specifications
			3A, 3B	LP/H	No	CS:A-179	Temperature design of impingement plate did not meet specifications
11	1	1	FU, FL, GU, GL, HU, HL	HP/H	Yes	Monel	Poor impingement plate
13	2	1	4	LP/H	No	CS	Impingement plate too small
			5	LP/H	Yes	CS	Impingement plate too small

NOTES: LP = low pressure
IP = intermediate pressure
HP = high pressure
H = horizontal
*Replacement FWH

Table 7-1 (cont.)

UTILITY	PLANT	UNIT	FWH	TYPE/ ORIENTATION	HAS DESUPERHEATER ZONE?	TUBE MATERIAL	REPORTED CAUSE OF DAMAGE
			5r*	LP/H	Yes	CS	Possibly wet steam
14	1	2	6	LP/H	No	CS:A-179	Overload during startup
20	2	3	4	LP/H	No	CS:A-556-C2	Restricted space caused high steam velocity
24	1	1	2	HP/H	Yes	CS	Design of impingement plate inadequate
26	2	1	7W	HP/H	Yes	CS	Stress corrosion cracking of impingement plate
30	1	1, 2 2	6A, 6B 8A	HP/H	Yes	CS:SA-210-C	Impingement plate attachment did not allow for thermal expansion
31	1	2	1A, 1B, 2A, 2B, 3A, 3B	HP/H	Yes	CS:A556-C2	Impingement plate improperly anchored
32	1	1	6	LP/H	Yes	CS:A-179	Incoming metal debris struck tubes
36	1	1	3S, 4S	LP/H	Yes	CS:A-179	Shellside erosion at extraction steam inlet
38	2	1	4	LP/H	No	CS:A-179	Impingement plate too small
40	1	1,2	3	LP/H	Yes	CS:A-556-C2	Impingement plate broke loose
	2	1,2	3	LP/H	Yes	CS:A-556-C2	Impingement plate broke loose

Table 7-1 (cont.)

UTILITY	PLANT	UNIT	FWH	TYPE/ ORIENTATION	HAS DESUPERHEATER ZONE?	TUBE MATERIAL	REPORTED CAUSE OF DAMAGE
41	1	1-4	3	IP/H	Yes	90-10 Cu-Ni	Impingement plate under-sized
		3,4	2	IP/H	Yes	Monel	Impingement plate under-sized
44	3	1	4A, 4B	HP/H	No	CS:A-210C	Poor impingement plate design

Several utilities speculated that the steam impingement damage was caused by wet steam, excessive steam velocity, or both. Utility 13 installed larger diameter inlet piping to reducing incoming velocities, but one FWH continued to experience impingement problems. The extraction steam conditions were then monitored to determine if wet steam was present, but the monitoring was inconclusive. Utility 14 attributed the problem in one FWH to overload conditions that existed during startup. Lower heaters were bypassed during startup, which caused higher extraction flow in the problem FWH, resulting in steam impingement damage. The problem was solved by changing the startup procedure. Utility 20 claimed that the steam space between tube bundle and shell was too restrictive in one of its FWHs, causing excessive velocities that damaged six tubes on the outer perimeter of the bundle. The tubes were plugged and no other corrective action was taken. Utility 32 monitored the extraction steam with thermocouples to determine if wet steam was causing the steam impingement damage in one of its problem FWHs. It was found that the steam was superheated except at startup. Also, metal debris from a turbine expansion joint was found in this FWH, so it was speculated that this metal debris may have initially cut open a tube, which then leaked into the steam space, leading to damaging of adjacent tubes. A larger impingement plate was installed to correct the problem.

Finally, one FWH at Utility 26 had stress corrosion cracking in its stainless steel impingement plate, which subsequently caused damage to two tubes. The plate was replaced, and the water chemistry corrected to prevent future stress corrosion problems.

7.2 STEAM IMPINGEMENT AS DISCUSSED IN THE LITERATURE

The causes and the prevention of steam impingement damage in FWHs are not widely discussed in the literature. One investigation (24) refers to the damage mechanism as "liquid impingement erosion," which is defined as mechanical erosion that can occur only when relatively large water droplets, carried in the steam, impinge on the material surface at a high velocity. The rate of material removal increases by the fifth or sixth power of the droplet velocity, and by the third power of the droplet size. For carbon steel, damage need not be expected below a droplet size of approximately 100 microns and a fluid velocity of about 164 ft/sec (50 m/sec). This investigation also concluded that steam impingement damage can be prevented by using a stainless steel impingement plate and that the problem rarely occurs in low-pressure FWHs.

Several investigations discuss the problem of condensation occurring in the desuperheating zone. High velocity steam can carry condensed water droplets and cause impingement damage in the desuperheater zone or at the entrance of the condensing zone. Spence (25) recommends that the steam leaving the desuperheating zone be at least 28°C above saturation temperature. However, some condensation in the desuperheating zone is inevitable during startup and at partial load. Brown-Boveri (26) has developed a design to prevent steam impingement damage at the entrance to the condensing zone. Steam leaving the desuperheating zone enters a central steam distribution duct inside the tube bundle. The duct extends along the entire length of the tube bundle, and the steam leaves the duct through lateral openings directed toward the outer shell. This allows the steam to be distributed at minimal velocity.

7.3 STEAM IMPINGEMENT AS ADDRESSED IN INDUSTRY STANDARDS

The HEI Standards for Closed Feedwater Heaters requires the installation of a stainless steel impingement plate at each shell inlet nozzle. The plate must be large enough to intercept the incoming steam, assuming a 45° angle of diffusion from the point at which the steam enters the shell. The HEI standard also specifies that inlet nozzles must be sized such that the following values are not exceeded:

$\frac{G^2}{\rho} = 4000$	for flashing liquid in a drain inlet nozzle
$\frac{G^2}{\rho} = 1000$	for steam from a flash tank in a drains inlet nozzle, assuming velocity does not exceed 150 fps (30 m/sec)
$V = 4$	for liquid from a flash tank in a drain inlet nozzle
$V = \frac{250}{(psia)^{0.09}}$	for dry or saturated steam in a steam inlet nozzle

where

G = mass velocity, lbs/ft^2-sec

ρ = density, lbs/ft^3

V = steam velocity, ft/sec

The steam inlet nozzle and impingement plate must be arranged to allow enough space to prevent the velocity of the steam entering the steam distribution zone from exceeding the velocity at the steam inlet nozzle. In no case should this distance be less than the nozzle's internal diameter divided by 4. The HEI standard does not place restrictions on maximum velocity or kinetic energy for steam flow within the desuperheating zone.

The TEMA standard requires an impingement plate at shell entrances where either the fluid entrance value of ρV^2 (also written as G^2/ρ) exceeds 1500 for single-phase fluids, or where the entering fluid is a liquid-vapor mixture. In no case should the shell or bundle entrance areas result in a value of ρV^2 in excess of 4000 (ρ is density in lbs/ft^3, V is velocity in ft/sec, and G is mass velocity in lbs/sec-ft^2). These requirements are intended to prevent impingement damage to the tube bundle.

Neither standard addresses the method of attaching the impingement plate and methods of attachment vary among FWH vendors. The plates may be attached to tie rods, baffles, tube supports, or the shell, using bolts, welds, or both. One utility representative prefers that impingement plates be interlocked with baffles or tube supports, i.e. each plate has slots through which the baffles or tube supports protrude at a 90° angle with the plate. With this arrangement, the plate is restrained from lateral movement if the attachment welds fail.

7.4 STEAM IMPINGEMENT AS ADDRESSED IN PURCHASE SPECIFICATIONS

Typical utility purchase specifications address steam impingement by requiring a 1/4-inch-thick austenitic stainless steel impingement plate at shell inlet nozzles. The size, shape, and method of attachment are usually not specified. The problem of steam impingement due to high-velocity wet steam within the tube bundle (after the steam has passed the impingement plate) is rarely addressed.

Some utilities are requiring that impingement plates be made of ferritic stainless steel, because it is more compatible with carbon steel in terms of weldability and thermal expansion. One utility specified the use of a bolted drains impingement plate to avoid welding dissimilar metals. The same utility required that desuperheater zone steam velocity not exceed 30 ft/sec (9.14 m/sec), although it was not clear that the purpose was to avoid steam impingement damage.

Another utility always installs a desuperheater zone bypass -- an external pipe connecting the steam inlet to the condensing zone. Its purpose is to permit bypassing of the desuperheating zone during startup and overload conditions to prevent possible damage due to high-velocity and/or wet steam.

7.5 CONCLUSIONS AND RECOMMENDATIONS

The results from the utility survey and the literature search indicate that there are at least four causes of steam impingement damage:

1. An impingement plate breaks loose.
2. The design of the impingement plate is inadequate to protect the tubes.
3. Wet steam conditions exist in the desuperheater zone due to:
   - droplets present in the incoming steam;
   - condensation occurring within the desuperheating zone;
   - a tube leak.
4. Dry steam leaves the desuperheater zone and enters the moist condensing zone at excessive velocities.

A loose impingement plate can cause damage by impacting the tubes directly or by allowing steam impingement damage when the tubes are left unprotected. In the survey results, a faulty method of attachment was generally reported as the reason for loose plates. The method of attachment varies among vendors and is rarely specified by utilities in purchase specifications. Industry standards do not address the subject of impingement plate attachment.

The second cause is faulty design of the plate itself, rather than its method of attachment. In some cases, the faulty plate was reported to be too small. However, none of the utilities that were surveyed provided plate dimensions, and it is uncertain whether the plate size was within current HEI standards. Plate shape (curved or flat), materials, and plate thickness are not addressed in industry standards.

The third cause of steam impingement damage involves the presence of water droplets in the steam. Utility and vendor representatives agreed that the presence of droplets, together with high velocity, is required for steam impingement damage to occur. Presumably, an impingement plate should protect the tubes under the nozzle, regardless of whether the incoming steam is wet or dry. However, it is conceivable that after the steam passes the impingement plate, droplet velocities could remain sufficiently high to cause damage, especially in the desuperheating zone. An impingement plate affords no protection in that situation. Industry standards do not adequately address this type of damage, and the literature does not discuss it in detail. The fourth cause is similar to the third, except that damage occurs in the condensing zone, rather than the desuperheating zone.

It is recommended that guidelines be developed in the following two areas to assist utilities in dealing with FWH steam impingement problems:

- Impingement plate design: Guidelines on impingement plate thickness, geometry, material, and method of attachment are needed for use in preparing FWH purchase specifications or modifying impingement plates in existing FWHs.

- Steam impingement parameters: Guidelines are needed that provide limit values of relevant parameters (e.g., steam quality, velocity, water droplet size, angle of incidence, kinetic energy) for which steam impingement damage is likely to occur, especially in areas where an impingement plate provides no protection (e.g., the entrance to condensing zone).

Such guidelines would help predict the likelihood of steam impingement damage for a given FWH design under various operating conditions. The need for external modifications (such as a desuperheater zone bypass), operating procedure modifications, or an improved FWH design could then be determined.

Section 8

TUBE PLUGGING PROBLEMS

8.1 PROBLEMS AND SOLUTIONS REPORTED*

Tube plugging is a corrective measure used to keep feedwater heaters (FWHs) operational after failure of one or more tubes. Quite often, the original tube failures or other serious problems with the FWHs over-shadow the problems experienced with tube plugging maintenance actions. As a result, tube plugging failures were often not reported in the FWH survey unless they were significant in comparison to other problems or unless the procedures for effecting tube plugging were particularly troublesome. The interviews conducted during this study as a follow-up to the survey show a wide-spread lack of confidence in the various tube plugging techniques available to the utilities. These interview results suggest that the actual incidence of failure of tube plugging repair is significantly greater than shown in the limited statisics of this survey. (See Tables 8-1 and 8-2.) The plugging problems reported during the survey are summarized in the following subsections.

8.1.1 Poor Plugging Procedures

By far, the principal cause of failure was reported to be the poor procedures employed in the tube plugging, although lack of data often prevented diagnosis of the specific deficiencies involved. Two cases reported that the procedure provided by the vendor had serious shortcomings that actually caused the problems. In one case, the procedure called for reaming the tube and tubesheet prior to welding, to such an extent that inadequate cladding remained in proximity to the tube-to-tubesheet weld repair. Since the cladding is needed for proper bonding of the weld to the tube material, this deficiency led to failure at repair attempts and eventually resulted in FWH replacement.

Another utility reported that the vendor's procedure was not appropriate for tube-to-tubesheet leaks, as it prescribed welding a plug only to the tube, rather than to the tubesheet as would be necessary for repairing such leaks. This report also

*Conditions and solutions as reported by utility respondees. The solutions or causal relationships are not necessarily endorsed by EPRI or the authors.

TABLE 8-1

PRIMARY CAUSES OF PLUGGING FAILURES AS
REPORTED IN THE SURVEY

Primary Cause of Failure	Tapered Plug	Welded	Tapered Plug	Welded
Inadequate plugging procedure	3	11	2	8
Improper FWH material	-	8	-	4
Improper weld preparations	-	1	-	-
Unknown	-	1	-	-

TABLE 8-2

CONTRIBUTING CAUSES OF PLUGGING FAILURES AS
REPORTED IN THE SURVEY

Contributing Cause	Number of Failures
Lack of access and space for maintenance	6
Inadequate cleanliness for plugging	3
Moisture present when welding	7

stated that it was difficult to follow to the tungston inert gas (TIG) welding procedure prescribed by the vendor, owing to poor accessibility, moisture, and dirt in the repair area. This utility shifted to more conventional electrode welding procedures for high-pressure FWHs and to non-welded tapered Elliot plugs for low-pressure FWHs.

Whereas tapered plugs are normally used only for low- or intermediate-pressure repairs, another plant had such poor experience with welded plug procedures that they resorted to using non-welded tapered plugs on their copper-nickel tubes even for high-pressure application (no data is available on the results). Another plant reported problems with the use of tapered Elliot plugs on a high-pressure carbon steel FWH experiencing weld cracking from the shock of hammering the tapered plugs. This led to leakage, ligament damage, and eventual tubesheet replacement. In another case, the original procedure involved grinding the tubesheet of a high-pressure carbon steel FWH and applying a massive weld to the affected area; this led to a large heat differential area, causing uneven expansion and contraction and, finally, leaks at the periphery of the weld area. The procedure now used in that plant prescribes repair of a single tube at a time, reaming out portions of the individual tubes and welding individual plugs to the tubesheet; the plugs have sections cut out to allow for temperature expansion.

Several utility maintenance personnel have advised that, regardless of the type of repair (welded plug or tapered plug), failure is likely if the procedure does not ensure proper reaming to achieve true, round holes before plugging. Another plant's maintenance personnel reported a preference for using explosive welding techniques to plug carbon steel tubes in high-pressure FWHs because they experienced seal weld cracks in adjacent tube-to-sheet welds when plugging by seal welding methods; these problems were attributed to the close proximity of tube welds and difficult welding conditions (poor access and limited space). There were no complaints in the survey about failures attributed to inadequate explosive welding procedures; however, this technique is new and has been used by few utilities. It was addressed extensively in articles reviewed for the literature search. (See Appendix C, Abstracts 16, 32, 36, 52, and 53.)

8.1.2 Improper FWH Material

One utility reported that the cause of tube plugging failures in 12 problem FWHs (8 high-pressure, 4 low-pressure) was improper tube material. They had reached the conclusion that carbon steel tubes and tubesheets have inadequate resistance to erosion/corrosion, which led to the failure of repairs as well as the original tube and tubesheet leaks. Replacements for these FWHs used stainless steel tubes and tubesheets. No other data or rationale is available in this case.

8.1.3 Improper Joint Preparations

Failure to properly prepare surfaces prior to welding was the reported cause of plugging failure in 1 high-pressure FWH and was mentioned as a probable contributing or secondary cause of failure in 10 other cases. The underlying causes of such problems are (1) poor access for machining and cleaning, (2) the inability to isolate the FWH adequately from the rest of the system, and (3) the reluctance to shut down operating plants long enough for proper maintenance.

8.1.4 Design: Lack of Access

Many maintenance personnel reported serious concern about the FWH designs that provide poor access for maintenance. Some were adamant that access to their hemispherical head configurations was so bad as to be unsafe for carrying out prescribed welding procedures. One company reported a policy change whereby all FWHs procured in the future would have full access to the tubesheet areas, and the hemispherical head configuration would no longer be used. Apparently, other utilities have been reluctant to spend more for such improved access. Others feel that the hemispherical head geometry can be adequate on large FWHs if attention is paid to this concern during FWH design.

8.2 TUBE PLUGGING AS DISCUSSED IN THE LITERATURE

The literature search revealed little published material that focused principally on tube plugging problems. However, four of the articles considered most pertinent to this study emphasized the need for improved tube plugging techniques and described the British explosive welding procedure as a new and promising system for such repairs.

In his investigations (27, 28), R. Hardwick of Yorkshire Imperial Metals described a method of installing tubes during the fabrication of heat exchangers, as originally designed by his company in 1966. Recognizing the difficulty of plugging failed tubes in the confined spaces of an installed heat exchanger and the poor performance of standard plugging techniques used the the past, Yorkshire later adapted their explosive welding procedure for use as a tube plugging process. In this method, a hollow nickel plug is inserted into the tubesheet hole and welded in place by the kinetic expansion effects of an explosive device detonated within the hollow plug. This maintenance procedure was commercially marketed in 1972 and was reported to have achieved 9,000 successful plug repairs by 1976. Since that time, the procedure has been readily available as a repair service to all plants in the British Central Electricity Generating Board (CEGB) system. It should be noted that these highly successful repairs were accomplished on FWHs having tubes welded on the back side of the tubesheet. Generally, the tubesheet holes in such FWHs are undamaged and simpler to plug than those in the U.S., where the tubes are welded to the face of the tubesheet.

Mssrs. Noe, Sahansra, and Costic of the Public Service Electric and Gas Company (PSE&G) report (29) on the experience of using explosion plugs at PSE&G units. (The same report is included in Section 4 of "Feedwater Heater Workshop Proceedings (30), published by EPRI in July 1979.) The authors experienced considerable success, but also found some difficulty in using this method on FWHs prone to secondary failure of adjacent tube welds. They suggest that the procedure as basically sound and worth perfecting for wider use. In addition to addressing the explosion tube plugging technique, Noe, Sahavra, and Costic (29) summarize various other tube plugging procedures in use today, and these are described below. The entire article is reprinted as Appendix D of this report.

8.2.1 Tapered Plug

Tapered plugs are used often in low- and intermediate-pressure heat exchangers. Their main deficiency is man-made, i.e., the plugs are driven into the tubesheet with such force that tubesheet ligaments have a tendency to crack. Failure may also occur if reaming done prior to plugging fails to achieve a true, round hole (also reported to be a problem with the various types of welded plugs).

8.2.2 Roller Expanded Plug

This plug is in the form of a blind nipple, obtained by machining bar stock or by plug welding an end of a section of tubing. To seal a tube, the plug is expansion rolled in place by mechanical rollers. Such plugs have been used primarily for low- and intermediate-pressure heat exchangers. Some utilities have also used them in high-pressure FWHs inside the tubesheet, in addition to the welded plugs at the face of the tubesheet, when cracked or "worm-holed" ligaments exist.

8.2.3 Welded Plug

The use of the welded plug (shaped to allow expansion), when carefully welded at the edge to sound, clean base metal, has resulted in trouble-free repairs. Welded plugs or clusters of plugs that formed massive, rigid welded areas have, however, developed peripheral weld or ligament cracks. (Appendix D describes a more sophisticated welded plug [shown in Figure 4, page D-17] devised to minimize these problems.)

8.2.4 Explosion Welded Plugs

This is a cartridge-like plug that is detonated inside a tube or tubesheet to form a metallurgical bond along a large area as described above (and in Appendix D). This method is simple, but requires specially trained and licensed personnel. PSE&G reports that only one type of plug material (nickel) is required to plug any tube or tubesheet material, and strong bonds are obtained even between dissimilar metals. However, the reaming of adjacent tube-weld roll-over to permit the insertion of protective, tapered, half-round rods has caused secondary tube failures in some instances when this method was used on U.S. FWH designs.

8.2.5 "Insurance" Plugging

Especially in high-pressure FWHs, a leak in one tube often leads to high-velocity feedwater jets and rapid erosion of other tubes adjacent to the leaking tube. At the time of plugging the failed tube, maintenance personnel rarely have information on the condition of the surrounding tubes and, therefore, may decide to plug them as an insurance measure against their failure soon after returning the FWH to service. The survey indicates that this practice is wide-spread; however, the experience of PSE&G (29) indicates insurance plugging must be accomplished carefully to avoid additional weld failures from the expansion and contraction of weld repair areas. In addition, a hydrostatic test at 1.5 times the rated pressure of the tubes may indicate no need for insurance plugging. PSE&G now uses an individual tube tester for this purpose and plugs only those tubes that leak under hydrostatic test.

8.3 TUBE PLUGGING AS ADDRESSED IN THE PURCHASE SPECIFICATIONS

As a general rule, purchase specifications do not address tube plugging except in a general requirement that the vendor provide operating and maintenance procedures for the FWH. In some cases, the vendor is specifically required to include recommended tube plugging procedures, but no criteria are specified to indicate the minimum acceptable features of those procedures.

8.4 TUBE PLUGGING AS ADDRESSED IN INDUSTRY STANDARDS

Section 7.7 of the HEI standards recommends that any alterations or repairs be made under the manufacturer's direction and in accordance with his procedures. However, the standards do not provide any specific criteria for tube plugging procedures. Section 7.6 of the HEI standards permits the vendor to plug a defective tube in a new FWH using an "acceptable permanent procedure," provided the purchaser is notified. The TEMA standards contain a similar provision specifying that a maximum of 1%, or 2 tubes, may be plugged on a new FWH, but that the method of plugging should be agreed upon between the manufacturer and the purchaser.

8.5 COMMENTS AND RECOMMENDATIONS

Based upon the material reviewed in this study, the following comments on tube plugging are offered in addition to the more specific observations reported above.

Among the utility personnel providing input to this study, there is a widespread lack of confidence in the available tube plugging procedures, including those recommended by the vendor for specific FWHs. Although part of this problem may be due to shortcomings in training, poor maintenance conditions, or simply failure to follow the procedures, the need to identify or to develop practical, technically sound plugging procedures is an urgent requirement for improved FWH performance.

There is wide variation in the experience level of the personnel who plan, supervise, and execute tube plugging repairs. In many cases, the lack of experience leads to repeating previous maintenance errors or attempting repair techniques that are not proper for the existing conditions. In some cases, these shortcomings are augmented by the lack of management emphasis on achieving proper, permanent repairs. Although quantitative data are not available on this point, it is clear that pressure to return the FWH (or the entire plant) to service has been the underlying cause of many tube plugging failures in the past through inadequate preparations and maintenance techniques.

All plugging techniques have inherent limitations. Hence, it appears necessary to provide the utilities with a range of procedures and with clear guidance on choosing the best for various circumstances and the special conditions or precautions required in each case.

The following actions are recommended to provide significant improvement in tube plugging performance and FWH reliability in the future.

A program should be initiated for developing comprehensive plugging procedures for each generic method of tube plugging in common use today based upon proven engineering practices and demonstrated performance. For the basic methods used in the past (e.g., tapered plugs, welded plugs), much of the effort would entail identification and review of the most successful procedures now in use and the procedures. Some testing would be required to determine applicability to different metals, suitability under various operating conditions, the limitations of the procedures, etc. The objective would be to provide, as models or standards, the best possible procedures with all known limitations and guidance to ensure success of the repair; supplementary guidance would include both the steps that must be considered, and the special recommended testing for use in (or modification of) the procedure with material or conditions in variance from those already determined adequate.

Plugging procedures should emphasize the need to determine the failure location and mode, if possible, before plugging; in some cases, this information is essential to success. For example, a tube failure within the portion of the tube inside the tubesheet normally requires removal of a portion of the tube and plugging of the tubesheet hole itself. A failure of this type is often accompanied by ligament damage, which requires close scrutiny and experienced judgment before proceeding with repairs.

As an extension of this theme, similar efforts are needed for the more promising new and special purpose plugging techniques. For example, an R&D program is needed to perfect the explosive plugging method, to develop detailed plugging procedures, and to permit its use for all tube-end weld configurations (or at least to define its limitations). Likewise, concepts like the "flower" plug, developed by PSE&G for repairing more than one tube in close proximity without incurring peripheral cracks from the bulk of the weld area, should be evaluated and made available to the utility industry as soon as properly validated. (See Appendix D for details on the flower plug.)

Further the development of individual tube testing (as described in Appendix D) to be used in lieu of insurance plugging and make equipment and procedures available to the industry.

Conduct studies to develop a means of sealing a ruptured tube or a tubesheet leak while still permitting some reduced flow through the repaired area.

Provide guidance to utilities that would assist them in addressing the subject of tube plugging in their FWH procurement specifications. For example, it would seem advisable to require the vendor to demonstrate specifically how FWH design enhances maintainability. Likewise, he should be required to provide the recommended plugging procedures suitable for his design and to explain how he has determined that these procedures are practical and reliable for his FWH design. The guidance should also address the importance of selecting a channel geometry that permits ease of access.

Section 9

MISCELLANEOUS ADDITIONAL FAILURES REPORTED*

This section comments briefly on the additional failures reported in the survey which appear to be less common or of less consequence to the utility industry at this time than those highlighted in earlier sections of this report. Also addressed are those problems in which the failure type or failure mechanism was unknown or unclear.

9.1 INADEQUATE TUBE-TO-TUBESHEET CONNECTIONS

In the survey, five utilities identified inadequacies in the tube-to-tubesheet joint fabrication as the probable cause of the problems reported in 28 feedwater heaters (FWHs) (27 high-pressure, 1 low-pressure), all with carbon steel tubes.

Utility 4 had four problem FWHs, each of which had tubes that had been rolled and then welded. Two of those FWHs had tubes rolled in two places, and this rolling procedure was suspected to have caused thermal stresses, joint failures, and subsequent FWH replacement. The other two FWHs were repaired by plugging the affected tubesheet holes.

Utility 20 also reported four problem FWHs with rolled and welded joints. In each case, one tube had been rolled beyond the tubesheet, setting up high stresses that eventually caused joint failures. Repairs were accomplished by plugging the tube holes.

Utility 34 reported joint failures in a group of five FWHs with tube joints of an unusual design (no longer used): their tubes were attached to the tubesheets with internal bore welds at the back of the tubesheet. Chronic weld failures occurred in these FWHs within months of startup. No such failures have been experienced by this plant in the last eight years, since those FWHs were replaced with conventional designs. (Contrary to the U.S. experience, utilities in Europe have had considerable success with welds at the rear of the tubesheet.)

*Conditions and solutions as reported by utility respondees. The solutions or causal relationships are not necessarily endorsed by EPRI or the authors.

Utility 38 reported inadequate joints in four FWHs with tubes that had been expanded and welded into the tubesheets. The one low-pressure FWH was replaced after ten years of service. The other FWHs were repaired rather than replaced, with "extensive maintenance" reported as the only effect of the problems encountered. In one of the high-pressure FWHs, slag pockets were found in the joint weld, but there was no specific evidence available to substantiate the failure mode for the other FWHs.

Utility 44 reported poor original tube-to-tubesheet welds on all six high-pressure FWHs at one plant. The welds were ground out and rewelded on four FWHs, and the other two, which also experienced tube inlet erosion, were replaced. Utility 44 also reported bad tube-to-tubesheet welds on five high-pressure FWHs at another plant. Four of them required tube bundle replacement. All eleven of these problem FWHs at Utility 44 had carbon steel tubes welded to a carbon steel tubesheet with no tubesheet overlay.

Although the information summarized above indicates less concern than expected for problems resulting from inadequate tube-to-tubesheet welds or expansions during initial fabrication, the literature survey offered information that tends to support and explain this optimistic observation in the evolution of FWH experience. For many years, non-ferrous rolled and welded tube-to-tubesheet joints provided satisfactory service. High levels of reliability were achieved, and hundreds of thousands of tubes were welded without service difficulties. However, shortly after the construction of the first high-pressure FWHs that were equipped with carbon steel tubes for the higher performance steam plants, many manufacturers experienced trouble with in-service welded tube joints, which had appeared satisfactory in shop tests. Detailed investigations and extensive welding development programs were undertaken, which resulted in better understanding of the failure mechanisms and the complex interactions of the metallurgy, chemistry, and operational stresses involved.

By 1967, the literature no longer focused on the earlier problems experienced with tube-to-tubesheet fabrication, but rather focused on the success experienced with the latest procedures developed by vendors to fabricate successful joints that withstood the rigors of extensive operating experience as well as the shop tests. As an example of the progress reflected in the literature, one investigation (31), published in 1967, described in detail the latest procedure used by a vendor who claimed that his procedure had experienced zero leaks in service after 400,000 carbon steel and non-ferrous tube welds had been made. Though the details of the procedure may be somewhat outdated by subsequent refinements, the principles involved and the general thrust are pertinent indications of the progress made by the late-1960s. Accordingly, a portion of the summary of this investigation (31) is included here:

> With a process that has a perfect service record, it is difficult to single out the property, parameter, or weld joint detail which contributes most to the success of the process. Obviously, near surgical cleanliness is required for all tube welds, as it is required for all successful gas tunsten-arc welds. It has been found in this and other investigations that joint simplicity increases reliability as it adds to reproducibility. Automatic processes are considerably more consistent and predictable than manual processes. Auxiliary gas shielding decreases the changes for atmospheric contamination of the weld. Selection of a filler metal with a high level of deoxidizers minimizes porosity.
>
> The metallurgical and chemical characteristics of the weld and weld heat-affected zone probably deserve the major attention. It is interesting to note that the metallurgical characteristics, which may have led to the success of copper-nickel and Monel tubed heat exchangers, are duplicated when nickel-chromium-iron is used as a filler metal for welding carbon steel. Both exhibit extremely high notch toughness with good tensile strength, yield strength, extremely high ductility, and low hardness. The corrosion and erosion resistance of both systems are excellent.
>
> It is apparent that a complete lack of porosity cannot be present for almost half a million non-radiographable welds, so this is not the secret. The ability of a weld with a natural root crack and possible small porosity hole to resist high thermal and mechanical stresses without failure must be primarily a function of the strength and notch insensitivity of the weld metal. In addition, high resistance to erosion and corrosion, which may waste away sound metal over a porosity spot, must be a contributing factor.

The literature contains more recent articles addressing specific techniques that have proven faster, better, or more reliable for each of the vendors in the fabrication of FWHs. These successes are not confined to the basic welding and tube expansion processes, but also include promising results from newer methods, especially explosive welding and explosive expansion (non-welding). The clear inference is that the problems in fabricating tube-to-tubesheet joints are well understood and that successful, proven methods are available. The key to minimizing failures in this area lies in continued, successful emphasis on the quality control applied during fabrication processes.

The HEI standards provide a table for determining the maximum operating temperatures to be used for various metals with expanded tube joints. Above those temperatures, welded joints are recommended utilizing construction details and procedures determined by the manufacturer. The TEMA standards provide specifications on tubesheet hole drilling tolerances. For expanded tube joints, TEMA also specifies the lengths of expansion and minimum tube hole grooving. These items are not addressed by the HEI standards. During an interview, one utility questioned the benefit of tube hole grooving, commenting that their tests had not shown any appreciable increase in pull-out strength or joint tightness. Another utility states a preference for expanding two separate portions of the tube-to-tubesheet joint with an unrolled space between; this space could be rolled later if evidence of leakage occurred. It is also not clear from the literature search or the survey how desirable tube expansion is when used in addition to welding.

To ensure that utilities follow the best proven practices in addressing these areas in their procurement specifications, detailed guidance should be provided in the industry standards and other authoritative references.

9.2 HEAD AND SHELLSIDE LEAKS

9.2.1 Gasket Problems

The survey reported 17 cases of gasket leakage in the head area (14 in high-pressure and 3 in low-pressure) -- fourteen involved manway gaskets and 3 involved channel gaskets. The basic causes were improper material (in 12 cases) and improper installation (in the other 5 cases). All were corrected with relatively minor effort by gasket replacement.

9.2.2 Head Leaks

One plant reported chronic leakage from L-seal welds on the head of 4 high-pressure FWHs; the problem was corrected by replacing the seals with an improved design when the tube bundles were replaced. Another low-pressure FWH experienced leakage past the seal welded diaphragm in the channel opening; to avoid recurrence, the seal welded diaphragm was replaced with a gasket. Poor welding in the head-to-shell weld caused leakage in 3 low-pressure and 4 high-pressure FWHs; they were repaired by rewelding. Another utility reported 4 cases of leakage in high-pressure FWHs resulting from ring failure in the breechlock after welding the head in place following maintenance. (No further details are available, except that these FWHs also experienced other problems and their replacement was under consideration.) One high-pressure FWH experienced leakage resulting from a distorted head seat; this was repaired by machining the seat area.

9.2.3 Relief Valve and Shellside Weld Leaks

One high-pressure FWH experienced repeated lifting of the relief valve on the shellside when steam pressure increased as a result of fouled tubes and poor heat transfer. Mechanical cleaning resolved the problem. Another high-pressure FWH experienced repeated failures of relief valves on the feedwater side following unit trip with the associated feed system pressure rise. The design of the valve was deficient and its spring disintegrated when the valve lifted. Two high-pressure FWHs experienced shell leaks from cracks originating at the subcooler support attachment welds; these FWHs also exhibited severe corrosion damage and were replaced.

9.3 FAILURE OF INTERNAL COMPONENTS (OTHER THAN TUBES OR IMPINGEMENT PLATES)

Several isolated cases of miscellaneous damage to internal components were reported: one FWH had a hole eroded in an outlet partition plate; in another, tie bars were bent and warped. No additional information was available on these problems.

9.4 FOREIGN MATERIAL IMPINGEMENT

One high-pressure FWH experienced tube-to-tubesheet leakage that was attributed to impingement erosion by pieces of a boiler feed pump check valve that had disintegrated. Similarly, on the shellside of a low-pressure FWH, pieces of a turbine expansion joint were found and were suspected to have contributed to tube erosion damage (which was also caused by wet steam impingement). A third problem was that of obstruction of the entrance to a drains subcooler by a block of wood that had lodged there and had to be removed through a hole cut in the shell.

9.5 TUBE FABRICATION

Only one failure reported in the survey was attributed to deficiencies in tube fabrication. This isolated case involved a high-pressure FWH with copper-nickel tubes that developed random straight line cracks parallel to the tube axes. There appeared to be no pattern to the location of the cracks, and no other explanation could be offered other than probable quality control deficiencies in fabrication of that tube run.

9.6 FAILURES FROM UNKNOWN CAUSES

This category includes those failures reported in the survey for which there was inadequate information available to assign a probable cause or failure mechanism, even after the site visits and phone surveys. In most of these cases, tube leakage was known to exist, but inspections had not been made or had resulted in insufficient data for one of the reasons indicated below; 130 FWH failures were in this "unknown" category, but 32 of these also had other failures that were identified and categorized. While 92 of these FWHs involved carbon steel tubes, the split between high-pressure and low-pressure FWHs was 74 to 51, with 5 intermediate-pressure FWHs. Forty-two of the FWHs in the "unknown" category were replaced or had their tube bundles replaced; 20 of these had no other identified failures reported.

There are many reasons why it is so difficult to obtain adequate data to identify FWH failure mechanisms. During operation, the FWHs are relatively inaccessible and are poorly instrumented so that early warnings of failure are generally unavailable. The operator often is unaware of tube leakage until he observes consistently high drain level indications or alarms. By then, the original tube leak may have led to secondary damage that, in turn, may eliminate the evidence of the initial problem. Operational delays between problem detection and the opportunity to gain access for repair can also lead to loss of evidence from secondary failures. Locating a tube leak can be very difficult, but it is one of the first requirements in determining the cause. After gaining access to the tubesheet area (usually via manways in the channel of the FWH) the failure may be detected visually. If not, various techniques can be used to locate tube failures, such as probalog or air tests with movable restrictions in the tube. Removal of the tube bundle from the FWH shell may also be required for a good failure diagnosis, but this is a major task and, even then, only the outer rows of tubes are clearly accessible for inspection. Added to these problems is administrative and personnel turnover, which can lead to loss of data and operating history over the many years of operation of the FWH. In several instances during the survey visits and followup phone calls, the key individual who may have been the source of more information was not available.

9.7 QUALITY CONTROL

One utility representative suggested that many of the failures due to unknown causes might be attributed to problems associated with quality control during FWH fabrication. He had experienced poor welding of FWH internals, such as desuperheater shrouds, drains subcooler shrouds, and impingement plates; problems with part alignment and fit, etc. These problems point to the need for appropriate quality control measures included in purchase specifications and frequent inspections during the manufacturing process by inspectors who are familiar with the details of FWH design and fabrication techniques.

SECTION 10

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Appendix A

DATA ON PROBLEM FEEDWATER HEATERS AT FOSSIL UNITS

Utility	Plant	Unit	Total No. of Heaters	Problem Heaters	Type/ Orientation	Tube Material	Problem Description	% Tubes Plugged	Heater or Bundle Replaced	Heater Age at 1st Failure (years)
1	1	1	8	3	LP/H	CS:A556-A2	3,7	30	B	NA*
				4	LP/H	CS:A556-A2	3,7	30	B	NA
	2	1	8	None						
	3	1	8	3	LP/H	CS:A-179	3,7	20	H	5
				4	LP/H	CS:A-179	3,7	20	H	5
	4	1	8	4	LP/H	CS:A-179	1	0.7	-	5
				6A	HP/H	CS:A-210-C	8	0	-	7
				3	LP/H	CS:A-179	1	1.3	-	3
2	1	1	10	5A	HP/H	CS:A-106-C	3,9	20	H	1
				5B	HP/H	CS:A-106-C	3,9	22	H	1
				6A	HP/H	CS:A-106-C	3,9	8.3	H or B	1
				6B	HP/H	CS:A-106-C	3,9	11	H or B	1
	2	1	10	5A	HP/H	CS:A-210-C	3	16	H	2
				5B	HP/H	CS:A-210-C	3	9	H	2
		2	10	5A	HP/H	CS:A-210-C	3	6	H or B	2
				5B	HP/H	CS:A-210-C	3	8	H or B	2

1. Numbers and/or letter designations refer to individual heaters

2. LP = Low pressure
   IP = Intermediate pressure
   HP = High pressure
   H = Horizontal
   VCD = Vertical channel down
   VCU = Vertical channel up

3. CS = carbon steel
   SS = stainless steel

4. Problem Types:
   1. Steam impingement
   2. Tube inlet erosion-corrosion
   3. Level control and/or drains cooler zone problems
   4. Tube vibration
   5. Tube plugging
   6. Corrosion
   7. Unknown
   8. Failure of internal component (other than tube of impingement plate)
   9. Head or shell leak
   10. Inadequate tube-tubesheet weld or expansion
   11. Foreign material impingement
   12. Tube manufacturing defect

5. H = heater will be or has been replaced, or is being considered for replacement

   B = tube bundle will be or has been replaced, or is being considered for replacement

*Information not available

Utility	Plant	Unit	Total No. of Heaters	Problem Heaters	Type/ Orientation	Tube Material	Problem Description	% Tubes Plugged	Heater or Bundle Replaced	Heater Age at 1st Failure (years)
		3	10	5A	HP/H	CS:A-210-C	3	2.3	H or B	2
				5B	HP/H	CS:A-210-C	3	1.3	H or B	2
	3	1	6	3	LP/H	CS:A-179	6	12	H or B	4
		2	6	None						
		3	6	None						
3	1	1	11	7E	HP/H	CS:SA-106-C	3	NA	-	10
				3E,3W	LP/H	CS:SA-179	3	NA	B	8
	2	1	12	8E,8W	HP/H	CS:A-210	7,5	NA	H	5
				1E,1W	LP/H	CS:SA-179	1	NA	B	11
				2E,2W	LP/H	CS:SA-179	1	NA	B	11
				3E,3W	LP/H	CS:SA-179	1	NA	B	9
				7E,7W	HP/H	CS:A-210	7,5	NA	H	5
	3	1	10	7	LP/H	CS:A-179	4	NA	B	2-3
				6	LP/H	SS:A-249-304	4	NA	H	2-3
	4	1	10	7	LP/H	SS:A-249-304	4	NA	H	2-3
				6	LP/H	SS:A-249-304	4	NA	H	2-3
	5	1	7	8A	HP/H	CS:SA-210-C	7	14	H	1
				8B	HP/H	CS:SA-210-C	7	6	H	1
		2	8	8A,8B	HP/H	CS:SA-210-C	7	NA	H	NA
				7A,7B	HP/H	CS:SA-210-C	7	NA	H	NA
	6	1	8	8A	HP/H	CS:SA-210-C	7	7	H	2-3
				8B	HP/H	CS:SA-210-C	7	22	H	2-3
	7	1	8	None						
		2	8	7A	HP/H	CS:SA-210-C	7	14.6	H or B	2
4	1	1	10	1N	HP/H	CS:SA-210-C	10,9	4.02	-	NA
				1S	HP/H	CS:SA-210-C	10,9	3.14	-	NA
				2N,2S	LP/H	CS:SA-179	6	NA	H	NA
		2	10	1N,1S	HP/P	CS:SA-210-C	10,9	NA	H	1
				2N	LP/H	CS:SA-179	6	NA	H	1
				2S	LP/H	CS:SA-179	6	8.6	-	1
5	1	1	5	2A,2B	LP/H	CS:SA-179	1	12	H	NA
				3A,3B	LP/H	CS:SA-179	1	11	H	NA
6	1	1	8	HP	HP/H	CS:A-210-C	3	NA	H	6
		2	8	None						
7	1	1	8	3	HP/H	CS:A-556-C2	4	10.3	H	1 month

Utility	Plant	Unit	Total No. of Heaters	Problem Heaters	Type/ Orientation	Tube Material	Problem Description	% Tubes Plugged	Heater or Bundle Replaced	Heater Age at 1st Failure (years)
				2	HP/H	CS:A-556-C2	4	21.6	H	1 month
				1	HP/H	CS:A-556-C2	4	10.2	H	1 month
				5	LP/H	CS:A-556-A2	4	40	H	1 month
				4	LP/H	CS:A-556-A2	4	40	H	1 month
	2	1	8	3	HP/H	CS:SA-210-C	4	12	H	2
				1	HP/H	CS:SA-210-C	4	12	H	2
				5	LP/H	CS:SA-179	4	20	H	2
		2	7	2	HP/H	CS:A-210-C	4,6	< 10	H	4
				1	HP/H	CS:A-210-C	4,6	< 10	H	4
8	1	1	6	None						
	2	1	6	HP	HP/H	CS	9,11	1	-	NA
9	1	1	10	6A,6B	IP/H	CS:SA-179	6	NA	B	8
	2	1	10	6A,6B	IP/H	CS:SA-179	6	NA	B	6
10	1	1	9	7A,7B	HP/H	70-30 Cu-Ni	6	10	B	2
		2	9	None						
11	1	1	12	FU,FL	HP/H	S.R. Monel	1	NA	H	1
				GU,GL,HU,HL	HP/H	S.R. Monel	1	1-5	-	NA
	2	1	11	5N,5S	HP/H	CS:A556-C2	6	6	-	4
				6N,6S	HP/H	CS:A556-C2	6	4	-	2
				7N,7S	HP/H	CS:A556-C2	6	4	-	3
		2	11	5N,5S	HP/H	CS:A556-C2	6	4	-	3
				6N,6S	HP/H	CS:A556-C2	6	0.5	-	1
				7N,7S	HP/H	CS:A556-C2	6	1	-	3
	3	1	10	1B	LP/H	CS:SA-214	7	9.6	-	9
				2B	LP/H	CS:SA-214	7	5.9	-	10
				C	LP/VCU	CS:SA-214	7	10.6	-	0
				D	LP/VCU	CS:SA-214	7	NA	B	0
				1F	HP/H	CS:SA-210	7	3.6	-	11
				2F	HP/H	CS:SA-210	7	8.5	-	1
				1G	HP/H	CS:SA-210	7	0.6	-	11
		2	10	1B	LP/H	CS:SA-214	7	4.7	-	12
				2B	LP/H	CS:SA-214	7	3.1	-	14
				C	LP/VCU	CS:SA-214	7	8	-	0
				D	LP/VCU	CS:SA-214	7	6.6	-	3
				1F	HP/H	CS:SA-210	7	1.8	-	6
				2F	HP/H	CS:SA-210	7	5	-	4

Utility	Plant	Unit	Total No. of Heaters	Problem Heaters	Type/ Orientation	Tube Material	Problem Description	% Tubes Plugged	Heater or Bundle Replaced	Heater Age at 1st Failure (years)
				1G	HP/H	CS:SA-210	7	0.5	-	NA
				2G	HP/H	CS:SA-210	7	0.1	-	12
	4	1	8	3	LP/VCD	CS:SA-179	7,5,2	65.2	H	5
				4	LP/VCD	CS:SA-179	7,5,2	54.9	H	5
				6N	HP/VCD	CS:SA-210	7,5,2	10.1	-	8
				6S	HP/VCD	CS:SA-210	7,5,2	12.5	-	8
				7N	HP/VCD	CS:SA-210	7,5,2	3	-	8
				7S	HP/VCD	CS:SA-210	7,5,2	3.4	-	8
		2	8	3	LP/VCD	CS:SA-179	7,5,2	56.4	H	5
				4	LP/VCD	CS:SA-179	7,5,2	32.5	H	4
				6N	HP/VCD	CS:SA-210	7,5,2	15.2	-	3
				6S	HP/VCD	CS:SA-210	7,5,2	44.1	H	3
				7N	HP/VCD	CS:SA-210	7,5,2	2.8	-	5
				7S	HP/VCD	CS:SA-210	7,5,2	7.4	-	8
	5	1-5	45	1A,1B	LP/H	SS:A-249-304	3	0	-	NA
				2,3,4	LP/VCD	SS:A-249-304	3	0	-	NA
				6A,6B,7A,7B	HP/H	SS:A-249-304	3	0	-	NA
12	1	1	14	35	LP/H	90-10 Cu-Ni	7	4	-	15
				36N	HP/VCU	Cufenloy 30	7,5	3	-	NA
				36S	HP/VCU	Cufenoy 30	7,5	3	-	14
	2	1	N/A	None						
13	1	1	9	2B	LP/H*	SS:A-249-304	7,3	3.6	-	5
				6	HP/H	CS:A-556-C2	2	6.3	-	4
				7	HP/H	CS:A-556-C2	2	0.9	-	4
	2	1	7	4	LP/H	CS	1,4	NA	H	5
				5	LP/H	CS	1,4	NA	H	1
				5r**	LP/H	CS	1	3.8	-	1.5
				6	HP/H	CS	5	NA	-	6
14	1	1	10	4	IP/H	CS:A-179	3	NA	H	0
				3A	HP/VCD	CS:SA-210-C	3	12	H	5
				3B	HP/VCD	CS:SA-210-C	3	11	H	5
		2	10	6	LP/H	CS:A-179	1	NA	H	7
		3	10	3A,3B	HP/VCD	CS:SA-210-C	3	10	H	5
				4	IP/H	CS:A-179	3	8.7	-	0

*Straight tubes
**Replacement heater

Utility	Plant	Unit	Total No. of Heaters	Problem Heaters	Type/ Orientation	Tube Material	Problem Description	% Tubes Plugged	Heater or Bundle Replaced	Heater Age at 1st Failure (years)
		4	10	4	IP/H	CS:A-179	7	9	-	9
15	1	1	8	4	LP/H	Admiralty	7	NA	-	9
				6	LP/H	70-30 CuNi	7	NA	-	1
	2	1	8	4	LP/H	CS:SA-179	6	NA	-	NA
				3	LP/H	CS:SA-179	6	NA	-	NA
		2	8	6N	HP/H	CS:SA-210-C	5	NA	B	7
				3	LP/H	CS:SA-179	6	NA	-	NA
				4	LP/H	CS:SA-179	6	NA	-	NA
		3	8	3	LP/H	CS:SA-179	6	NA	-	NA
				4	LP/H	CS:SA-179	6	NA	-	NA
		4		6S	HP/H	CS:SA-210-C	5	NA	B	4
				4	LP/H	CS:SA-179	6	NA	-	NA
				3	LP/H	CS:SA-179	6	NA	-	NA
16	1	1	7	4	LP	CS:A-179	7	7.76	-	2
				2	HP	CS:A-210-C	3	2.3	-	1
17	1	1	7	6	HP/VCD	Monel	7	13	-	10
	2	1	8	7	HP/H	Cufenloy	4,6	NA	B	3
				6	HP/H	Cufenloy	7	1.3	-	4
18	1	1	9	3	LP/H	Admiralty	7	13 tubes	-	2
				5	LP/H	90-10 CuNi	7	7 tubes	-	2
		2	9	2A	LP/H	Admiralty	7	11 tubes	-	2
				2B	LP/H	Admiralty	7	2 tubes	-	2
				3	LP/H	Admiralty	7	3 tubes	-	1.5
				5	LP/H	90-10 CuNi	7	5 tubes	-	2
19	1	1	9	2	IP/H	CS:A-210-C	3	NA	H	5
				4	LP/H	CS:A-179	3	NA	H	4
	2	1	8	4	LP/VCD	CS:A-179	7	40	B	6
				5	LP/VCD	CS:A-179	7	5	-	6
				6	LP/VCD	CS:A-179	7	10	-	6
				7	LP/VCD	CS:A-179	7	15	-	6
	3	1	8	2A,2B	HP/H	CS:A-210-C	7	1	-	6.5
		2	8	1A,1B	HP/H	CS:A-210-C	7	3.4	-	5
				2A	HP/H	CS:A-210-C	7	NA	H	5
				2B	HP/H	CS:A-210-C	7	NA	-	5
20	1	1	8	4A	LP/H	CS:A-556-A2	7	2 tubes	-	4
				4B	LP/H	CS:A-556-A2	7	3 tubes	-	4

Utility	Plant	Unit	Total No. of Heaters	Problem Heaters	Type/ Orientation	Tube Material	Problem Description	% Tubes Plugged	Heater or Bundle Replaced	Heater Age at 1st Failure (years)
				7	LP/H	CS:SA556-A2	9	NA	-	3
	2	1	8	1A,1B,2A,2B	HP/H	CS	8	NA	-	8
		2	8	1A,1B,2A,2B	HP/H	CS	8	NA	-	8
		3	8	1A,1B,2A,2B	HP/H	CS:A556-C2	10,5	5	-	2
				4	LP/H	CS:A556-C2	1	6 tubes	-	4
	4	1	7	1	HP/H	CS:A-106-C	9	NA	-	9
21	1	1	7	G	HP/H	SS	7	NA	-	1
	2	1	6	F1,F2	HP/H	70-30 CuNi	8,3,9	NA	B	5
				G1,G2	HP/H	70-30 CuNi	3,7,9	7	B	5
	3	1	10	B1	LP/H	CS:A-179	7	3.94	-	NA
				F1	HP/H	CS:A556-C2	7	7.76	B	NA
				F2	HP/H	CS:A556	7	7.79	B	NA
				G1	HP/H	CS:A556-C2	7	2.86	-	NA
				G2	HP/H	CS:A-556-C2	7	4.06	-	NA
		2	10	B1	LP/H	CS:A556-C2	7	1.5	-	NA
				F1	HP/H	CS:SA556-C2	7	2.38	-	NA
				F2	HP/H	CS:SA556-C2	7	1	-	NA
		3	10	A1	LP/H	Admiralty SB-111	7,3	0.26	-	NA
				A2	LP/H	Admiralty SB-111	7,3	2.37	-	NA
				B1,B2	LP/H	Admiralty SB-111	3	NA	-	NA
				F1	HP/H	70-30 CuNi	7	0.52	-	NA
				F2	HP/H	70-30 CuNi	7	0.41	-	NA
				G1	HP/H	70-30 CuNi	7	5.58	H	3
				G2	HP/H	70-30 CuNi	7	4	-	3
22	1	1	7	None						
23	1	1	8	D	LP/VCD	Admiralty SB-395	7	0.98	-	6
				F2	HP/H	70-30 CuNi SB-395	6	0.65	-	6
				G1	HP/H	70-30 CuNi SB-395	6	0.93	-	5
		2	7	F	HP/VCD	70-30 CuNi SB-395	6	0.17	-	2
				G	HP/VCD	70-30 CuNi SB-395	6	0.05	-	2
24	1	1	7	3	LP/H	CS:A-214	7	20	B and H	1

Utility	Plant	Unit	Total No. of Heaters	Problem Heaters	Type/ Orientation	Tube Material	Problem Description	% Tubes Plugged	Heater or Bundle Replaced	Heater Age at 1st Failure (years)
				2	HP/H	CS	1,5	6.6	-	5
	1	1	7	4	LP/H	CS:A556-A2	7	7.2	-	3
25	1	1	6	6	HP/VCD	Monel	7	7	H	18
		2	10	6A	HP/H	Monel	6	30	-	7
26	1	1	8	2	LP/H	CS:A556-A2	11	NA	-	0
	2	1	8	7E	HP/H	CS	7	NA	-	NA
				7W	HP/H	CS	8,1	NA	-	NA
		2	8	None						
27	1	1	8	1	HP/H	CS:SA-210-C	3	10	H	11
				2	HP/H	CS:SA-210-C	3	NA	-	NA
				3	HP/H	CS:SA-210-C	3	7	-	11
		2	7	1	HP/H	CS:SA-210-C	3	10	H	9
				2	HP/H	CS:SA-210-C	3	NA	-	NA
				3	HP/H	CS:SA-210-C	3	4	-	9
28	1	1	7	4	IP/H	90-10 CuNi SB-395	4	NA	B	3-4
				5	IP/H	B-163 Monel	4	NA	B	3-4
				6	HP/H	B-163 Monel	4	NA	-	3-4
		2	7	4	IP/H	90-10 CuNi SB-395	4	NA	B	3-4
				5	IP/H	B-163 Monel	4	NA	B	NA
				6	HP/H	B-163 Monel	4	NA	-	NA
29	1	1	6	1	HP/H	B-163 Monel	4	NA	-	< 1
				2	IP/H	B-163 Monel	4	NA	-	< 1
		2	6	1	HP/H	B-163 Monel	4	NA	-	< 1
				2	IP/H	B-163 Monel	4	NA	-	< 1
	2	1-4	24	3	IP/H	90-10 CuNi B-395	4	NA	-	1
30	1	1	14	3B	LP/H	CS:SA-179	7	14.3	H or B	0
				6A	HP/H	CS:SA-210-C	3,2,6,1	10.6	H	NA
				6B	HP/H	CS:SA-210-C	3,1,2,6	2.7	H	NA
		2	14	6A	HP/H	CS:SA-210-C	3,1,2,6,9	7.1	H	NA
				6B	HP/H	CS:SA-210-C	3,1,2,6,9	7.2	H	NA
				8A	HP/H	CS:SA-210-C	1,2	6.1	-	2
				3A	LP/H	CS:SA-179	7	17.7	H or B	3
	2	1	14	3A	LP/H	CS:SA-179	7	16.47	H or B	0
				3B	LP/H	CS:SA-179	7	21.1	H or B	0
		2	14	6A	HP/H	CS:SA-106-C	7,2	8.93	H	0

Utility	Plant	Unit	Total No. of Heaters	Problem Heaters	Type/ Orientation	Tube Material	Problem Description	% Tubes Plugged	Heater or Bundle Replaced	Heater Age at 1st Failure (years)
				7A	HP/H	CS:SA-106-C	7,2	16.83	H	0
31	1	1	11	None						
		2	11	1A,1B,2A,2A,3A,3B	HP/H	CS:A556-C2	1,3	< 1	-	1
32	1	1	10	6	LP/H	CS:SA-179	1,11	1.5	H	6
		2	10	None						
	2	1	10	None						
	3	1	10	None						
		2	10	None						
33	1	1	8	3	IP/H	CS:A-179	4	2	H	1
		2	7	2	IP/H	CS:A-179	4	14	H	NA
				3	IP/H	CS:A-179	4	15	H	NA
	2	1	3	None						
34	1	1	10	28B	HP/H	CS:SA-210-C	4,10	NA	H	< 1
				27A,27B	HP/H	CS:SA-210-C	4,10	NA	H	< 1
				26A,26B	HP/H	CS:SA-210-C	4,10	NA	H	< 1
35	1	1	8	5	LP/VCU	CS:A556-A2	3	15	-	4
				1	HP/H	CS:A-210-C	2,8	2	-	4
				2	HP/H	CS:A-210-C	2,8	4	-	4
				3	HP/H	CS:A-210-C	2,8	2	-	4
36	1	1	14	3S	LP/H	CS:A-179	1,3	28.4	H	0
				4S	LP/H	CS:A-179	1,3	20.2	H	0
37	1	1	7	A1	LP/H	CS:SA-556-A2	9	NA	-	0.7
				A2	LP/H	CS:SA-556-A2	9	NA	-	0.3
				F	HP/VCD	CS:SA-556-C2	3	NA	-	NA
38	1	1	8	1	HP/H	SS	7	0.15	-	NA
				2	HP/H	CS	10	2.36	-	NA
				3	LP/H*	SS	9	NA	-	NA
				4	LP/H*	SS	9	NA	-	NA
	2	1	7	1	HP/H	CS:A-106-C	10	2.96	-	0
				2	HP/H	CS:A-106-C	10,2	14.61	-	0
				3	LP/H	CS:A-179	10	22	H	0
				3	LP/H*	SS:SA-249-304	7	3.14	-	0
				4	LP/H	CS:A-179	1	10.55	-	NA
				6	LP/H	CS:A-179	7	7.41	-	NA
				7	LP/H	CS:A-179	7	0.50	-	NA

*Straight tubes

Utility	Plant	Unit	Total No. of Heaters	Problem Heaters	Type/ Orientation	Tube Material	Problem Description	% Tubes Plugged	Heater or Bundle Replaced	Heater Age at 1st Failure (years)
39	1	1	6	None						
	2	1	7	1A,1B	HP/H	CS:SA-556-C2	7	NA	B	5
				2	IP/H	CS:SA-179	7	11.4	B	7
	3	1	6	2	IP/H	CS:A-210-C	7	NA	H	2
	4	1	8	5	LP/H	CS:A-556-A2	7	10	-	2
				7	LP/H	SS:A-249-304	7	1 tube	-	3
				2	LP/H	CS:A-556-B2	7	2	-	1
				4	LP/H	CS:A-556-A2	7	2	-	1
40	1	1	7	1,2	HP/H	CS	7	NA	-	5
				3	LP/H	CS:A-556-A2	1	NA	H	3
		2	7	1,2	HP/H	CS	7	NA	-	5
				3	LP/H	CS:A-556-A2	1	NA	H	3
	2	1	7	1,2	HP/H	CS:A-556-C2	7	NA	-	NA
				3	LP/H	CS:A-556-A2	1	NA	H	3
		2	7	1,2	HP/H	CS:A-556-C2	7	NA	-	NA
				3	LP/H	CS:A-556-A2	1	NA	H	3
		3	8	None						
	3	1	8	1A,1B,2A,2B	HP/H	CS:A-556-C2	9	NA	-	3
		2	8	1A,1B,2A,2B	HP/H	CS:A-556-C2	9	NA	-	3
		3	8	1A,1B,2A,2B	HP/H	CS:A-556-C2	9	NA	-	3
41	1	1	7	1	HP/H	Monel 163B	7,5	1.7	-	1
				2	IP/H	Monel 163B	7,5	6.8	-	1
				3	IP/H	90-10 CuNi SB-396	1,5	2.0	-	1
		2	7	1	HP/H	Monel 163B	7,5	2.1	-	1
				2	IP/H	Monel 163B	7,5	5.6	-	1
				3	IP/H	90-10 CuNi SB-395	1,5	2.5	-	1
		3	7	1	HP/H	Monel 163B	7,5	2.9	-	1
				2	IP/H	Monel 163B	1,5	7.5	-	1
				3	IP/H	90-10 CuNi SB-395	1,5	6.0	-	1
		4	7	1	HP/H	Monel 163B	7,5	3.0	-	1
				2	IP/H	Monel 163B	1,5	5.5	-	1
				3	IP/H	90-10 CuNi SB-395	1,5	6.2	-	1
	2	1	7	2	IP/H	90-10 CuNi	6	NA	-	1
				3	IP/H	90-10 CuNi	4	NA	-	2
		2	7	2	IP/H	90-10 CuNi	6	NA	-	1

Utility	Plant	Unit	Total No. of Heaters	Problem Heaters	Type/ Orientation	Tube Material	Problem Description	% Tubes Plugged	Heater or Bundle Replaced	Heater Age at 1st Failure (years)
				3	IP/H	90-10 CuNi	4	NA	-	2
42	1	1	10	1B	HP/H	Monel SB-163	8	< 1	-	0.5
	2	1	10	1A,1B	HP/H	Monel SB-163	7	< 1	-	6
				7A,7B,7C	LP/H	Admiralty B-395	9	NA	-	0
				2A,2B	HP/H	Monel SB-163	7	< 1	-	6
	3	1	9	2A,2B	HP/VCD	Monel B-163	6,3	40	H	11
				1A,1B	HP/VCD	Monel B-163	6,3	40	H	11
43	1	1	9	F2	HP/H	70-30 CuNi	12	11	B	2
44	1	1	14	1A,1B	HP/H	CS:A-210C	10	1.5	-	1
				2A,2B	HP/H	CS:A-210C	10	2	-	1
				3A,3B	HP/H	CS:A-210C	2,10	10	H	0
				3A,3B*	HP/H	CS:A-210C	2	2.4	H	1
				4A,4B	IP/H	CS:A-179	3	10	B	1
	2	1	14	2A	HP/H	CS:A-210C	10	8	B	0
				3A	HP/H	CS:A-210C	10	6	B	N/A
		2	14	1A	HP/H	CS:A-210C	10	11	B	0
				2A	HP/H	CS:A-210C	10	18	B	0
				2B	HP/H	CS:A-210C	10	4	-	0
	3	1	14	None						
		2	14	None						
		3	14	4A,4B	HP/H	CS:A-210C	1	8	H	2

*Replacement heaters

Appendix B

DATA ON PROBLEM FEEDWATER HEATERS

AT NUCLEAR UNITS

Table B-1
SUMMARY OF SURVEY RESULTS FOR NUCLEAR UNITS

		No. of Utilities	No. of Units	No. of HP Heaters	No. of LP Heaters	Tube Material CS	Tube Material SS	Tube Material Cu Alloy	Tube Material Monel	No. of Heaters or Bundles Replaced
1.	Steam impingement	3	3	4	2	3	3	0	0	0
2.	Tube inlet end erosion-corrosion	0	0	0	0	0	0	0	0	0
3.	Drains cooler flashing/ level control problems	6	7	6	9	0	11	4	0	7
4.	Tube vibration	4	4	4	10	0	12	2	0	0
5.	Tube plugging problems	0	0	0	0	0	0	0	0	0
6.	Corrosion	5	5	2	11	2	0	11	0	0
7.	Unknown	3	3	4	2	1	0	5	0	0
8.	Failure of internal non-tube component	1	1	0	3	0	0	3	0	0
9.	Head or shell leak	1	1	1	0	0	1	0	0	0
10.	Tube-tubesheet joint failure	0	0	0	0	0	0	0	0	0
11.	Foreign material impingement	0	0	0	0	0	0	0	0	0
12.	Tube manufacturing defect	0	0	0	0	0	0	0	0	0
13.	Copper carry-over from tubes into turbine	1	3	6	6	0	0	12	0	12

Totals:

No. of feedwater heaters 385
No. of problem feedwater heaters 60
No. of nuclear utilities responding 18
No. of nuclear units 31

Table B-2
PROBLEM HEATERS AT NUCLEAR UNITS

Utility	Plant	Unit	Total No. of Heaters	Problem Heaters	Type/ Orientation	Tube Material	Problem Description	% Tubes Plugged	Heater or Bundle Replaced	Heater Age at 1st Failure (years)
1	1	1	10	None						
		2	10	6A	HP/H	SS	1	NA		1
1	1	1	16	None						
		2	16	None						
3	1	1	12	4A,4B	LP/H	Admiralty	6	NA	B	5
	2	1	10	None						
		2	10	None						
4	1	1	12	None						
		2	12	None						
	2	1	24	None						
		2	24	None						
	3	1	12	None						
		2	12	None						
5	1	1	12	1A,1B	HP/P	80-20 Cu-Ni B-111	6	NA	H	7
				3A,3B	LP/H	80-20 Cu-Ni B-111	6	NA	H	7
6	1	1	12	1A,1B	HP/NA	SS-A-249-3042	3	2.3		1
7	1	1	4	All	NA	Copper Alloy	13	0	B	NA
		2	4	All	NA	Copper Alloy	13	0	B	NA
	2	1	4	All	NA	Copper Alloy	13	0	B	NA
8	1	1	12	None						
9	1	1	14	2A	HP/H	CS:SA-210-AL	1	2.2		5
				2B	HP/H	CS:SA-210-AL	1	1.9		3
				4B	HP/H	CS:SA-210-AL	1,7	4.9		< 2
				8A	LP/H	CS: A-179	6	9.9	H or B	0
				8B	LP/H	CS: A-179	6	9.3	H or B	0
10	1	1	15	115,125,	HP/H	SS-304	4	< 5		8
				135	HP/H	SS-304	4,9	< 5		8
				112,132, 134	LP/H	SS-304	4	< 1		9
				123	LP/H	SS-304	4	< 1		8

Table B-2 (cont)

Utility	Plant	Unit	Total No. of Heaters	Problem Heaters	Type/ Orientation	Tube Material	Problem Description	% Tubes Plugged	Heater or Bundle Replaced	Heater Age at 1st Failure (years)
11	1	1	10	IP1,IP2	LP/H	SS-A-249-304L	3	NA	H	3
		2	14	3A,3B,4A,	LP/H	Admiralty SB111	6	NA	B	1
12	1	1	15	2A,2B,2C	LP/H	SS-304L-SA-249	3	25-30	B	3-4
		2	15	2A,2B,2C	LP/H	SS-304L-SA-249	3	25-30	B	3-4
13	1	1	16	7A,7B	HP/H	90-10 Cu-Ni	3,7	NA		0
				6B	HP/H	90-10 Cu-Ni	3,7	< 1		0
				2B,2C	LP/H	Admiralty	6	20		3
14	1	1	18	None						
15	1	1	10	3B	HP/H	Admiralty	3,8	10.4		4
				4A,4B	LP/H	90-10 Cu-Ni	8			4
16	1	1	10	2A,2B	LP/H	Cu-Ni	7,4	5		10
17	1	1	10	4A	HP/H	SS-A-249-304L	3,4	2		1.5
				4B	HP/H	SS-A-249-304L	3	0		1.5
18	1	1	10	3A,3B	LP/H	SS-A-249-304	1,4	NA		NA
				5A	LP/H	SS-A-249-304	4	NA		NA
				5B	LP/H	SS-A-249-304	4	NA		NA

Appendix C

LITERATURE SEARCH

ON FEEDWATER HEATERS

LITERATURE SEARCH ON FEEDWATER HEATERS

C.1 INTRODUCTION

A literature search, covering the period 1965 - present, was conducted on the subject of feedwater heaters in fossil-fueled power plants. The search included the following:

- Computer and manual search of the Engineering Index,* which contains articles from 1899 titles, including U.S. and foreign professional and industrial journals, as well as proceedings, transactions and special publications of engineering societies, scientific and technical associations, universities, laboratories, research institutions, government agencies, and industrial organizations.
- A "RECON" computer search, which was conducted by the Technical Information Center of the U.S. Department of Energy, and which mainly searches the Nuclear Science Abstracts file and the Energy Information Data Base file.
- A manual search of the U.S. DOE Applied Science and Technology Index.
- A manual search of the U.S. DOE Energy Research Abstracts.
- A manual search of the U.S. DOE Fossil Energy Update.

C.2. RESULTS

A total of approximately 240 articles of interest were initially identified in the various searches described above. Approximately one-half of these were identified as possibly pertaining to the scope of this project, and copies were obtained. Finally, 72 were selected as directly relevant to the project. Each of these is summarized in Section III of this report.

The 72 articles cover a wide range of topics, including manufacturing methods, design techniques, and operating problems. A review of these articles has resulted in the following useful inputs to the overall study.

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*Engineering Index, Inc., United Engineering Center, 345 East 47th Street, New York, N.Y. 10017.

- Identification of feedwater heater problems that have already been addressed in the literature: investigations of a variety of past feedwater heater problems are reported in the literature. This information can be used to correlate problems reported by utilities in the EPRI questionnaires as either: 1) the recurrence of an old problem thought to be well understood, or 2) the appearance of a new problem that may suggest areas for additional research. Some specific problem areas that are addressed in the literature are erosion-corrosion at tube inlets (2,27,33,69,72),* erosion-corosion of tube ID's (69), failure of tube-to-tubesheet welds (10,16,27,28,30,35), exfoliation of coppernickel tubes (13,40), stress-corrosion cracking of tubes (17,24), liquid impingement erosion on the steam side (23), tube plugging (52), and tube vibration (56,58,59,70).

- Familiarization with foreign experience: Several articles (4,8,16,19, 20,22,23,24,32,34,47,49,50,63 65,67) deal with foreign feedwater heater design practices and operating experience, particularly in the United Kingdom and West Germany. Although these articles are not sufficiently detailed to permit a thorough comparison of U.S. and foreign feedwater heaters, they suggest differences that warrant further investigation.

- Recommendations for design, manufacture, repair, or operation: Many of the articles recommend methods for designing, manufacturing, repairing, and operating feedwater heaters. Examples include recommended oxygen concentration (10,27,63), pH (10,27,63,71), tube-to-tubesheet welding techniques (16,27,28,30,35,36), tube materials (34,40), design methods (49,57,59,68) and tube plugging methods (52). The recommendations will be compared with published industry standards and with the utilities' responses to the EPRI questionnaire in order to determine areas where uncertainty exists. This may suggest areas where more standards development is needed.

C.3 SUMMARIES OF ARTICLES

1. "The Development and Production of High Pressure Feed et al., Heaters for Modern Central Power Stations," J.R. Spence, et al., Institute of Mechanical Engineers, Proceedings 1967-68, Vol. 182, Part 1, No. 36, pp. 735-756.

The paper describes features of large high-pressure (HP) feedwater heaters developed and manufactured in the United Kingdom during recent years. Attention is devoted to heaters with steel tubes. An outline of important design considerations is given, including reference to the incorporation of integral desuperheating and drain cooling sections.

This is followed by consideration of tubeplates, headers, tubes, and tube welding, from both design and construction standpoints. Particular reference is made to

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*Numbers refer to articles in Section C.3.

quality control procedures for heater components and for final assembly. The Foster Wheeler process for butt welding tubes to the tubeplate is described, and details are given of the cleanliness conditions under which this process must be carried out to ensure weld integrity.

In a final section dealing with current developments, details are given of a new heater design incorporating a toroidal header. This design permits the full feed-flow for a 660 MW set to be passed through a single train of HP heaters, without incurring the penalty of excessively large forgings or castings. The arrangement has been found to result in major cost savings, when compared with twin train heaters using conventional flat tubeplates.

2. "Hydraulic Impact Forces Causing Water-Side Inlet Impingement Attack on Carbon Steel Tubed High Pressure Feedwater Heaters," S. Takahashi and T. Horichi, presented at ASME Winter Annual Meeting, Los Angeles, California, November 16-20, 1969.

The paper describes the mechanism of inlet impingement attack in carbon steel tubed HP feedwater heaters. The attack has been experienced at the inlet of the water side of the tubes when the inlet water temperature is 130-200°C and the velocity 2 meters per second (m/sec). No attack occurred at temperatures greater than 230°C or with the velocities less than 1.6 m/sec.

Through experiments using mock rust, it was found that large vortexes produced in the water inlet chamber functioned as repeated mechanical impact forces, acting to detach rust from the tube walls. Inlet impingement occurs at places where the pressure fluctuations from the vortexes are greatest. Amputation of the boundary layer by the vena contracta produced at the inlet part of the tubes acts to further the impingement attack. The use of stream diffusers reduced the attack by 40%, and the use of a bell-mouthed nozzle for the tube inlet eliminated the remainder.

3. "Reduce Stress-Corrosion Cracking in Feedwater Heaters," S.O. Reynolds, Jr., and F.W. Pement, Power, Vol. 115, No. 4, April 1971, pp.83-84.

This paper presents an overview of stress-corrosion cracking in feedwater heater tubes. Tube materials in high-pressure heaters in most fossil-fueled plants are either cold-drawn and tempered Monel, 70/30 copper-nickel, or carbon steel. Elimination of any one of three factors -- stress, composition range, or environment -- will eradicate a given stress-corrosion problem.

The responsibility for preventing stress corrosion lies with the feedwater heater designer and the plant operator. However, the tube manufacturer can help by minimizing residual stresses, avoiding tube contamination, and educating plant operators about potential chemistry problems during hydrostatic testing and hot chemical cleaning.

4. "On Extra-Long Feed-Water Heater Tubes," Hisashi Nokamura and Hideo Deguchi, the Sumitomo Search, No. 2, November 1969, pp.29-43.

This paper describes the process used by Sumitomo to manufacture steel feedwater heater tubes up to 130 feet long. Care is taken to remove all surface imperfections and to eliminate flaws. During the cold drawing process, tube surfaces are inspected by magnetic particle flaw detection or fluorescent penetrant inspection. In addition, ultrasonic and eddy current inspections are used to confirm the absence of internal defects. As a measure to prevent stress corrosion during service, tubes with small bending radii are heat treated at the bending section for stress relief. A suitable rust preventive oil is selected for packaging after its rust preventive properties and removability have been tested under actual export conditions by trial shipments to the overseas users. The chemical and mechanical properties of the various Sumitomo tubes are given.

5. "Material Options for Steam Cycle Heat Exchangers," Robert G. Schwleger and Sheldon D. Strauss, Power, Vol. 123, No. 6, June 1979, pp. S1-S16.

One part of this paper discusses materials for feedwater heater tubes. The material must 1) have strength at elevated temperatures, 2) resist corrosion and erosion, 3) possess good heat transfer properties, and 4) be economical. No single alloy offers an optimum balance among all these properties. Before the age of high-pressure boilers, copper-base alloy tubes were commonly used. As system pressures increased, higher strength materials were required. Today, in plants with sub-critical drum-type boilers, the preferred tube material for low-pressure heaters is Type 304 stainless steel or 90/10 copper-nickel. Cold drawn and tempered Monel or Type 304 intermediate and high-pressure heaters. For plants with super-critical boilers, Type 304 stainless steel and carbon steel are specified for low-pressure heaters, carbon steel for intermediate and high-pressure heaters. A discussion of the advantages and disadvantages of each material is included.

6. "Explosive Forming Tightens Heater Tubes," H.J. Bierman, Power, Vol. 111, No. 11, November 1967, p. 92.

This paper describes the method used at Foster Wheeler for expanding the tubes inside the tube sheets of high-pressure feedwater heaters. Plastic inserts containing a selected charge of explosive are detonated inside each tube simultaneously. The explosive force provides a uniform expansion of the tube into the tubesheet. The advantages over conventional roller expanding include less distortion on the inner surface, less likelihood of stress corrosion, and more continuous and satisfactory surface contact at the tube-tubesheet interface.

7. "Erosion Tests on Feed-Heater Tubes," The Brown-Boveri Review, Vol. 54, No. 10/11, October/November 1967, pp.696-700.

A series of tests were conducted to determine the relationship between water velocity and erosion inside feedwater heater tubes. The temperature, pressure, tube material, type of fixing, in-flow conditions, radius of bend in U-tube, dissolved O_2 content in the water, and water velocity were varied. The tests showed that no erosion is expected to take place in feedwater heater tubes or their inlets if purely deaerated water is used, even at water velocities of up to 10 m/sec. However, erosion-corrosion can be expected to occur at the sharp deflecting edges when using feedwater that chemically attacks the tube material.

8. "Welding Steel Tubes in High Pressure Feed-Heaters," The Brown Boveri Review, Vol. 54, No. 10/11, October/November 1967, pp. 693-695.

This paper describes the process developed by Brown-Boveri for welding the steel tubes into feedwater heaters. The tubes are inserted into the tubesheet until they just protrude and then are roller expanded for a tight fit. A ring of special alloy is placed on the protruding end and then melted by an Argonarc process, forming a fillet weld to seal the joint. The spaces between the joints are then filled with weld metal.

9. "Influence of the Partial Pressure of Oxygen on the Corrosion Mechanism of Copper-Nickel Alloys in the Presence of Caustic Soda," The Brown Boveri Review, Vol 54, No. 10/11, Ocotber/November 1967, pp. 703-706.

Intercrystalline corrosion of copper-nickel tubes caused by caustic soda, often in conjunction with stress corrosion, occurred after only a few months' service in isolated feedwater heaters. Laboratory tests were conducted to determine the factors that contribute to the corrosion. It was found that at elevated temperatures, copper-nickel alloys can be very susceptible to stress corrosion in the presence of caustic soda and at low oxygen partial pressures. Most sensitive are the alloys with 70%-80% copper. While no corrosion takes place in the virtual absence of oxygen, uniform exfoliation of the tubes occurs at high partial pressures.

10. "High Pressure Steel-Tubed Feedwater Heater Considerations," William J. Bow, Proceedings of the American Power Conference, Volume XXVIII, 1967, pp. 490-495.

This paper discusses some of the problems that have occurred with carbon steel feedwater heater tubes that have replaced copper-base alloy tubes in today's high-pressure fossil-fueled power plants. One problem has been failure in tube-to-tubesheet welds caused either by porosity in the welds, due to inadequate cleaning of tubes before welding, or by extreme hardness and embrittlement in the joint, due to excessive integration of carbon into the filler metal during welding. A stress analysis shows that locating welds on the shell side, rather than the channel side, will reduce the stresses experienced during thermal transients. Foster Wheeler developed an internal bore welding process to enable welding of tubes to the shell side of the tubesheet that has proven successful in England.

The paper states that there has been some tendency to overlook essential changes in operating practices that should be recognized when using carbon steel tubes as compared with practices previously used with copper-based/alloy tubes. Their survey of the experience of many power plants resulted in a recommendation that the following limits be maintained at the entrance to the high-pressure heaters:

- Oxygen concentration .007 ppm (maximum)
- pH 9.6 for minimum corrosion of carbon steel heaters
- Total iron and copper concentrations less than 10 ppb (each)

11. "Report on Investigation of Brittle Failure of Feedwater Heater Forging," William Apblett, Jr., and Kenneth S. Brundige, Proceedings of the American Power Conference, Volume XXVII, 1965, pp. 451-461.

A high-pressure feedwater heater failed catastrophically while being hydrostatically proof tested. A detailed metallurgical investigation of the causes of the failure was conducted. It was concluded that the failure resulted from the coincidence of a number of factors, each unfavorable to the stability of the vessel. These factors include: 1) a relatively high brittle to ductile transition temperature for the base material forging; 2) an embrittled heat affected zone in the weld joining the pass partition plate to the channel; and 3) a high triaxial stress level at the point of crack initiation.

12. "Exfoliation-Type Corrosion of Cupro-Nickel Feedwater Heater Tubes and Removal of Corrosion Products by Chemical Cleaning," J.M. Decker and J.C. March, Combustion, August 1964, pp. 47-48.

Exfoliation was found to occur in systems that are operated only during peak periods. During outages, the tubes come in contact with air, which provides oxygen to oxidize the metal. Exfoliation can be prevented by keeping air from entering the steam sides of feedwater heaters during outages. To clean tubes that had suffered exfoliation, the steam side of the heater is filled with 10% hydrochloric acid inhibited to protect iron components.

13. "Corrosion of Feedwater Heater Tubing Alloys in Peaking Service," G.C. Weidersum, and E.A. Tice, Transactions of the ASME, Journal of Engineering for Power, July 1965, pp. 324-328.

Feedwater heater tubes in plants that had been relegated to peak-load service began to experience exfoliation, which had not occurred when the plant was being used for continuous base-load operation. In most cases the tubes were 70/30 copper-nickel. To study this problem, a pilot-size heat exchanger, containing a variety of alloy tubes, was operated under peaking conditions for almost three years in parallel with a feedwater heater in a generating station. The test showed that the formation of exfoliating scale on feedwater heater tubes in peaking service was limited to and characteristic of 70/30 copper-nickel alloy. Modifying the alloy with up to 1.5% aluminum does not prevent exfoliation. The addition of 5% iron appears to prevent exfoliation of annealed tubing and minimizes it in cold-worked areas. A number of other alloys form only a thin, adherent oxide film in this service and no measurable metal loss occurs: 60/40, 80/20, and 90/10 copper-nickel, and AISI Types 304, 316 and 347 stainless steels. Materials that retain their "as-installed" appearance under these conditions are: Monel Alloy 400, Inconel Alloy 600, and titanium. Carbon steel and low-alloy steel show a moderate amount of pitting on both inside and outside surfaces. Stress-relieving forms a black adherent oxide that provides some corrosion resistance on the steam side of the tube. Type 410 stainless steel and Nickel 200 form only a thin oxide on their outer surface, but are pitted slightly on their inside surface.

14. "Design Trends in United States Utility Feedwater Heaters and Condensers," R.L. Coit, Combustion, Vol. 46, No. 8, February 1975, pp. 14-27.

The current trend for specifying feedwater tube materials for subcritical fossil plants is to specify copper bearing material combinations by more than two to one over ferrous material combinations. However, ferrous materials are making substantial gains in this area. In supercritical fossil plants, almost 90% of the heaters ordered between 1965 and 1971 were carbon steel or combinations of carbon and stainless steel in the same cycle. Monel and 70/30 copper-nickel (drawn and stress relieved) are being currently specified for approximately 10% of the heaters.

Currently, the most common practice is to specify expanded tube-to-tubesheet joints on low-pressure heaters and welded tube to tubesheet joints on high-pressure heaters. All alloys could fail by stress corrosion mechanisms present in many current power plant environments. Design considerations must include optimization of venting and minimization of areas where concentration of harmful corrodants can occur. To minimize stress corrosion cracking, all tubing alloys should be made with low residual stress processing. Recent advances in the mechanics of explosive forming and the physics of explosive welding have permitted these processes to be used for tube-to-tubesheet joints.

15. "Corrosion Protection of Boilers and Equipment in Idle Periods," C.V. Runyon and L.H. Vaughn, National Engineer, November 1971, pp. 14-18.

This article outlines recommendations that could reduce corrosion of boilers, condensers, turbines and feedwater heaters during non-operating conditions. Some of these recommendations are: 1) Ship carbon steel feedwater heaters with positive pressure of nitrogen gas both on the water side and the shell side; 2) Perform hydrostatic testing with treated demineralized water having minimum concentrations of 10 ppm of ammonia and 200 ppm of hydrazine; 3) During idle periods, use wet storage for both the water side and the shell side of the feedwater heater, and maintain an overpressure of nitrogen on the system.

16. "The Application of Explosive Welding to Industrial Heat Exchangers," R. Hardwick, FWP Journal, Vol XV, No. 1, January 1975, pp. 7-18.

This article describes an explosive welding process used to fabricate tube-to-tubesheet joints. The process has also been adapted to seal leaks that occur during the service life of conventionally welded heat exchangers. Sealing these units is achieved by explosively welding a plug into the leaking tube or tubeplate. This plugging process has been used on several hundreds of leaking tubes in high-pressure feedwater heaters throughout the Central Electricity Generating Board (CEGB) and has proved successful.

17. "Performance of MONEL Alloy 400 in Feedwater Heaters," D.W. Rahoi, et al., Transactions of the ASME, Journal of Engineering for Power, January 1973, pp. 27-35.

This paper is a condensation of a large volume of data from the examination of service failures and laboratory testing conducted over the last 10 years of the use of Monel Alloy 400 tubing in high-pressure feedwater heaters. An accelerated stress-corrosion-cracking test employing ammonium hyroxide or hydrazine has been devised that will cause Monel Alloy 400 to fail by a mechanism very similar to that experienced in service. No Monel Alloy 400 cracking resulted in any specimen stressed below 50,000 psi in the ammonium hydroxide tests.

18. "Effects of Abnormal Operation on Feedwater Heaters," T.J. Rabas, et al., Combustion, Vol. 44, No. 9, March 1973, pp. 6-13.

This paper discusses the causes of some abnormal operating conditions and the adverse effects these conditions can have on the design, construction and operation of closed feedwater heaters. Five different abnormal operating conditions are partial loading, increased turbine capacity, emergency turbine operation with heaters removed from service, drain pump failure on a pump forward cycle, and startup. Westinghouse uses a feedwater heater performance computer program to predict the heater performance for any of these abnormal operating conditions. Predicted flows, temperatures, and pressure drops from this program are used as input for other programs that perform mechanical design and tube vibration calculations. The feedwater heater performance program consists of two parts: 1) a single feedwater heater rating procedure and 2) a coupling routine for all the heaters in the string being studied. The most common cause of heater damage at overload conditions is excessive tube vibration. To obtain satisfactory operation of feedwater heaters at hazardous abnormal operating conditions, two approaches can be taken: 1) the heater can be designed to operate without damage; or 2) the piping system can be designed to eliminate the hazardous condition.

19. "Features of Controlling the Level in Regenerative Feedheaters with Cascade Drain Connections," A.Z. Smetana, I.N. Kyuner, Thermal Engineering, Vol. 19, No. 9, 1972, pp. 95-98.

This article discusses the optimum method of drain level control in a string of feedwater heaters with cascade drain connections. Using principles of automatic control theory, it is shown that a generalized resonance can occur in the level control system, where the deviation of the controlled variable can be significant. Using a PID controller action to maintain the level in feedwater heaters could significantly reduce the influence of generalized resonance.

20. "Design and Operation of Large High-Pressure Feedheaters," A. Sonnenmoser, Brown-Boveri Review, Volume 60, July/August 1973, pp. 352-359.

This article describes Brown-Boveri's experience with tube-to- tubeplate joints in large high-pressure feedwater heaters. The operational performance of high-pressure feedwater heaters with steel tubes welded according to the Brown-Boveri system has been good. At the usual pH values (9.0 - 9.5) and O_2 concentrations (0.002 - 0.007 ppm) and with water chambers and tube inlets designed to promote optimum water flow, erosion at the tubes and tube inlets can be eliminated, even at high water velocities. A stress analysis was conducted for a large high-pressure feedwater heater to be used in a 1000 MW plant. It is shown that the maximum size of high-pressure feedwater heaters, based on the tube plate principle, is determined not so much by the thermal stresses involved but, rather, by the manufacturing facilities available (forging, drilling the tube plates, transporting the finished unit, etc.) A suitable cast alloy steel, containing 2.5% chromium and 1% molybdenum, is recommended for the water inlet chambers of larger high-pressure feedwater heaters.

21. "Chemical Cleaning of Feedwater Heaters," J.P. Engle, Materials Performance, Vol. 13, No. 7, July 1974, pp. 30-33.

Chemical cleaning of the feedwater system of a modern utility boiler prior to start-up requires consideration of the feedwater heaters. This paper gives reasons why the heaters should be cleaned prior to service. Alkaline cleaning for removal of greases, oils, and preservatives, followed by removal of mill scale with inhibited acid is recommended. Incomplete removal of preservative compounds could result in contamination of ion exchange resin beds, thus further compounding the problem. The removal of deposits formed during operation requires greater care than pre-operational cleaning due to the composition of the deposits closely resembling the chemical composition of the tubes.

There are two generalized approaches for removing copper and iron oxides:

1. An ammonia solution containing an oxidizing agent for dissolving deposits that are primarily copper compounds.

2. A solution of inhibited mineral acid (such as hydrochloric acid) containing a copper complexing agent for dissolving iron oxide and complex copper. Neither formulation is given blanket approval for use. Either may result in excessive corrosion unless properly used and applied under the proper conditions.

22. "Investigation of the Operation of Feedwater Heaters of Steam Turbine Boilers," Ye.I. Beneson, et al., Heat Transfer--Soviet Research, Vol. 6, No. 4, July-August 1974, pp. 35-39.

An experimental investigation of the performance of a steam-turbine feedwater heater is described. The investigation, carried out at one of the heat and electric power stations of the Kirov Power District, had as its purposes: 1) obtaining experimental curves of feedwater heaters, including conditions below atmospheric heating steam pressures; 2) comparing the experimental curves with design equations corresponding to the technique assumed in designing the heaters; 3) accumulation of experimental data for the thermal design of feedwater heaters. It is found that the heaters in question had an efficiency below their design value that is attributed to tube fouling. Additionally, it was found that reducing the heating takeoff pressure below atmospheric pressure improves the turbine facility operation. It is recommended that this pressure be reduced to the lowest possible value permitted by water heating conditions.

23. "Corrosion and Erosion in Feedwater Preheaters - Cause and Prevention," P.H. Efferty, et al., 6th European Congress on Metallic Corrosion, London: Society of Chemical Industry, 1977, pp. 343-348.

About one-third of the damaged LP and HP feedwater heaters examined in large power station units had been affected by corrosion, erosion, or impingement attack. Depending on its location, damage was split into two categories: attack from either the feedwater or the steam side.

Damage on the feedwater side is usually attributable to pitting corrosion, erosion, and stress-induced corrosion. However, since such damage can be ruled out almost completely by normal production quality control, maintenance of feedwater quality standards, and suitable flow velocities and expansion rates, it is now a relatively unusual phenomenon.

Damage on the steam side is generally caused by impingement corrosion and liquid impingement erosion, but rarely by normal corrosion. Practically all cases of impingement corrosion damage can be prevented by adequate alkalization and oxygen conditioning, provided the velocity of the condensate film does not exceed 10 m/sec.

Liquid impingement erosion can be prevented by design improvements, such as installing impact, guide, and separation plates made of austenitic CrNi steel. At flow velocities of less than 50 m/sec, it is often sufficient to simply reduce the amount of entrained water.

Pitting corrosion on the superheated steam side without a detectable flow influence can be kept under control by improving superheated steam quality.

24. "Stress Corrosion Cracking of Cupronickel and Monel Metal Tubes in High Pressure Feedwater Heater," Shiro Sato and Koji Nagata, Sumitomo Light Metal Technical Reports, Vol. 15, No. 4, October 1974, pp. 40-57. [Text in Japanese]

Several instances have been experienced in which copper-nickel and Monel tubes used for high-pressure feedwater heaters failed by stress corrosion cracking (SCC). The investigations of these in-service failures have been made to clarify the conditions in which SCC would occur. Moreover, an experimental study has been made to reproduce the phenomenon of these failures by using an autoclave in which the stressed and non-stressed specimens were exposed to pure water and steam at temperatures of 300°C - 350°C. The results obtained were as follows:

- Copper-nickel suffered intergranular corrosion in degassed and oxygen bearing steam at 300°C - 350°C. It was found in several runs of the tests that the intergranular corrosion was accelerated to intergranular cracking by an applied tensile stress of 13.5kg/mm^2 and 18.5kg/mm^2 for 10% copper-nickel and 30% copper-nickel, respectively.

- Intergranular cracking was affected considerably by the steam temperature and the temper of specimens. Namely, the lower the steam temperature, the lower was the threshold stress of cracking. With regard to the temper of specimens, cold worked specimens tended to rupture within the test duration more readily than annealed specimens.

- Monel metal was less liable to suffer intergranular corrosion and did not fail under applied tensile stress up to 45kg/mm^2. Cracking of this metal was successfully reproduced under the experimental conditions of high pH adjusted by ammonium hydroxide with applied tensile stress above 35kg/mm^2. Microscopic observation revealed that ammonia in steam and water was effective in promoting intergranualar attack of Monel metal.

- The investigations on the failed Monel metal tubes by SCC in service revealed that these tubes had a high level of residual tensile stress, which was caused by straightening and bending during tube manufacturing.
- It is suggested that, in order to avoid the danger of stress corrosion cracking, the relief of residual stress is necessary not only for copper-nickel tubes, but also for Monel tubes when used for high-pressure feed-water heaters.

25. "Choosing Cu-Alloy Tubes for Heat Exchangers," Louis Caruso, Power, August 1971, pp. 73-75.

This article gives general advice for selecting copper alloy tubes for low-pressure feedwater heaters. A majority of heaters employ U-tube bundles, and when the tubes are bent over small radii, excessive thinning of the tube wall may result. To compensate for this, a heavier gage tube, or a dual-gage tube with a heavier wall in the bend, should be specified. When the heater is being designed, attention should be focussed on the nozzles and tube supports. Impingement baffles should be used where necessary. A study of tube dynamic behavior should be conducted to determine whether equal or uneven spacing of supports is betbetter for minimizing vibration. Tube inlets should be properly flared to reduce flow eddies. Efficient operation of feedwater heaters can be maintained by periodic mechanical or chemical cleaning and by adequate venting to eliminate accumulation of non-condensables that reduce heat transfer. If ammonia, hydrazine, or other amines are used for oxygen or pH control, U-bends should be stess relieved to reduce the probability of stress-corrosion cracking.

26. "Quality Control Procedures for Welded Feed Heaters," J.W. Addie, AEI Engineering, July-August, 1966, pp. 209-214.

Two welding processes that have been applied to feedwater heaters are the subject of this article. The first is the AEI seal welding process in which the tube projects from the water side of the spigoted tubeplate, and a filler ring is placed around the tube and seated on the spigot. The second is the internal bore welding (Foster-Wheeler) process in which the tube-end seats in a machined recess in a spigot raised on the steam side of the tubeplate.

Quality control must be established at the design stage with the selection of materials, then followed by careful checking and cleaning of the components and continued with strict observance of welding and testing procedures specified after meticulous development. The effectiveness of the quality control applied is best judged by the behavior of the product under non-destructive examination taking the number of repairs scheduled as the criterion.

27. "Innovation in Carbon-Steel Tubed Heater Design, Fabrication and Operation," K.S. Brundige, et al., ASME Winter Annual Meeting, New York, 1966.

The successful application of carbon steel tubed feedwater heaters depends on correct operation as well as creative design and competent fabrication. A survey of utility practices combined with research and development work, field inspections and tests resulted in innovations encompassing heater design, fabrication, and operating practice.

Early steel tube heaters, subjected to severe thermal stresses, were in trouble almost immediately as the steam generation started. Scheduled and unscheduled tripouts, tests, and so on, resulted in leaks in the joints from which the industry learned that the precautions that had been taken were inadequate. Investigation of these early heaters showed that the welds were not as perfect as had been expected and suffered from subsurface porosity. Also, they exhibited excessive hardness. The problem was solved by using a filler metal that was practically carbon free, by which the tube could be welded without porosity or unusual hardness developing.

Another improvement is explosive tube expanding to replace conventional roller expanding techniques for creating a tight joint between tube and tubesheet. The explosive method reduces work hardening to a minimum.

Another Foster-Wheeler innovation is the "internal bore weld," which places the tube-to-tubesheet weld on the shell side of the tubesheet, rather than on the channel side. The advantage is that the shell side stesses are significantly lower, so that the welds can withstand several times as many thermal transient cycles. Also, tubesheet holes have a smaller diameter, so that the tubesheet can be thinner.

Corrosion of carbon steel may be kept to a minimum only if a stable protective oxide film can be formed on its surface. Such a film is difficult to achieve in practice without the proper environment. Many carbon steel feedwater heaters have experienced both water and steamside corrosion attacks, including:

- tube wastage
- pitting
- generalized tube wall thinning
- corrosion-erosion throughout the heaters

A survey was conducted in the U.S. to pinpoint the causes of inlet tube metal wastage. Corrosion-erosion at the entrance of tubes has been experienced with various manufacturers' heaters employing their respective tube joint geometries. Conversely, these same types of joint geometry have been found to give trouble free operation with suitable water chemistry. Successful operation of carbon steel tubed heaters is dependent upon pH control with minimum corrosion occuring when pH is greater than 9.6. When pH is between 9.3 and 9.6, inlet flow distribution devices can be installed to reduce inlet tube wastage attack. High pH in the preboiler cycle calls for careful material selection. A combination of ferrous and non-ferrous tubing in high- and low-pressure heaters is not a desirable arrangement. Water chemistry practice should limit the hydrazine concentration to 20 ppb at a point early in the condensate cycle. Later in the cycle a volatile chemical such as ammonia must be added continuously for pH control. Oxygen concentrations should be maintained less than 7 ppb.

28. "Carbon-Steel, Feedwater-Heater Tube-to-Tubesheet Joints," A. Lohmeier, S.D. Reynolds, Jr., ASME Winter Annual Meeting, Chicago, 1965.

This paper discusses carbon steel tube weld failure caused by leakage paths generated from porosity within the weld and local stress mechanisms resulting from operation. Such defects are normally the result of the presence of volatile contaminants present during welding. Service experience and laboratory tests show that weld defects, not detected from normal leak testing procedures, can propagate into leakage paths after a number of cycles of operation. Stresses due to normal operation, hydrotest, and thermal transients, combined with residual stresses due to tube expanding and aggravated by the presence of inclusions or flaws, can provide the stress mechanism necessary for defect propagation to form leak paths. Expanding the tube in addition to welding enhances the reliability of the tube joint.

Tube-to-tubesheet weld metallurgy should provide the tubesheet cladding, tube-weld chemistry, joint design, and physical properties necessary to result in a joint having sufficient ductility and fracture toughness to preclude propagation to failure of a local porosity point. The recessed tube-to-tubesheet weld process, utilizing fusion of the tube with Inconel cladding is considered to give the most reliable tube-to-tubesheet joint for high-pressure carbon steel tubed feedwater heater applications.

Reliability is further increased by gas testing, a high level of quality control, and pressure cycle testing of welded feedwater heater tube sheets to detect incipient weld failures at the factory.

29. "Chloride Contamination of Tubing," S.E. Doughty, Power Engineering, September, 1969, pp. 47-49.

To lessen the problem of chloride stress corrosion in austenitic stainless steel feedwater heater tubing, some materials specification engineers have imposed severe restrictions on manufacturing processes. However, the problem lies not in the manufacturing process, but in the handling and storage of tubes after production. Definite chloride contamination from the atmosphere occurs during the handling, inspection, and storing of tubes. Restrictions on manufacturing processes are not effective in curbing chloride levels.

30. "Tube Welding for Conventional and Nuclear Power Plant Heat Exchangers," S.D. Reynolds, Jr., ASME Annual Meeting, Los Angeles, 1969.

Increased reliability of tube-to-tubesheet joints is achieved by tube welding. This method of sealing the tube-to-tubesheet joints, has been successfully used on low-pressure and high-pressure heat exchangers. The highest level of reliability is achieved by utilizing automatic welding methods. Where metallurgical and weld-ability rules permit, simple gas tungsten arc tube welds can be made with wrought thin wall tubes and wrought tubesheets. When it is not practical to clad a tube-sheet due to thickness, filler metal may be added by various methods to improve weldability. The highest level of reliability in high-pressure heat exchanger service has been achieved by using nickel alloy or stainless steel weld clad tube-sheets and the automatic gas tungsten arc welding process. Feedwater heaters with ferrous and nonferrous tubes and high nickel alloy clad tubesheets have had an essentially perfect record with only one reported tube weld leak since the inception of this process in the early 1960s. Tube rolling following tube welding has not been shown to have positive engineering merit and, in some cases, is detrimental to the weld.

31. "New Uses for Cleaning with Water," J. Barton Carver, Power, May 1976, pp. 40-41.

This article describes how high-velocity water (up to 1800 fps) can be used to clean power plant equipment, including U-tube feedwater heaters.

32. "Explosive Plugging and Factors Which Have Influenced Commercial Viability," R. Hardwick, Explosive Welding, The Welding Institute, Abington, Cambridge, England, 1976, pp. 28-30.

Yorkshire Imperial Metals Limited has developed a method of sealing leaks in high-pressure feedwater heaters by means of explosively welded plugs. The plug is a metal bar drilled out over a portion of its length to form a tube that is solid at one end. This plug is inserted, solid end first, into the leaking tubeplate hole and the known principles of explosive welding of tube-to-tubeplate joints are utilized to explosively weld the open end of the tube to the tubeplate. The tubular plug, thus welded, effectively seals off the tubeplate hole. The process can be carried out in a few hours, thereby minimizing downtime.

33. "Effect of Water Chemistry and Design on Corrosion of Carbon Steel Tubed Feedwater Heaters," E.B. Morris and Henry Phillips, Journal and Engineering for Power, ASME, April 1969, pp. 102-108.

In the early 1960s, an industry-wide trend toward carbon steel tubed feedwater heaters began. This applied especially to supercritical pressure units where copper alloys were responsible for turbine deposits of copper oxide. For subcritical application, economic factors prevailed in the selection of carbon steel. This paper covers the results of a specific study of chemical control factors and certain design conditions on corrosion of carbon steel heaters. The study was designed specifically to pinpoint the conditions involved in recent widespread experience with tube inlet-end corrosion-erosion.

Several totally unanticipated and unexplainable results were obtained, which perhaps raise more questions than are answered. For example, corrosion-erosion was greatest in the top heater when two HP heaters were connected in series with terminal temperatures of 330^{o}F, 430^{o}F, and 530^{o}F. Previous studies had shown that inlet-end corrosion erosion occurs only at temperatures below 400^{o}F. Another example is that single string operation, at twice normal velocity, did not significantly increase iron pickup across the heaters. It was evident that whatever factor was responsible for the iron level pickup reduction occurred during an approximate one-month period preceding the twice-velocity test and when no test data were being taken. Whatever the effect, it continued until the termination of the test program and beyond. Perhaps an unknown, but beneficial, contaminant was introduced into the cycle.

34. "Materials for Tubes Used in the Manufacture of High-Pressure Feed-Heaters," The Brown Boveri Review, Vol. 54, No. 10/11, October-November 1967, pp. 700-702.

Copper-nickel tubing has been used in the manufacture of feed-water heaters because of its good heat transfer characteristics and corrosion resistance. Successful countermeasures, both in design and operation, have been taken to prevent exfoliation corrosion that was a significant problem with these tubes. There have recently been cases of damage to copper-nickel alloy tubes that are of a completely different and previously unknown nature. The damage was a tube rupture initiated by a crack parallel to the tube in an area not subjected to particularly high steam velocity. Investigation showed that the conditions that lead to rupture are 1) mechanical stresses, 2) presence of water, steam, and oxygen, and 3) high temperature. It is concluded that copper-nickel tubes should be used only with moderate temperatures and pressures. For high pressures, tubes should be plain or low-alloy steel, stainless steel, or nickel-copper alloy (70/30).

35. "Solving Critical Leakage Problem in High-Pressure Feedwater Heaters," Power Engineering, April 1967, pp. 60-62.

Service difficulties with carbon steel tubes developed shortly after construction of the first high-pressure feedwater heaters using them. Leaks were developing due to weld failure at the tube-to-tubesheet joint. The leak paths in the tube welds grew from gas porosity caused by the presence of moisture, iron oxide, oil, or other foreign material in the interface between tube and tubesheet. Propagation of leak paths was attributed to limited ductility of weld material and the adjacent heat affected zone. The use of Inconel as a tubesheet cladding solved this problem because it has the following desirable properties:

- Coefficient of thermal expansion similar to that of steel
- As deposited on the tubesheet, it has higher tensile strength, yield strength, ductility, and notch toughness than the carbon steel forging of the tubesheet
- Corrosion and erosion resistance
- Heat affected zone with mechanical properties equal to those of the cladding
- Metallurgically compatible with carbon steel over a wide range of dilution
- Can be applied to the tubesheet with reliable inert gas metal arc process.

Inconel tubewelds deter the propagation of porosity effects. A recessed weld employing fusion of the tube with the Inconel cladding, is believed to be the most reliable tube-to-tubesheet joint yet developed for high-pressure heaters with carbon steel tubes.

36. "Explosives Expand Tube Into Tubesheet," Electrical World, Vol. 167, No. 24, June 12, 1967, p. 139.

Explosive forming has been adopted by Foster Wheeler as a commercial standard for all high-pressure feedwater heaters where tube expansion is to be performed. Advantages over roller expanding are:

- The inner surface of the tube has a considerably less severe surface distortion.
- The inner surface grain structure is less disturbed, has no noticeable work hardening, and is considerably less likely to be subject to stress corrosion.
- Satisfactory and continuous surface contact at the tube-to-tubesheet interface is consistently assured by means of the controlled charge applied.

37. "High-Pressure Feedwater Heaters Welded Quickly and More Efficiently with Semiautomatic Process," Welding Journal, Vol. 45, No. 11, November 1966, pp. 924-925.

Greatly increased weld deposition rate and higher deposition efficiency were gained when the Southwestern Engineering Co. switched from manual welding with covered electrodes to semiautomatic welding with a mild steel flux-cored filler metal for joining sections of their 70-ton, high-pressure feedwater heaters with the hemispherical head design. The time savings was 50%, and deposition efficiency was increased 15%-20%.

38. "Chemically Cleaning Feedwater Heaters Using Ammonium Persulfate," John J. Roosen and Larry J. Smolinski, Combustion, Vol. 37, No. 4, October 1965, pp. 39-41.

A number of cases of fouling by metallic copper deposits have been found in the 70/30 copper-nickel high-pressure heater tubes of Detroit Edison turbine generator units operating in the 1800 psig to 2400 psig range. Mechanical methods of cleaning have been used in attempts to remove deposits but were not completely effective. Chemical methods appeared to be the only feasible means of cleaning the entire heater. A solution of ammonium persulfate and ammonium hydroxide at room temperature were used for removal of copper deposits. This solution is followed by 15^{o}F inhibited hydrochloric acid for removal of any remaining deposits. A satisfactory cleaning job was obtained in all cases.

39. "Building Heat Exchangers for Power Plants," F. J. Winsor, Welding Design and Fabrication, August 1978, pp. 78-80.

Tubing material for both high-pressure and low-pressure heaters may be one of the following: SA556 or SA557 carbon steel; SA213 or SA688 stainless steel (usually Type 304 with 0.05% max C, or Type 304L); SB163 (Monel); or SB111 70/30 copper-nickel. Tubesheets for HP heaters are usually forged, commonly of SA266 Cl.2 steel. Tubesheets for low-pressure heaters may be either rolled plate or forgings. Tubes for HP heaters are generally welded to tubesheets. Roller expansion is most frequently used for low-pressure heater tubes, but specifications occasionally demand both rolling and welding. When welding is required, the tubesheet is first overlaid with weld deposited cladding to facilitate joining. Carbon steel tubes call for a low-carbon steel overlay, while stainless steel tubes require either Type 309L or a combination of 309L or 308L for the overlay. For Monel or copper-nickel tubes, Foster-Wheeler overlays either Monel or a combination of Monel and 70/30 copper-nickel.

After overlaying, workers machine the cladding to obtain chips for chemical analysis. Machined cladding is then ultrasonically examined, and tubesheets are gun-drilled on a numerically controlled machine. After the shell is installed over the tube bundle, a portable clean room is positioned to surround the tube sheet so that the welder can join the tubes to the tubesheet without contaminating welds. For tubewall thicknesses less than approximately 16 gauge (0.065 inch), Foster Wheeler prefers to use an end-weld type of joint, where the tube is fixed approximately flush with the clad face of the tubesheet and the weld is made without filler metal. Thicker tubewalls are welded with multipass fillet joints, employing projecting tube ends. Tube-to-tubesheet welds are usually inspected, then tested for leaks with either a soap-and-air solution, or a liquid refrigerant, or both. After this, tubes are expanded throughout the tubesheet thickness, usually by roller expanding in LP heaters and by kinetic expansion with explosives in HP heaters.

40. "Avoiding Exfoliating Corrosion in Cu-Ni Feed Heater Tubes," J.E. Castle, et al., Engineering and Boiler House Review, Vol. 81, No. 2, February 1966, pp. 38-41.

Feedwater heater tubes made of copper-nickel had given trouble in a number of CEGB power stations. Soon after stations changed from base load to two-shift operation, exfoliating corrosion appeared, particularly in tubes of 70/30 copper-nickel alloy. Laboratory investigations were conducted on commercial grade 90/10, 80/20, and 70/30 copper-nickel alloys, pure copper, pure nickel, Monel, mild steel and a modified 70/30 alloy containing 2% iron and 2% manganese. Exfoliating corrosion took place only in the presence of oxygen.

A theoretical basis for the exfoliation was determined. When oxidation of the copper-nickel alloy takes place in a plentiful supply of oxygen, cuprous oxide is formed first, since copper irons diffuse more rapidly from the alloy than nickel irons. On the other hand, nickel oxide is thermodynamically more stable than cuprous oxide and, without any oxygen, the alloy can continue to oxidize by means of the reaction:

$$Cu_2O + Ni \rightarrow 2Cu + NiO$$

Thus, when oxygen comes in contact with a hot copper-nickel surface, cuprous oxide is initially formed. If heating then continues in the absence of atmospheric oxygen, combined oxygen may diffuse into the alloy, forming a subscale of nickel oxide in a matrix of copper. Beyond a certain concentration of nickel, the compacting of nickel oxide particles caused by the segregation of copper will provide a barrier to oxidation. Such a corrosion peak is found at about 70/30 copper-nickel. Monel (40/60) was found relatively immune from attack.

Exfoliation might thus be prevented by excluding the oxygen, using octadecylamine as a corrosion inhibitor, or retubing with Monel, 90/10 copper-nickel, or mild steel.

41. "Selection and Design of Closed Feedwater Heaters," A.B. Clemmer, S. Lemezis, ASME Winter Annual Meeting, Chicago, 1965.

This article discusses the details of a procedure used by Westinghouse to design feedwater heaters. There are three criteria in selecting heaters for a power plant:

1. Thermal and hydraulic design must be an optimum balance between beneficial effect on plant efficiency and capital investment in each heater and its appurtenances.

2. Absolute reliability of mechanical design and construction is targeted. A heater that is out of service contributes nothing to plant efficiency and upsets steam and condensate flow patterns through

the plant, while continuing to absorb its full share of amortization charges.

3. There must be no deleterious effect on performance of other plant components due to its operation. This point is mainly concerned with a choice of tube materials consistent with good boiler operation under the particular condensate treatment selected, although the handling of heater vents and drains can exert an influence on the operability of the plant.

The thermal and hydraulic design is done by computer and has as its aim the definition of combinations of surface area, number of tubes, number of passes, water velocity through tubes, and distribution of surface between heater sections that will do the specified job. Each such contribution will be embodied in a physical structure, and economic optimization then revolves around choosing the structure that will result in minimum revenue requirements under the evaluation rules that apply to the entire power plant of which the heater will be a part. The prime variable for differentiating a series of designs, all of which are given the same thermal performance, is the choice of water velocity in the tubes.

42. "Turbine Reliability Hinges on Steam Purity," S.D. Strauss, Power, November 1979, pp. S-22 - S-25.

Although this article focuses on turbine problems, it also contains results of a survey of feedwater treatment practices at 51 fossil-fueled power plants. The survey shows the concentration of sodium, silica, sulfates, chlorides, nitrates, and dissolved oxygen, and the conductivity and pH of the feedwater at each plant. This information may be useful in correlating feedwater heater corrosion problems reported by utilities in our survey.

43. "Improving Plant Performance," Bob Schwieger, Power, November 1979, pp. S-8 - S-9.

This article summarizes the results of Power's 1979 fossil-fueled central station survey. A current trend is to use Type 304 stainless steel tubes in low-pressure feedwater heaters. At least one architect/engineer thinks the material performs so well that it recommends selection of a pressure rating for the high-pressure circuit to accomodate the use of stainless there also. (At pressures above 4000 psig to 4500 psig, carbon steel is more economical than stainless.) There has also been a trend to locate the lowest pressure heater in the condenser neck.

44. "AEP Succeeds with Large New Units," Electrical World, August 1, 1976, pp. 28-33.

This article describes the design and performance of American Electric Power's new 1300 MWe coal-fired units. Eight stages of regenerative feedwater heating raise feedwater temperature before entry into the steam generator. All heaters, with the exception of the fifth-stage deaerator, are shell and tube design. The Struthers-Wells LP heaters are arranged in two parallel paths of four heaters. The Foster-Wheeler HP heaters are arranged in three parallel paths of three heaters. With this design (Foster Wheeler), the unit can operate at full load, even when one string of LP and HP heaters is out of service. All heaters are installed horizontally and drain in a cascading arrangement. The HP heater drains can be returned to the condenser through an alternate drain piping arrangement. The carbon steel HP heater tubes underwent extensive quality-assurance tests and examinations to minimize tube leaks and tube-to-tubesheet weld failures. They were eddy current and ultrasonically examined prior to bending, and then they were stress relieved. After tubes were welded to tubesheets, they were explosively expanded with stainless steel inserts.

45. "Economics of Feedwater Heater Replacement," T.H. Fehring and R.A. Gaggioli, Transactions of the ASME, Journal of Engineering for Power, July 1977, pp. 482-489.

As feedwater heaters age, performance deteriorates and leaks invariably occur. In order to keep the heater functioning properly, and to avoid the possibility of water backing into the turbine and causing damage, the leaking tubes are plugged. Usually, the initially plugged tubes cause small, if any, deterioration of performance. Eventually, the number of plugged tubes will affect the overall cycle efficiency. This paper presents a straightforward method for calculating the economical time for repair or replacement without the need for extensive heat balance calculations or special rules of thumb. While the analysis presented here, based on the useful energy concept (i.e., Second Law analysis), is used to solve an operating problem, the same methods can be readily applied at the design stage, and can be used on any other component in the power cycle as well.

46. "Operating Economics and Unit Availability," R.W. Sarau, ASME-IEEE Joint Power Generation Conference, Long Beach, California, 1977.

Feedwater heaters, specifically high-pressure heaters, have been troublesome items in higher pressure units. Their performance can seriously alter the unit heat rate when it becomes necessary to remove them from service. This effect can cause an increase in the heat rate curve and also could cause a compounding effect by limiting unit generation because of boiler or turbine considerations.

Examination of a typical unit shows an increase of approximately 2% in station heat rate by removal of two high-pressure heaters from a string of four. Should it become necessary to remove all high-pressure heaters from service, the turbine-generator load typically would be severely limited. The problem of feedwater heater tube failures is aggravated by the fact that online repairs are frequently impossible to accomplish because of the inability to isolate the heaters on either the water or steam side and effectively bypass the malfunctioning heater from service. While it is of the utmost necessity to assure that all reasonable measures are taken to maintain operating units at their optimum heat rates, these results are overshadowed by even minor increases in unit outage times. Availability and reliability are still the dominant influences in determining the operating economics of units.

47. "High Pressure Single-Housing Collector Preheaters for the 800 MW Power Unit," Ya. L. Polynovskii, Soviet Power Engineering, No. 9, September 1977, pp. 540-543.

The article describes the design of a high-pressure feedwater heater for 800 MWe - 1200 MWe power units. The heaters employ single plant multi-tube spiral coils in a single housing. The design has advantages over the present two-housing heaters with single plane, single tube coils.

48. "Don't Replace That Old Feedwater Heater, Rebuild It," Electric Light and Power, January 1979.

This article describes the procedure used by Quabbin Industries to rebuild damaged feedwater heaters. In one job, a 49-foot low-pressure heater was repaired and reinstalled in five weeks. The original shell and hemispherical head were salvaged, but the tubes were replaced with Type 304 stainless steel and the heater was rebuilt six feet longer. The rebuilt heater cost 63.5% of the cost of a replacement.

49. "Thermodynamic Design of Reliable Economically Optimal Feedheaters," H. Riegger, Brown-Boveri Review, Vol. 65, August 1978, pp. 529-535.

The economically sound design of a feedwater heater is possible if the following parameters are known:

- Anticipated mode of operation (base, medium, or peak load, frequency of start-up).
- Parity factor -- i.e., capitalized value of changes in heat consumption.

The following values then can be optimized:

- Terminal temperature difference of the condensation section and terminal temperature difference of heater with integral desuperheaters.
- Terminal temperature difference of the subcooling zone.
- Feedwater velocity in the heater tubes.
- Diameter of heater tubes.

If the desuperheater is not of the correct size, condensation on its surface will commence at the point at which the temperature of the tube wall reaches the local saturation temperature. If the steam velocity in the desuperheater is relatively high as well, with certain tube materials, erosion-corrosion can be expected. It may happen that the steam temperature required at the superheater outlet is not available even at the inlet, in which case a desuperheating zone is not practical. Erosion-corrosion damage may also occur outside the desuperheating zone, especially at those points where the steam leaving the desuperheating zone at a considerable velocity impinges upon the moist surface of the condensation zone. To prevent this, the steam outlet from the last desuperheating reversing chamber is designed to ensure that the inlet steam velocity into the condensation surface is minimal and any collision of the two flowing phases is avoided. Also, the ring gap velocity is maintained within proven limits and selected according to the arrangement, tube material, and heater size.

The following parameters are taken into account when optimizing the desuperheater:

- The theoretically possible feedwater temperature rise in the desuperheater.
- The loss in pressure caused by the steam velocity in the desuperheating zone, and the associated reduction in power output.
- The required heating surface of the desuperheating zone.
- The permissible ring gap velocity at the outlet from the last chamber of the desuperheating zone.

A computer is used to establish the economically optimal desuperheating design, terminal temperature difference in the subcooling zone, feedwater velocity, and tube diameter. Results thus far have show that:

- With increasing heater sizes and with LP heaters, larger tube diameters are more economical.
- The optimal solution often depends on the tube material.
- With HP heaters of a conventional plant having carbon steel tubes welded to the plates, the optimal velocity is higher than with the other heaters.
- The optimal velocities are always below the limits of tube inlet erosion.
- Considerable economic losses may result from the application of very low velocities such as are frequently specified by customers.

50. "Reliable Drain Coolers for Feedwater Heating," H. Riegger and J. Wochele, Brown-Boveri Review, Vol. 65, August 1978, pp. 536-540.

Subcooling zones are often provided in feedheater stages with large amounts of drain so as to improve thermodynamic efficiency. Technical operating problems with drain coolers include local flashing of the condensate in the drain cooler, steam penetration into the drain cooling zone, and backflow of entrained moisture into the turbine after a turbine trip. Flow-related flashing is prevented by a suitable design based on calculations that ensure that the cooling down of condensate is in keeping with the pressure drop. Baffles welded tight to the subcooler shell prevent internal leakage at this point. Small ring gaps and low condensate pressure differences ensure that the resulting leakage lies within controllable limits. Of the numerous types of subcooler designs, Brown-Boveri prefers those with drain coolers flooded on the condensate side.

51. "Thermodynamic and Economically Sound Design of Feedheating Equipment," J. Schwander, Brown-Boveri Review, Vol. 65, August 1978, pp. 523-528.

This article discusses the thermodynamic effect of drain coolers and drain pumps at individual feedwater heaters, cross-connected desuperheaters, drain coolers for the condensate from the reheater, and two-stage reheaters. Knowledge of the parity factors or, where appropriate, of the valuation of increase of capacity, as well as of the capital cost of the equipment, allows one to determine if an arrangement is economically sound. It is concluded that drain coolers are generally logical, except at the highest high-pressure heater and the highest low-pressure heater. Drain pumps should generally be useful at one or two feedwater heating stages. A cross-connected desuperheater near the end of the feed train pump pays for itself only in particular cases and with expensive fuel.

52. "Report on Explosion Plugs in Feedwater Heaters," R.H. Noe, et al., Public Service Electric and Gas Co., January 1979.

The technique of explosion weld plugging tubes in feedwater heaters and heat exchangers is recommended selectively for tube-end weld configurations that are not conducive to secondary failures. Tapered plugs have been used many times in low and moderate pressure heat exchangers only. The main deficiency is man-made, i.e., the plugs are being driven into the tubesheet with such a force so as to crack the tubesheet ligaments.

Roller expanded plugs have been mostly used for low- and moderate-pressure exchangers. The Public Service Electric and Gas Company (PSE&G) has also used them in HP heaters inside the tubesheet in addition to the welded plugs at the face of the tubesheet when cracked ligaments, or worm-holed ligaments, or both exist.

A single plug of a shape that allows expansion, carefully welded at the edge to a sound clean base metal, has resulted in trouble-free, permanent tube end repair. A welded plug or a cluster of plugs that form a massive, rigid welded area have developed peripheral weld cracks, or ligament cracks, or both.

Fifty-seven plugs detonated by technicians in HP heaters in two PSE&G plants have been successfully bonded to the tubesheet metal. Reaming out a portion of the failed tube from the tubesheet hole is usually a necessity. Rolling a portion of the tube at the back of the tubesheet is a requirement to prevent vibration of the failed tube.

The advantages of explosively welded plugs are:

- They can be located and detonated at any place within the tubesheet.
- Only one type of plug material (nickel) is required to plug any tube or tubesheet material.
- Bonding takes place between dissimilar metals without disturbing the inherent characteristics of either metal.

Disadvantages are:

- The reaming of adjacent tube-weld roll-over to permit insertion of protective tapered half-round rods has sometimes caused secondary tube failures.
- The technique, while simple, requires specialized, licensed personnel. It may often be difficult to obtain prompt service, particularly during a forced outage.

53. "Explosive Forming Speeds In Place Retubing of Feedwater Heaters," F.J. Locke, et al., Power, September 1978, pp. 84-85.

It is difficult to install feedwater heater replacement tubes in the field using conventional tube rolling methods. An alternate method of replacing feedwater heater tubes is with the use of a technique known as kinetic expansion. This technique allows work in limited access situations, offers less risk of tube or tubesheet damage, and requires a shorter time to complete. It was used in the retubing of the low-pressure feedwater heaters on two 100-MWe units at Detroit Edison's Conners' Creek plant. First, testing was done on representative tube samples to obtain information on insert parameters that would yield a pressure-tight connection. In the case of stainless steel tubing, it was necessary to cut concentric grooves in the tubesheet holes, so the tube material would flow into the grooves to form a tight seal and provide additional pull-out strength. A shock-absorption box was fabricated and installed around the end of the heater after the flanged waterbox cover was removed. Each charge consisted of a 12-15 inch length of detonating cord encased in a polyethylene cylinder.

When subjected to a thermal transient possibly more severe than would be experienced by an operating feedwater heater, all kinetically expanded joints remained pressure-tight. It was possible to achieve 160 tube-end expansions per hour, a significant savings in outage time and replacement expense.

54. "Standards for Closed Feedwater Heaters," Heater Exchanger Institute, Third Edition, 1979.

This standard provides practical information on nomenclature, dimensions, testing, and performance of closed feedwater heaters. Included are recommended maximum tube side and steam side velocities, maximum shell side pressure drop, maximum temperatures, methods to determine nozzle loads, material specifications, heater protective measures, and installation, inspection, cleaning and maintenance procedures.

55. "Closed Feedwater Heaters - Performance Test Code," ANSI/ASME, PTC 12.1 - 1978.

This code provides rules for determining the performance of a closed feedwater heater with regard to terminal temperature difference, temperature rise of feedwater, approach, pressure drops, and amount of non-condensables in drains.

56. "Feedwater Heater Workshop Proceedings," Section 2, Discussion Summary, EPRI WS-78-133, Electric Power Research Institute and Joseph Oat Corporation, New Orleans, March 13-14, 1979.

Although this workshop focused on nuclear plant feedwater heaters, many of the findings are applicable to fossil plants as well. Brief summaries of the findings of the five working groups are summarized below.

Current Design Standards

This group concluded that the Heat Exchanger Institute (HEI) standards for feedwater heaters are inadequate. Some specific deficiencies are that the HEI standards:

- Have inadequate tubesheet design formulas;
- Do not lay down a sound practice for attachment of impingement plates;
- Give no rules for sizing the thickness of pass partition plates;
- Do not specify significant design dimensions such as clearance between baffles and shells;
- May be specifying a maximum flow velocity that is too high;
- Do not provide design rules for calculating thermal stress in U-tube bends;
- Do not provide guidelines for proper plug installation;
- Do not address the subject of the thermal design of feedwater heaters.

Causes and Impact of Vibration

This group developed a simplified mathematical description of the tube vibration mechanisms of vortex shedding and fluidelastic whirling. It was recommended that the work undertaken by Heat Transfer Research, Inc. (HTRI) and Argonne National

Laboratories in this area be reviewed, that a data bank on flow induced vibration problems be established, that a test facility be set up to study the problem, and that further work in the area of baffle damage be pursued. A paper was presented that discussed the various methods available for designing against tube vibration damage.

Materials Selection/Corrosion

This group deduced that impingement baffle problems are a design standard deficiency rather than a materials problem. The major problem in existing tube-to-tubesheet combinations appears to be in welding carbon steel tubes to low-carbon steel weld overlay. Problems experienced with drain coolers and seal plates could be alleviated with design guidelines rather than with material changes. Finally, recommendations were developed for tube plug materials.

Layout Considerations/Design Specifications

This group concluded that the preferred method of installation from the utility viewpoint is to have all heaters horizontal and to have the lowest pressure heaters installed in the condenser neck. Specifications should include detailed material descriptions, all anticipated operating conditions, mechanical design criteria (such as drain connection locations, velocity criteria, venting requirements, and criteria for head accessibility), nozzle head requirements, customized operating manual, and heater storage criteria. Further research was recommended in the areas of two-phase flow/flashing in the drain cooling section, heat transfer coefficients, modeling of channel head and nozzle locations, level controller tapping point, and support, tube, and ligament spacings.

Operating and Maintenance Experiences and Heater Protection

This group identified 17 problems and solutions at operating plants, such as the following:

- Use of Inconel 82 overlay reduces leak potential for welding of carbon steel tubesheets.
- There is insufficient experience on drain cooler inlet designs.
- Users need a data base for identification of trouble areas to review vendor designs.

- There is a need for better justification for sizing of vents.
- One fix for inlet tube erosion was placing a perforated baffle ahead of the tubesheet (at the expense of increased tubeside pressure loss).
- Users need improved performance monitoring over existing terminal differences.
- Dry air is the preferred method for heater lay-up.

57. "Feedwater Heater Design Standards and Practices," A. Brothman, Feedwater Heater Workshop Proceedings, EPRI WS-78-133, Electric Power Research Institute and Joseph Oat Corporation, New Orleans, Louisiana, March 13-14, 1979.

This paper discusses the problems that can occur in feedwater heaters and recommends design practices to alleviate the problems. Feedwater heaters can be designed for high reliability provided that:

- Heater specifications provide adequate service information and do not urge design criteria that impair rational design;
- Upgraded design practices are applied to design of the heater's pressure envelope members;
- Upgraded and analytical methods are used to anticipate and avoid bundle vibration, thermal strain, and hydraulic problems; and
- Manufacturing and quality assurance programs are rigorously formulated and implemented.

In general, the suggested design and analytical methods are more sophisticated than presently required by HEI standards, TEMA standards, or the ASME Pressure Vessel Code. Specific recommendations are made concerning:

- Calculating tubesheet stresses,
- Calculating flange stresses,
- Determining gasket width,
- Using welded seal diaphragms, rather than conventional gasketed joints,
- Estimating vibration risk,
- Predicting thermal strain problems,
- Eliminating drain cooler cavitation hazards.

Finally, it is noted that the risk of some heater problems may actually be greater at low loads than at overloads. Therefore, adequate design specifications must establish the duty range of the heater from partial to overload conditions.

58. "Causes and Impact of Tube Vibration in Feedwater Heaters," W.T. Powell, Feedwater Heater Workshop Proceedings, EPRI WS-78-133, Electric Power Research Institute and Joseph Oat Corporation, New Orleans, Louisiana, March 13-14, 1979.

Tube failures due to vibration occur in two basic modes. One is large amplitude vibration resulting in the tubes contacting each other sufficiently to cause thinning, which most often occurs in the desuperheater zone. The other mode, which occurs where the fluid density is high, such as in the drain cooler section, is a high-frequency fretting or chafing against adjacent tubes or tube support points. Tube vibration problems have become more prevalent in past years because the tendency of utilities to chose equipment strictly on capital cost considerations has resulted in equipment designed with minimal design margin. Equipment designers must become more familiar with the various flow-induced vibration characteristic of their specific equipment. The installation of accelerometers on operating tubes is recommended to obtain insight into actual fluid flow conditions.

59. "A Design Procedure for Minimizing Tube Vibration Damage in High Pressure Feedwater Heaters," J.F. Sebald, Feedwater Heater Workshop Proceedings, EPRI WS-78-133, Electric Power Research Institute and Joseph Oat Corporation, New Orleans, Louisiana, March 13-14, 1979.

Damaging vibration is one of the common causes of feedwater heater tube failure. In feedwater heaters, tube failure from fretting in the support baffles seems to have a significantly higher incidence than failure from fretting at mid-span. The effect of lift on the tubes usually predominates, while the effect of drag has less significance. An example of an order of magnitude engineering analysis is given for a heater with vibration problems (X) and one without (Y). The calculated results showed that mid-span tube contact would be present in almost all flow zones of heater X but none in heater Y. It is felt that the simple analytical method shown can be used to deal effectively with feedwater heater tube vibration problems. However, research is needed to develop more precise values of the lift coefficient.

60. "Service History of Monel Alloy 400 In High Pressure Feedwater Heaters," Dennis Rahoi, Feedwater Heater Workshop Proceedings, EPRI WS-78-133, Electric Power Research Institute and Joseph Oat Corporation, New Orleans, Louisiana, March 13-14, 1979.

For the thirty-five years of service and the 70 million feet of Monel 400 tubing installed in high-pressure feedwater heaters, very few failures have occurred. Early problems with stress corrosion were corrected by changes in the manufacturing methods resulting in lower residual stresses. Residual hoop stresses vary widely, depending on the method of straightening.

61. "Feedwater Heaters - How to Specify Them," C.F. Andreone, Feedwater Heater Workshop Proceedings, EPRI WS-78-133, Electric Power Research Institute and Joseph Oat Corporation, New Orleans, Louisiana, March 13-14, 1979.

The engineer writing the specifications must carefully consider whether downstream heaters will be overloaded due to bypassing of the heater being specified. He must decide whether heaters will be horizontal or vertical. Horizontal heaters have certain advantages, including better level control, easier inspection and maintenance, and more efficient condensing zone heat transfer surface. The user should review the operating manual prepared by the manufacturer to ensure that all necessary details are included.

62. "Heater Drain Systems," A.L. Cahn, Feedwater Heater Workshop Proceedings, EPRI WS-78-133, Electric Power Research Institute and Joseph Oat Corporation, New Orleans, Louisiana, March 13-14, 1979.

This paper addresses the problem of flashing in drain lines. A general method is outlined for sizing the drain system using the critical end pressure formula. Erosion problems are prevented by ensuring that the momentum force on any elbow is less than 75 pounds.

63. "Heater Protection From the Design Engineer's Point of View," W. Schlechtriem and H. Parussel, Feedwater Heater Workshop Proceedings, EPRI WS-78-133, Electric Power Research Institute and Joseph Oat Corporation, New Orleans, Louisiana, March 13-14, 1979.

This article describes in general the viewpoint of the European feedwater heater design engineer. The design engineer must ensure that all abnormal operating conditions are considered in the design. Materials used predominantly in Europe for tubes are carbon steels or low carbon alloy steel. Tubes are attached by electric arc welding; only LP heater tubes are expanded. Typically a water velocity of approximately 2m/sec is used. Strict quality control procedures are used during manufacturing. When construction and testing is complete, the heaters is dried and filled with nitrogen at 8 psig. Recently several users have employed a dehumidifier system instead.

Spring loaded direct acting safety valves are installed on the shell side and are sized for the worst case steam input conditions. When two strings of heaters are used, condensate level control valves must be sized for a larger range to accomodate full flow through one string.

A guaranteed residual oxygen content of .005 mg/kg is common. For alkaline mode of operation ammonia is metered into the water to achieve a pH of 9-9.5, which is usually the point at which erosion-corrosion is no longer expected. The residual oxygen is chemically bound by the introduction of hydrazine. All this is to achieve the formation of a protective magnetic layer (Fe, O_4).

Surveillance of temperatures and pressures, in some cases using a computer aids in recognizing failure modes. Access must be provided in the design to permit ease of periodic tests and maintenance. The feedwater pipeline must be protected against overpressure by safety valves. Level controllers as well as water loops are used for controlling condensate. High level alarms should be provided.

64. "Tubesheet Failure in a High Pressure Feedwater Heater -- Monroe Power Plant," P.E. Heidman, Feedwater Heater Workshop Proceedings, EPRI WS-78-133, Electric Power Research Institute and Joseph Oat Corporation, New Orleans, Louisiana, March 13-14, 1979.

In 1978, a washout of a high pressure feedwater heater tube sheet occurred at Detroit Edision's 800 MS coal fired Monroe Power Plant - Unit 2. The heater was removed from service and inspected by Foster-Wheeler. It was determined that the failure was initiated by a small leak in the return section of a U-tube. Improper plugging procedures in conjunction with faulty isolation valves created a condition which allowed high pressure feedwater to find a leak-path between the tube O.D. and the tube sheet hole. The subsequent worm-holing destroyed the tube sheet ligaments and caused the ultimate failure of the heater.

65. "Design and Operating Experience for Header-Type Feedwater Heaters for Large Power Plants," Walter Schlechtriem, Feedwater Heater Workshop Proceedings, EPRI WS-78-133, Electric Power Research Institute and Joseph Oat Corporation, New Orleans, Louisiana, March 13-14, 1979.

Header-type HP feedwater heaters are commonly used in Europe and have definite advantages over the channel type HP heaters. Whereas the channel type requires very thick tubesheets that can represent serious thermal problems, the header type has a rather uniform distribution of material due to the fact that the two headers and the tubes are arranged in the proven form that has been used in boiler manufacture for many years. The arrangement of the header type is more flexible, and the thermal performance is superior. The use of carbon steel tubes is largely accepted in Europe. The typical problem with the water chambers and the separation of the water flow in the head of the channel heater are conveniently solved by using the headers for water entry and exit. The headers have relatively thin walls and the welding connection between tube bundles and header can be achieved with provem welding methods.

66. "Thermal Stresses in the Tube Sheets of High Pressure Heaters," A. Sonnenmoser, Feedwater HEater Workshop Proceedings, EPRI WS-78-133, Electric Power Research Institute and Joseph Oat Corporation, New Orleans, Louisiana, March 13-14, 1979.

This article presents the results of thermal stress analyses of high pressure feedwater heater tubesheets. It was found that in steady state operation the highest stresses in the tubesheets occur at the edges of the outermost holes on either side of the diametral lave. These stresses are in practical terms independent of the thickness of the tubesheet. The highest stresses under transient operating conditions occur at the tube inlet rims when the heating or cooling time is very short (0 to 1 second). With longer heating or cooling times, the maximum stresses occur in the edges of the holes adjacent to the unperforated peripheral areas and in the corner holes of the tube pattern. These stresses are also practically independent of the tubesheet thickness.

67. "Operational Experiences and Repair Possibilities of Feedwater Heaters," A. Heinz, Der Maschinenschader, Vol. 45, No. 6, pp. 209-217.

This article presents the results of a survey of 122 high-pressure heaters in 20 German fossil-fired power plants. Various types of failures are described, including tube failures due to manufacturing defects, inlet tube-end erosion-corrosion, steam-side erosion-corrosion of tubes, tube-to-tubesheet weld leaks, leaks between tube and header, and cracked inlet and outlet nozzles.

Two types of heaters are prevalent in Germany: heaters with U-tubes welded into a tubesheet, and heaters with separate inlet and outlet headers. Both horizontal and vertical heaters are common. All of the heaters investigated were put into service between the years 1954 and 1966. Practically all of the damage occurred after less than 50,000 operating hours.

Erosion-corrosion on the water side of tubes can be expected when the velocity exceeds 2 m/sec. Pure corrosion rarely occurs on the steam side; more often it is a case of erosion-corrosion.

For U-tube heaters, tube-to-tubesheet welds have a high failure rate. The actual cause can rarely be determined because the initial damage is washed away during continued operation. For header-type heaters, leaks often within the first 1000 operating hours. Sometimes the tube breaks completely free from the header.

Another common problem is thermal stresses that cause failure of the weld between the partition plate and the water inlet chamber. Cracks in heads have also been discovered. Checking for cracks is highly recommended for heaters that have undergone repair.

Of the 122 HP heaters evaluated, 115 incidents of damage were discovered. Of these, 67% affected the tubes and 33% affected the water inlet chambers.

68. "Thermodynamic and Economic Analyses of Closed Feedwater Heaters for Supercritical Pressure Steam Turbine Cycles," Paul Leung and Raymond E. Moore, ASME Winter Annual Meeting, November 1967.

This paper presents an engineering and economic study leading to an optimum balance of performance and cost for closed feedwater heaters in an 800 MWe supercritical steam turbine cycle. The change in heat rate from varying the terminal temperature difference and the approach temperature difference of each feedwater heater in the cycle is calculated. The economic optimization is then performed by comparing the costs of the heaters at various performance levels to the costs of power generation at the various corresponding heat rates. It is concluded that the first point (highest pressure extraction point) heater has the most significant effect on turbine heat rate, steam flows, and final feedwater temperature. Each degree of variation in terminal temperature difference affects the heat rate by about 1.9, 0.45, 0.5, 0.45, 0.9, and 0.5 Btu/KWh for the first, second, third, fifth, six, and seventh point heaters, respectively. (The fourth point heater is the deaerator.) For all heaters, approach temperature difference selection has a relatively small effect on the cycle, both thermodynamically and economically. From both the economic and the heater design aspects, it appears that approach temperature differences less than +10^{o}F would seldom be justified.

69. "Corrosion Experience with Carbon-Steel Tubed Feedwater Heaters," R. R. Noe, H. W. Peterson, and L. J. Wyzalek, presented at American Power Conference, Chicago, April 1968.

This report describes the field and laboratory investigations conducted by Worthington Corporation on corrosion-erosion attacks in carbon-steel-tubed feedwter heaters. On the feedwter side, corrosion was attributed to:

- Deposits: Copper deposits from elsewhere in the feedwater system deposited on the surface of the tubesheet and accelerated pitting corrosion.
- Stress Concentration: Highly stressed areas within the channel and inside tubes suffered accelerated pitting corrosion.
- Stress Concentration: Highly stressed areas within the channel and inside tubes suffered accelerated corrosion.
- Velocities: High tube approach velocities caused by vortexes in the inlet channel led to inlet end corrosion. Flow distributions can decrease the intensity or completely eliminate these vortexes.
- Dissolved Oxygen: Inlet end tube wastage was most severe in units without deaerators in which heaters are not bypassed during periods of startup, shutdown, or light loads. During these periods, dissolved oxygen has not reached acceptable levels, and even stainless steel inserts would not provide protection.
- Temperature and pH: Inlet end corrosion-erosion occurs only in feedwater heaters operating in the 300°F to 400°F range and where the pH was below 9.0 for significant operating periods.
- Improper Care: Frequent shutdowns, during which the internal surfaces of tubes are exposed to an uncontrolled atmosphere without rapid drying, leads to tube deterioration.

On the steam side, the modes of corrosion attack among the three zones. In the desuperheating zone, corrosion attacks of the "fretting" and/or "fatigue" type can occur. These results from the combined action of corrosion and vibration-induced cyclic stress. In the condensing zone, corrosion generally did not occur. Occasionally, evidence of corrosion-erosion was found, which was attributed to areas of high local velocities where bundle to shell clearances were too restrictive to keep velocities from exceeding the corrosion threshold of 130 fps. In the subcooling zone, fretting and/or fatigue type corrosion was observed at the drain cooler suction inlet where operating conditions or system design produced flashing of condensate within the subcooling zone.

70. "Feedwater Heater Desuperheater Vibration Analysis," H. Wightman, Struthers-Wells Corporation.

A method for analyzing for vibration caused by fluidelastic whirling in the tube bundles of integral desuperheaters in feedwater heaters is presented. The method consists of calculating the actual steam crossflow velocities as a function of different baffle configurations, calculating the mode and natural frequencies of each typically supported tube, calculating the critical crossflow velocity (V_{crit}) at which fluidelastic whirling induced vibration will begin, and weighing the actual velocities and the natural frequencies, including amplitudes, to establish an effective crossflow velocity (V_{eff}). A V_{eff}/V_{crit} ratio is established, and comments are made relative to the design margins.

71. "Environmental Effects in the Design and Operation of Feedwater Heaters," F.X. Brown and W.T. Lindsay, Jr., presented at 29th Annual Meeting of the American Power Conference, Chicago, April 1967.

This article presents a general discussion of the mechanical and chemical aspects of the feedwater heater environment. Many problems, such as inlet end erosion and tube-to-tubesheet joint failures, do not fit neatly into either the mechanical or chemical areas. The authors recommend the following for feedwater heater operation:

1. High rate, high percentage internal demineralization.
2. Control pH at approximately 9.5 with cyclohexylamine for carbon steel tubed systems.
3. Good deaeration early in the cycle and good air leakage control.
4. Chemical oxygen scavenging with hydrazine only, added at a level only a few ppb in excess of the stoichiometric amounts required by oxygen after deaeration.
5. Use of the same materials for both high-pressure and low-pressure heaters.
6. Elimination of boiler solids carryover.
7. Absolute prevention of any possibility of mercury contamination of the system when copper-alloy materials are present.
8. Proper make-up purification.
9. Continuous venting of the vapor side of the heaters without cascading.

72. "A review of Operating Experiences and Design Criteria of Closed Feedwater Heaters," Heat Exchange Institute, January 30, 1967.

This article documents a presentation given by the Feedwater Heater Section of the Heat Exchange Institute to the Edison Electric Institute. The problem areas discussed in the formal presentation were tube materials, nil-ductility transition temperature, and piping reactions. It was noted that corrosion in carbon steel tubes is most severe when the pH is in the range of 8.5 to 9.0. The severity of attack is continually less as pH level increases, and attack is non-existent at the 9.6 level, provided adequate precautions have been taken to maintain low levels of oxygen and residual hydrazine. It was also noted that carbon steel tubed feedwater heaters in Europe have remained relatively trouble-free, perhaps because feedwater velocity within the tubes is limited to 6 ft/sec. Heaters should be individually vented to the deaerator or condenser. Results from a survey of 106 high-pressure feedwater heaters are presented. It was recommended that the Edison Electric Institute initiate a test program to evaluate various materials for feedwater heater service.

With regard to nil-ductility temperature, the Heat Exchange Institute recommends that until such time as definite correlations can be determined between impact and/or drop weight testing and suitability for service that all materials used for pressure parts of feedwater heaters be procured to the requirement of Charpy "V" notch values of 15 ft-lb average for three tests and 10 ft-lb minimum for any one test, at a maximum test temperature of 40°F, provided the test specimen is taken at a location truly representing the material and the maximum stressed direction.

Finally, it is recommended that all piping reactions which are to be taken into consideration in the design of a feedwater heater be included in the purchase specification.

Appendix D

REPORT ON EXPLOSION PLUGS IN

FEEDWATER HEATERS AND HEAT EXCHANGERS

Section 4

GROUP PRESENTATIONS

REPORT ON EXPLOSION PLUGS IN FEEDWATER HEATERS AND HEAT EXCHANGERS

Presented by

Tarlock S. Sahansra*
PUBLIC SERVICE ELECTRIC AND GAS COMPANY

EPRI Feedwater Heater Workshop
March 13-14, 1979
New Orleans, Louisiana

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* Prepared by R.R. Noe , M.W. Costic, and T. S. Sahansra

REPORT ON
EXPLOSION PLUGS
IN
FEEDWATER HEATERS AND HEAT EXCHANGERS

1. ABSTRACT

The technique of explosion weld plugging tubes in feedwater heaters and heat exchangers is sound and recommended selectively for tube-end weld configurations which are not conducive to secondary failures. The need for perfecting the technique to permit its use for all tube-end weld configurations is emphasized.

2. PURPOSE OF THE REPORT

- To determine the merits of the Explosion Tube Plugging technique in feedwater heaters and heat exchangers and its limitations as applied to high pressure feedwater heaters;

- To obtain first hand experience of this technique in anticipation of its need for other more demanding applications, such as Nuclear Steam Generators;

- To offer conclusions and recommendations.

3. INTRODUCTION

Shell and tube feedwater heaters and heat exchangers have been in use for many years and tube failures have been experienced since then. Various techniques have been devised to repair the tube failures. To fully understand the advantages and disadvantages of Explosion weld plugging of tubes, an overview of various tube failure modes and their plugging techniques is first presented.

3.1 Tube End Weld Configurations

Shell and tube feedwater heaters and heat exchangers have the tubes rolled, welded, or welded and rolled in the tubesheet. Mostly the high pressure heaters have their tubes welded and rolled in their tube-sheets, Figure 1, Appendix "A".

Another type of tube weld extensively used in Europe is shown in Figure No. 2, Appendix "A", where the tube is welded at the BACK of the tube-sheet.

A third method shown in Figure No. 3, Appendix "A", involves a drastic departure from the conventional exchanger design - multiple headers, reference 1, and drums, reference 2, Appendix "D" are used instead of a single tube-sheet and a socket or butt weld joins the tubes to the headers.

3.2 Tube Failure Modes

A heater tube failure may take place within the tube itself or at the tube to tube-sheet weld area.

3.2 Tube Failure Modes (Cont'd)

In a U-Tube design, as is the case for most high pressure feedwater heaters and steam generators, a tube failure can take place in any of the following areas: (a) in the U-bend, (b) in the straight portion of the tube outside of the tube-sheet, and (c) in the straight portion of the tube inside the tube-sheet. This condition does not exist where the tubes are welded on the back of the tube-sheets.

Failure at the tube to tube-sheet weld area may vary from pinholes to complete weld separation and damage to the tube-sheet ligament.

Secondary failures may result from fluid impinging upon adjacent tubes and/or tube-sheet ligaments. The probability and severity of secondary failures increase with delay in taking out of service the leaking heater. Photographs in Appendix "E" show various modes of heater failure.

3.3 Tube Plug Types

Several types of tube plugs have been devised, recommended and used in high pressure feedwater heaters and heat exchangers. A few tube plugs are shown in Appendix "B". They can be broadly classified as follows:

3.3.1 Tapered Plug - Figure No. 1, Appendix "B"

Sealing of the tube is obtained by driving a tapered plug into the tube or tube-sheet hole at the tube-sheet. Mechanical sealing is obtained by close contact of metals.

3.3.2 Roller Expanded Plugs - Figure No. 2, Appendix "B"

This plug is in the form of a blind nipple, obtained by machining a bar stock or by plug welding an end of a tubing. To seal a tube the plug is expansion rolled in place by mechanical rollers.

3.3.3 Welded Plug - Figure No. 3, A,B,C,D,E, Appendix "B"

Plugs of various geometries, depending upon preference, experience and hole(s) repair configuration, have been used for years. Recently, as the failure mechanism at the welded plug area has been better understood and its impact upon subsequent failure modes fully realized, a more sophisticated type of plug such as shown in Figure No. 5, Appendix "B" have been used at Public Service Electric and Gas Company, New Jersey.

3.3.4 Explosion Welded Plug - Figure No. 4, Appendix "B"

A cartridge-like plug control-detonated inside a tube or tube-sheet can be metallurgically bonded to it, if performed within specific geometrical arrangement and criteria.

3.3.5 Explosion Expanded Plug

In a process similar to that in 3.3.4 but with a lighter explosive charge, a plug can be kinetically expanded into a tube or a tube-sheet. This process is at present in use for expanding tubes and tube-inserts in tube-sheets.

3.3.6 Seal Plug

Seal plugs have been used for years for plugging condenser and moderate pressure heat exchangers utilizing different packings or seals. With improved materials and novel technology, it is conceivable that higher pressure exchanger tubes could be plugged in this fashion.

3.3.7 Hydraulically Expanded Plug

A nipple type plug hydraulically expanded inside a tube or tube-sheet can be permanently locked in place. This process is at present utilized by a European heat exchangers manufacturer for expanding tubes into tube-sheet.

4. FIELD EXPERIENCE

The experience gained in investigating the cause of tubes and welds failure modes in high pressure feedwater heaters in PSE&G system has provided a better understanding of the deficiencies of the conventional plugs, the limits of the novel plugs and the requirements for the optimum plug.

4. FIELD EXPERIENCE (Cont'd)

The experience with the various plugs is summarized below:

4.1 Tapered Plug

Tapered plugs have been used many times in low and moderate pressure exchangers only. The main deficiency is man-made, i.e., the plugs are being driven into the tube-sheet with such a force so as to crack the tube-sheet ligaments.

4.2 Roller Expanded Plug

They have mostly been used for low and moderate pressure exchangers. PSE&G has used them in high pressure feedwater heaters inside the tube-sheet in addition to the welded plugs at the face of the tube-sheet when cracked and/or worm-holed ligaments existed. (Figure No. 8, Appendix "B").

4.3 Welded Plug

A single plug of a shape which allows expansion, carefully welded at the edge to a sound, clean, base metal has resulted in a trouble free permanent tube-end repair.

A welded plug or cluster of plugs which formed a massive, rigid welded area configuration have, in the past, developed peripheral weld cracks and/or ligament cracks.

4.4 Explosion Welded Plug

57 plugs detonated by competent technicians in high pressure feedwater heaters in two PSE&G generating stations have been successfully bonded to the tube-sheet metal,

Additional two plugs detonated in these heaters leaked during the test,

Four secondary tube failures resulted from reaming the weld roll over in the tubes adjacent to the failed tube. For details, see Appendix "C".

5. OBSERVATIONS

Based upon our field experience, the following observations are made:

5.1 The type and extent of tube failure is to be individually determined.

5.2 The choice of tube or tube-sheet hole plugging is to be based on findings and experience.

5.3 Trained personnel experienced in both heat exchanger and explosion welding technique are to be used.

5.4 Reaming out a portion of the failed tube from the tube-sheet hole is, most of the time, a necessity.

5.5 Rolling a portion of the tube at the back of the tube-sheet is a requirement to prevent vibration of the failed tube(s).

5.6 A combination of explosion welded plug(s) on one end and conventional/novel welded plug(s) on the other end of the tube(s) is a distinct possibility where damaged ligaments exist.

5.7 The need for proper preparation of the explosion plug welding area is as important as in conventional welding.

5.8 The process is time consuming when the tube weld-end configuration is at the face of the tube-sheet.

5.9 The ligaments adjacent to the tube to be plugged are to be protected.

5.10 The insertion of tapered half-round rods in the tubes adjacent to the failed tube, many a time, requires reaming the tube-end weld when weld roll-over is present.

5.11 The reaming performed as per paragraph 5.10 can and has resulted in secondary tube-end failures.

6. ANALYSIS

6.1 Advantages

6.1.1 Explosive plug can be located and detonated at any place within the tube-sheet.

6.1.2 Only one type and material (nickel) plug is required to plug any tube or tube-sheet material.

6.1.3 Bonding takes place between dissimilar metals without disturbing the inherent characteristics of either metal.

6.2 Disadvantages

6.2.1 The reaming of adjacent tube-weld roll-over to permit insertion of protective tapered half-round rods has caused in some instances, secondary tube failures.

6.2.2 The technique while simple, requires specialized, licensed personnel. It may often be difficult to obtain prompt service, particularly during a forced outage.

7. DISCUSSION

All tube plugs have inherent limitations and deficiencies as indicated before. It is unfortunate that historically little attention has been paid to the tube failure location and mode. The attainment of this information is never an easy task, but it is essential for proper analysis and best cure, starting with the very first step which is the plugging of the very first tube.

The following discussion will further clarify these points:

7.1 Conventional Plug

When tube failure occurs at the U-bend region or within the straight portion of the tube outside the tube-sheet, it is, at times, adequate to plug the inside of the tube itself. This is true when no damage to the tube-sheet ligaments has been done. Knowlege of the location and the nature of the tube(s) failure will be a help in taking remedial measures, starting with the selection of tube plug type and the technique.

7.1.1 A tube failure within the straight portion of the tube inside the tube-sheet requires, most likely, the removal of a portion of the tube and the plugging of the tubesheet hole itself. Unfortunately, with a tube failure of this mode, very often, secondary ligament failures occur which require close scrutiny and sound judgment before plugging and/or repairing. More than one tube repair is, at times, required. The end result may be a cluster or a ridge of tubes plugged. This condition, as shown in Figure No. 6, Appendix "B", is also brought about by the industry and utility practice of "Safety" or "Insurance" or "Guard" plugging of feedwater heater tubes adjacent to a repaired tube, to preclude a second premature tube failure. This practice of "Safety" plugging has been discontinued at PSE&G since the adoption of the individual tube tester.

7.1.2 A tube end to tube-sheet weld area failure most likely requires the removal of a portion of the tube and the plugging of the tube-sheet hole, as described in paragraph 7.1.1.

7.1.3 Repair of multiple tube failure in a cluster or as a contiguous ridge produces a massive welded tube area at the face of the tube-sheet which, by its nature, is very rigid. Differential temperatures at the confines of this area does exist as the plugged tubes are not cooled by the feedwater but get heated by the hot desuperheater steam. Several hundred degrees temperature differential between the desuperheater steam and the feedwater temperatures is not uncommon. The end result is the cracking of the tube end repair welds and/or ligaments adjacent to these repairs in a never ending cancerous process. PSE&G has experienced this type of failures in the No. 28 high pressure feedwater heater at Linden Generating Station and No. 18 high pressure feedwater heater at Bergen Generating Station. Both heaters were condemned and removed from service. Photograph Nos. 1, 2, 3, and 4 Appendix "E" show details of this condition.

7.2 Novel Plugs

7.2.1 "Flower" Plug

"Flower" plugs similar to the one shown in Figure No. 5, Appendix "B", were developed by PSE&G and utilized in No. 78 high pressure feedwater heater at Kearny Generating Station; high pressure feedwater heater No. 16 at Hudson Generating Station - photograph No. 7, Appendix "E"; and at Bergen Generating Station No. 17 high pressure heater - photograph No. 7, Appendix "B". The degree of flexibility present at the plug periphery offers a better chance of withstanding its thermal expansion.

7.2.1 "Flower" Plug (Cont'd)

Because of worn out ligaments in heater No. 16 at Hudson Generating Station a flower plug was used to plug the cluster of failed tubes on one end and explosive plugs on the other.

7.2.2 Explosion Welded Plug

Since an explosion welded plug can be located anywhere within the tube-sheet hole, large temperature differential across the plugged hole can be avoided by welding this plug near the back of the tube-sheet. Explosion welded plugs can also be used in conjunction with other novel plugs.

7.2.3 Explosion Expanded Plug, Seal Welded plug and Hydraulically Expanded Plug

Opportunities are present in the above types of plugs, which are similar to the explosion welded plug with the following important differences:

(a) No metallurgical bond is claimed or is possible,

(b) No need exists for adjacent tube ligament protection.

8. OPTIMUM PLUG

An optimum plug, in our judgment and experience, should have the following characteristics:

8.1 Seal a tube leak within the straight portion of the tube while allowing the fluid to flow at a reduced rate, thus preserving the normal operating metal temperature.

8.2 Seal a tube leak within the tube-sheet or at the tube-sheet face while allowing the fluid to flow through for the above reasons.

8.3 Plug a tube or tube-sheet hole close to the back of the tube-sheet without flow of fluid, when tube failure is at the U-bend location, or the nature of failure precludes other repair.

8.4 Do the above in minimum time possible.

9. CONCLUSIONS

The explosion tube plugging technique is sound and is recommnded selectively for tube-end weld configuration that are not conducive to secondary failures. It is not recommended for any weld end configuration which requires reaming of weld roll-over for insertion of protective tapered half rods.

There is a need to perfect this and other techniques as well as to pursue other approaches.

10. RECOMMENDATIONS

10.1 Recognizing the inherent limitations of all available conventional plugs, with the full realization that none is par to the task, the following recommendations are offered to improve the "state-of-the-art" in Novel Plugs towards the goal of obtaining the Optimum Plug.

10.1.1 Probe the companies offering explosion plug services to recognize the need for perfecting the technique, and to permit its use for all tube-end weld configurations.

10.1.2 Make available to interested companies * the TX-312 (Photograph No. 9, Appendix E) Test Exchanger as well as Tube-Sheets of Replacement Feedwater heaters for experimenting with new techniques and approaches on test pieces which have seen years of service.

10.1.3 Continue the close cooperation between the Electric Production and the Engineering Department by keeping abreast with the new techniques, methods and plugs and by pioneering their use in TX-312 Test Exchanger and feedwater heaters.

* I.C.I Americas Inc. and Foster Wheeler Energy Corporation have indicated an interest in this approach and are receiving our full cooperation (see Appendix "C").

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(6) Explosive Welding Bonds Metals, Large Areas. By R. J. Carlson, V. D. Linse and R. H. Wittman, Battelle Memorial Institute.

APPENDIX A

TUBE END WELD CONFIGURATIONS

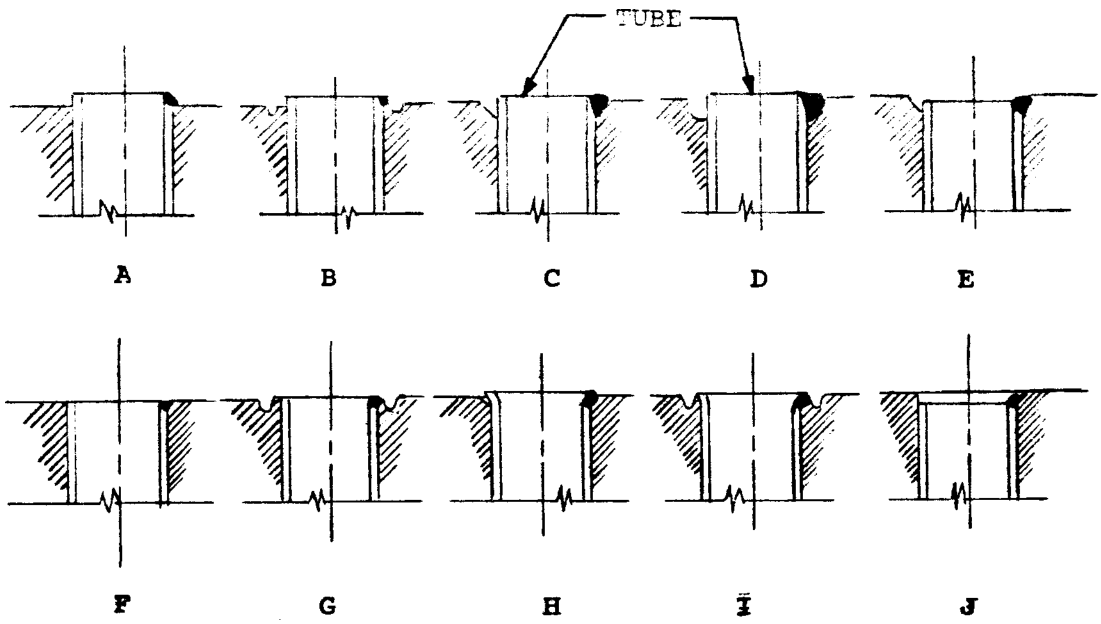


FIGURE NO. 1

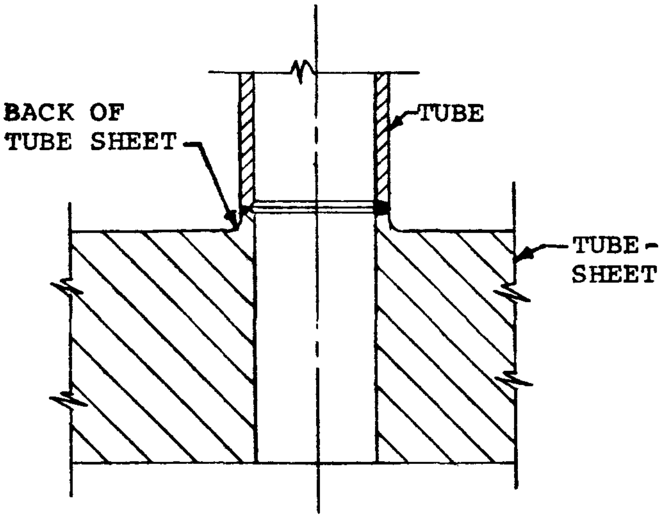


FIGURE NO. 2

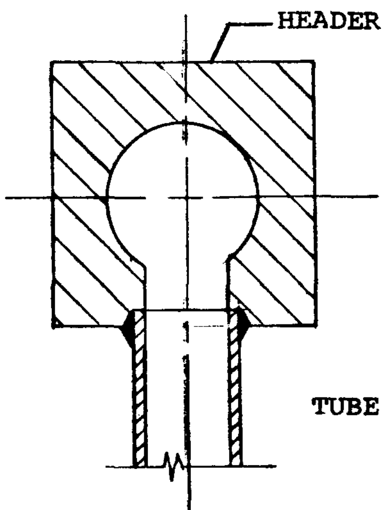


FIGURE NO. 3

APPENDIX B

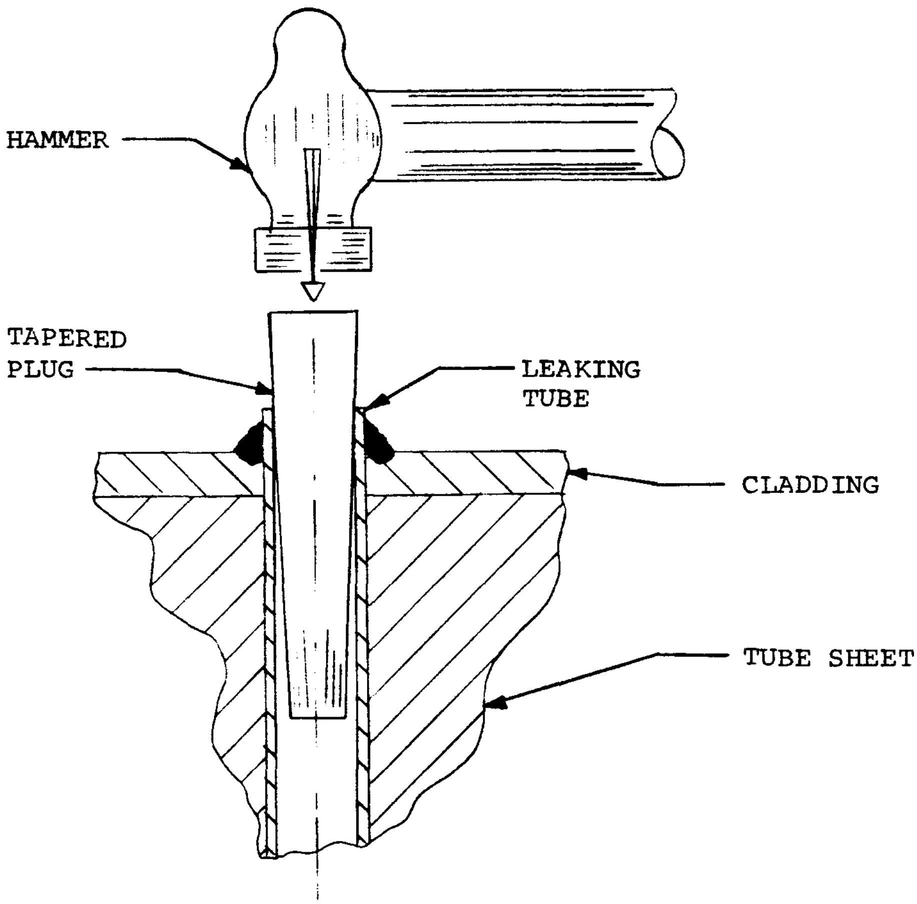


FIGURE NO. 1

TAPERED PLUG

APPENDIX B

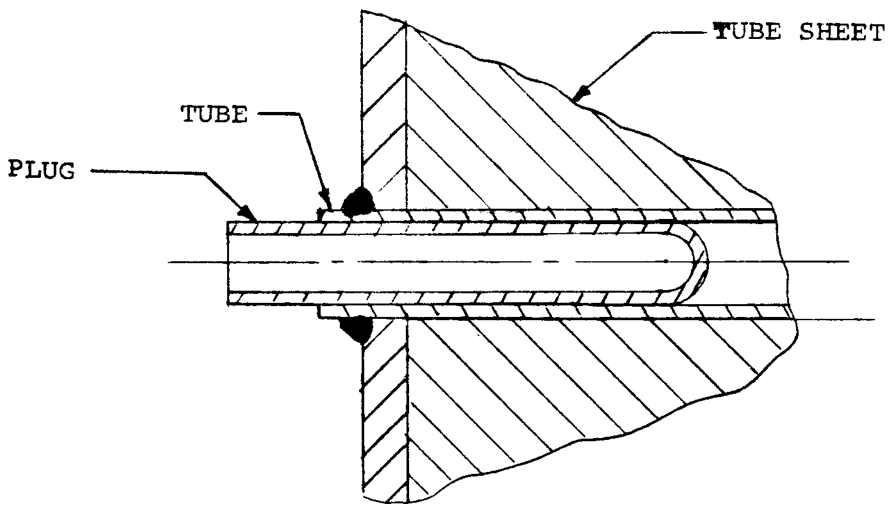


FIGURE NO. 2

ROLLER EXPANDED PLUG

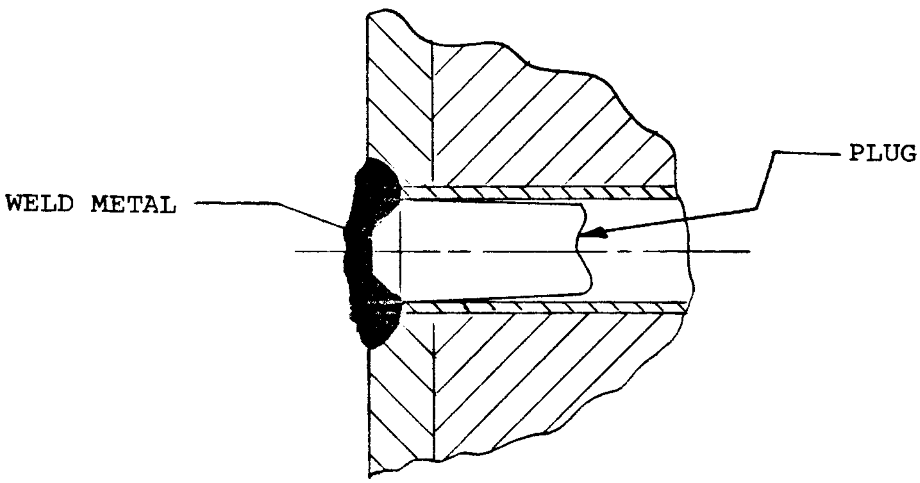


FIGURE NO. 3A
WELDED PLUG

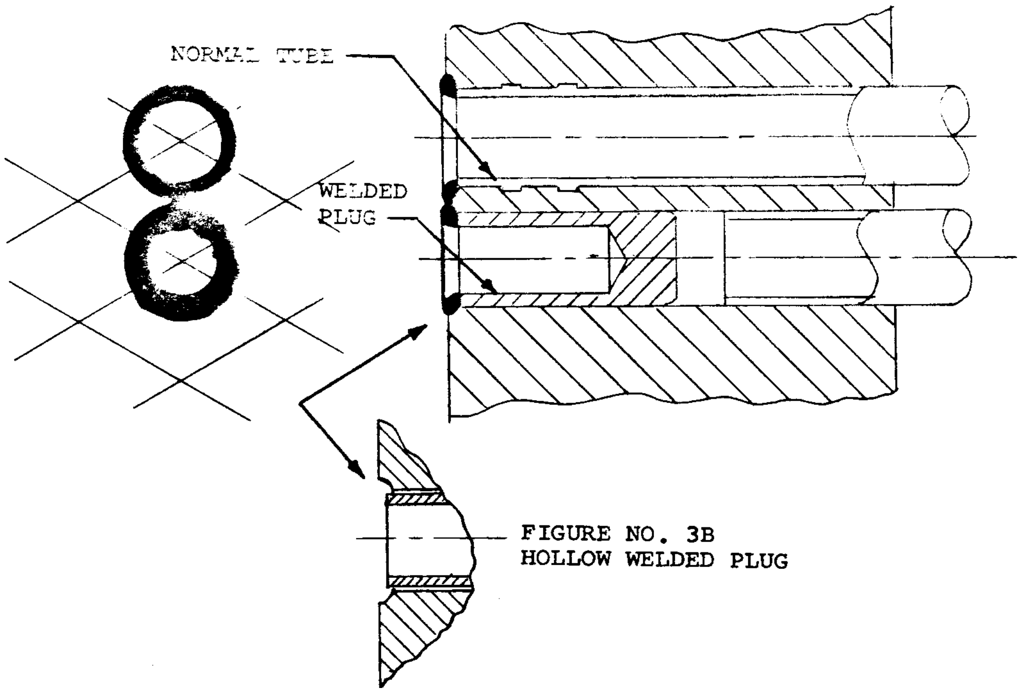


FIGURE NO. 3B
HOLLOW WELDED PLUG

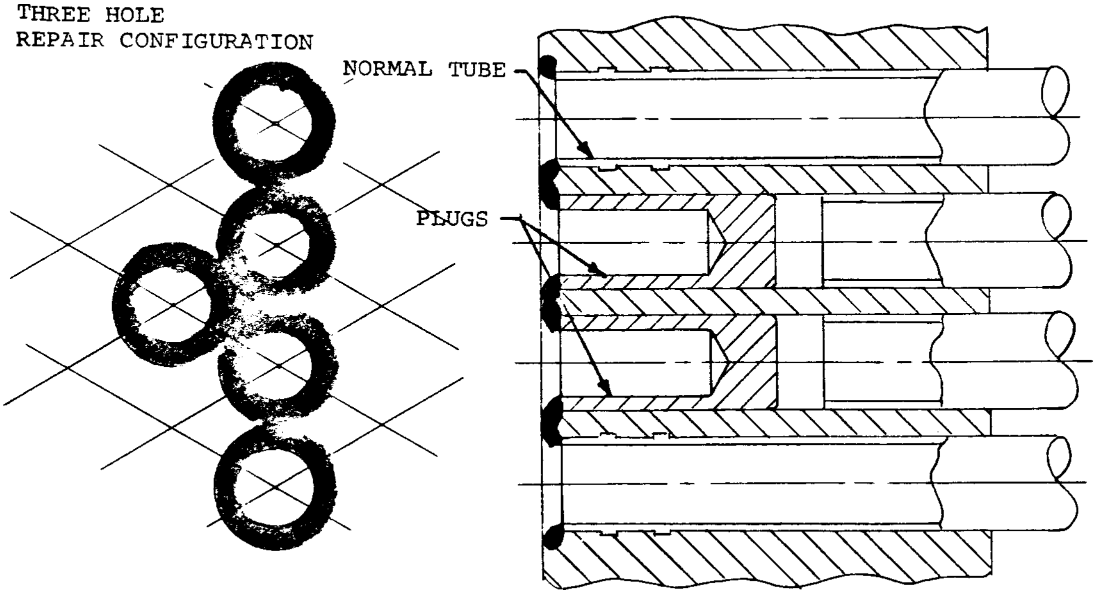


FIGURE NO. 3C
HOLLOW WELDED PLUGS

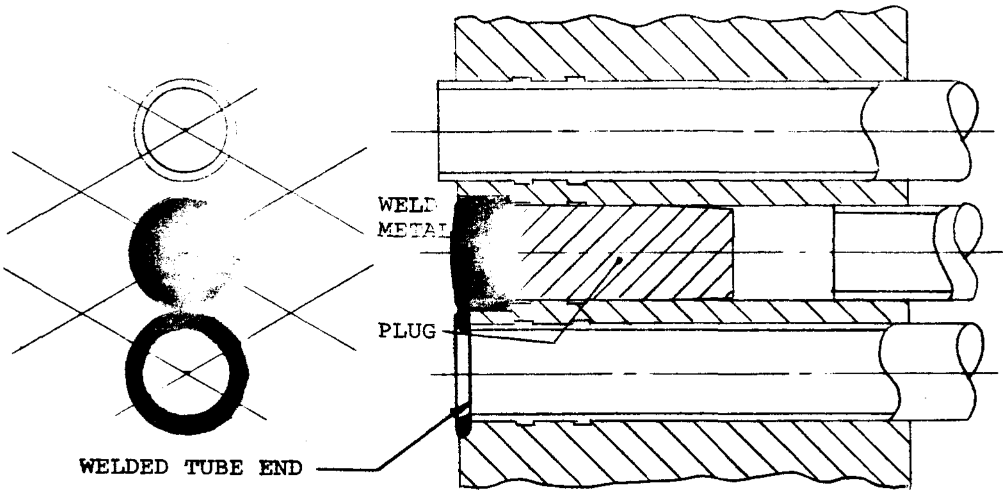


FIGURE NO. 3D
SOLID WELDED PLUG

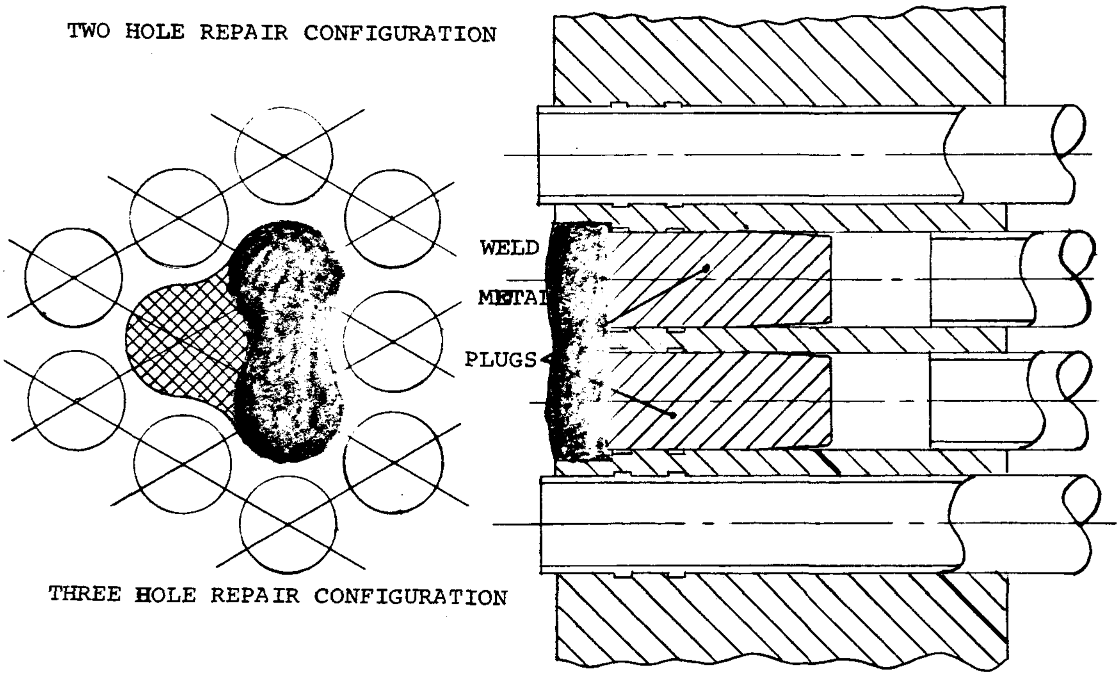
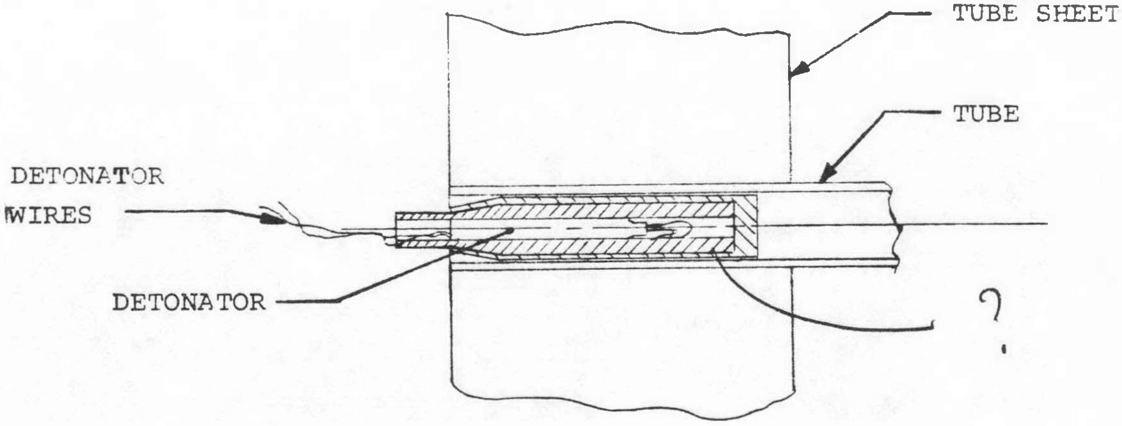
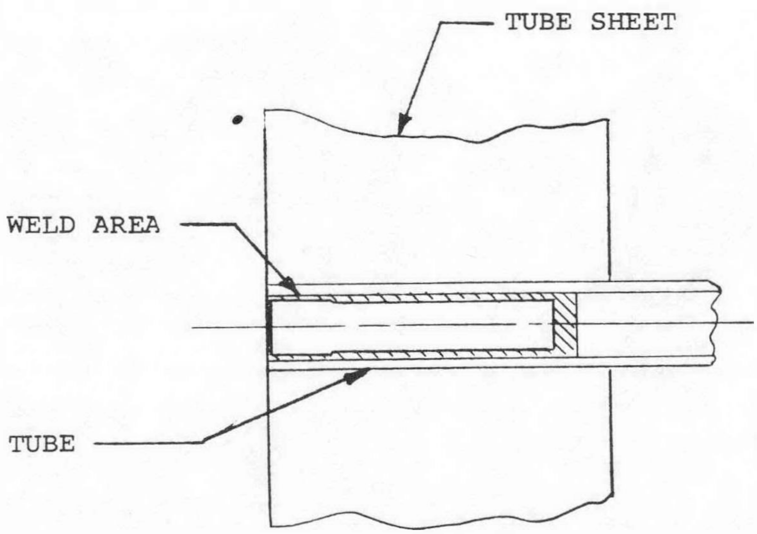


FIGURE NO. 3E
SOLID WELDED PLUGGED CLUSTER



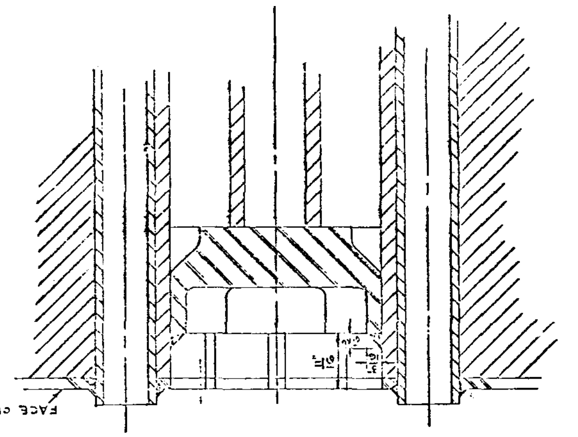
EXPLOSION PLUG PLACED IN TUBE READY FOR DETONATION



EXPLOSION PLUG AFTER DETONATION

FIGURE NO. 4

APPENDIX B



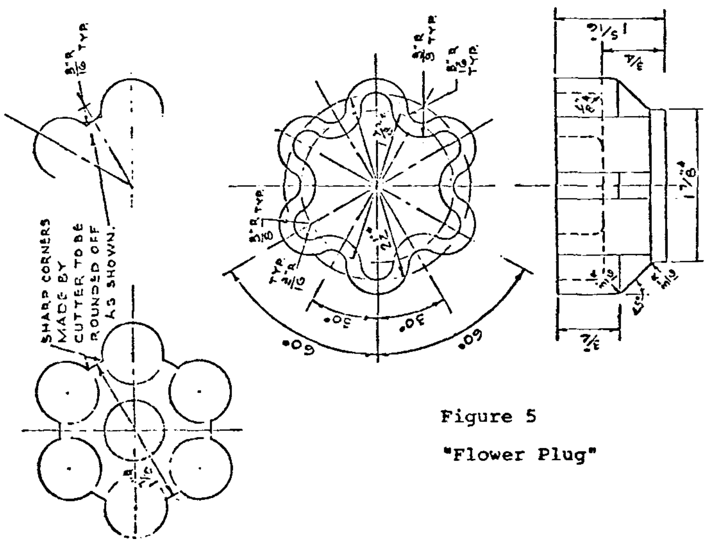
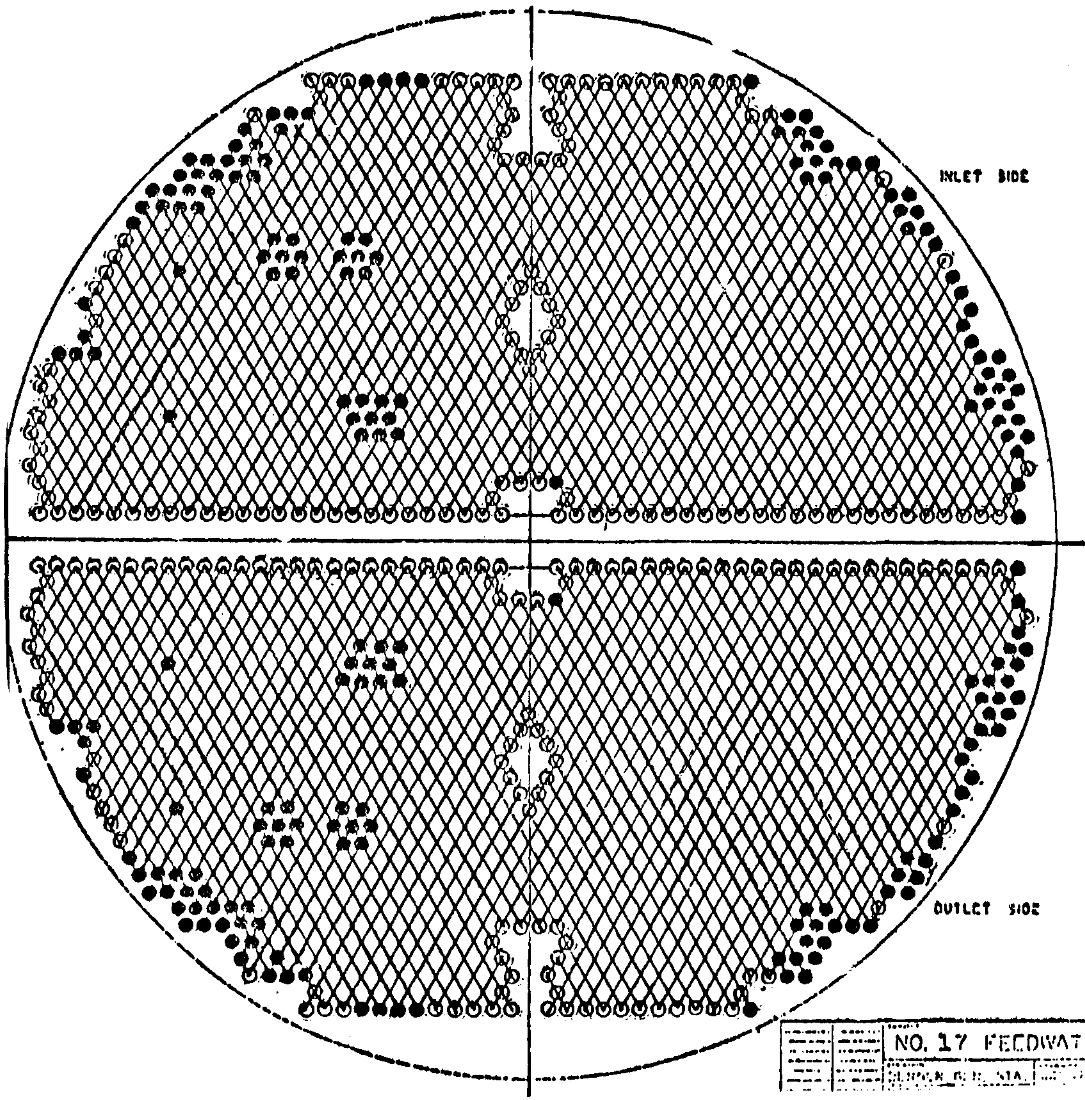


Figure 5

"Flower Plug"



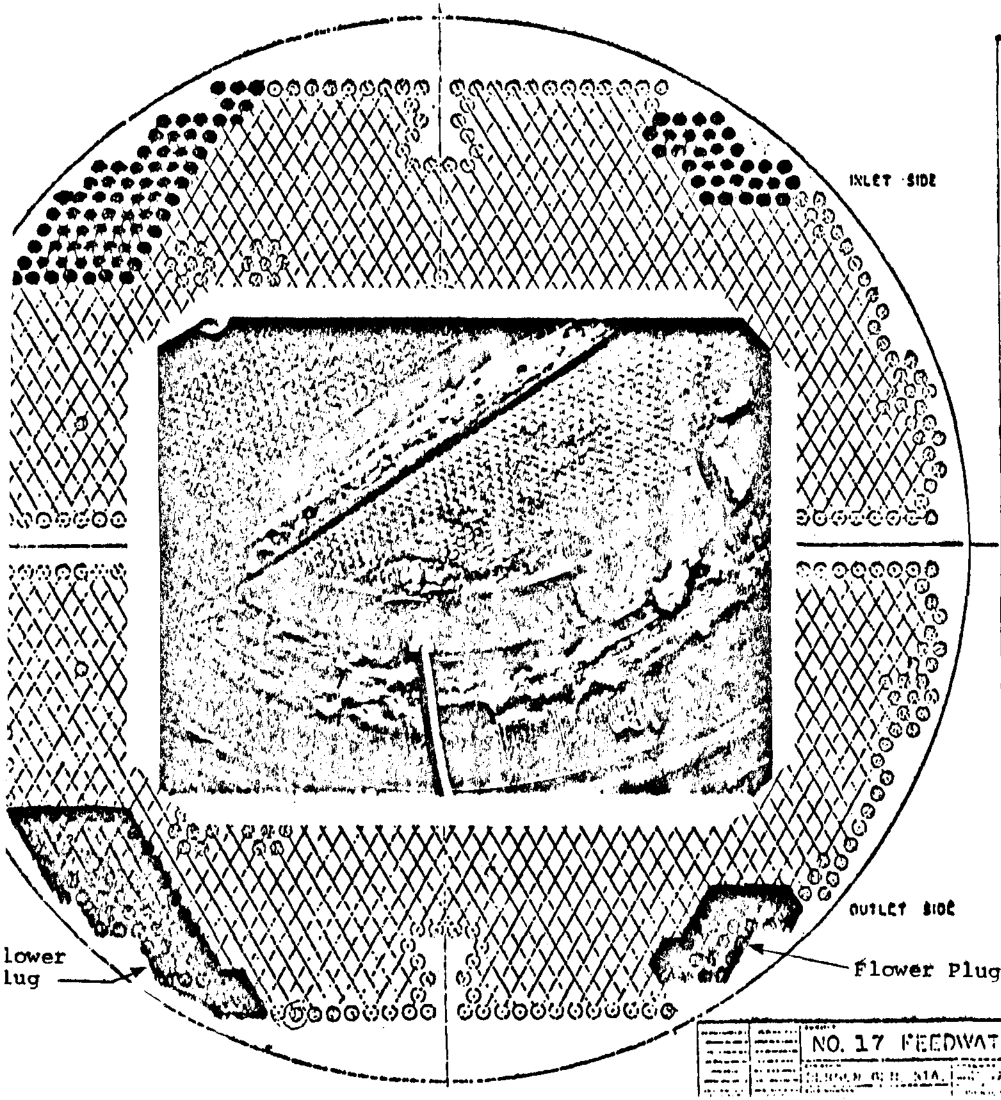
October, 1975

Status of No. 17
Feedwater Heater
1,256 Tubes.

105 Tubes Plugged
8.3%

APPENDIX B
FIGURE NO. 6

NO. 17 FEEDWATER HEATER



January 9, 1978 to
February 10, 1978

Flower Plugs
Installed
in Outlet Side.

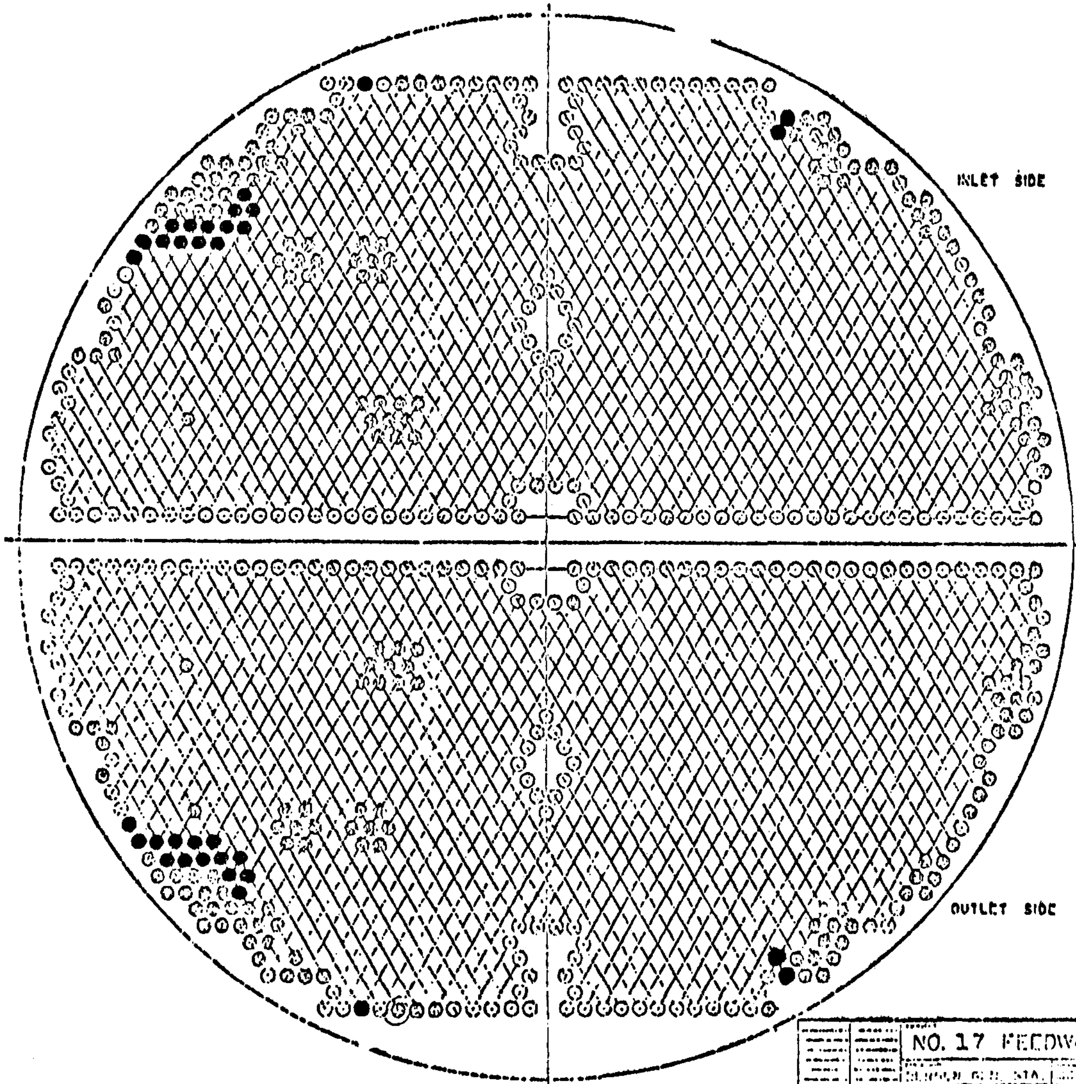
Additional 24 Tubes
Plugged.

167 Total Tubes
Plugged - 13%

APPENDIX B

Photograph No. 7

NO. 17 FEEDWATER HEATER



July 12, 1976 to
August 1, 1976

17 Additional Tubes
Plugged - 9.7%

Suspected Tube
Sheet Cracking
Problems.

Attempted Dual
Seal Plugs.

APPENDIX B
FIGURE NO. 8

NO. 17 FEEDWATER HEATER

APPENDIX C

EXPLOSION WELDED PLUGS

INTRODUCTION

IN 1975 we became aware that Yorkshire Imperial Metals Limited, England, had developed an explosion welded nickel plug which was being used with good results in Europe in high pressure feedwater heaters with tube weld-end configuration as shown in Figure 2, Appendix A. PSE&G requested a demonstration of this technique at Bergen Generating Station. The demonstration did not materialize until 1976 for difficulties Yorkshire encountered with explosive permits in the State of New Jersey. We were impressed by the demonstration and decided to try this new technique to gain first hand experience. We utilized this method of tube plugging at Hudson Generating Station high pressure feedwater heater No. 16 and at Bergen Generating Station high pressure feedwater heater No. 17.

I.C.I. Americas Inc., Valley Forge, Pennsylvania is now licensed to carry on this process in the U.S.A.

Wesingthouse and Babcock and Wilcox are also engaged in this service for special applications such as nuclear steam generators.

PROCEDURE

The explosion welded plugs are used by Yorkshire Imperial, Ltd. for plugging tube-sheet holes for feedwater heaters having tubes welded on the back of the tube-sheet.

In general, those holes are clean and have no worm holes. Plugging holes in such a heater is quite simple. The hole is cleaned by grinding and the explosion plug is placed at the face of the tube-sheet and detonated. The plug gets welded to the tube sheet.

In the U.S.A. the feedwater heaters, in general, have their tubes welded at the face of the tube sheet, as shown in Figure No. 1, Appendix "A", and therefore the geometry is quite different.
In case the tube to tube-sheet weld is not sound or tube has been damaged inside the tube-sheet, the following procedure is followed:

A portion of the tube to be plugged is drilled, ground and removed from the tube-sheet leaving a few inches of the tube in the back of the tube-sheet. The tube-sheet hole is polished and checked for any worms, cracks or gouging. The tube in the back of the tube-sheet is then rolled to avoid any tube vibration. The explosion plug is then inserted in the tube-sheet and held there by a special putty-like compound called Yorkshire flux and the plug leads connected to detonator.

PROCEDURE (Cont'd)

The adjoining tubes are filled with right size tapered half-round solid rods to avoid any damage to the ligaments. The charge is then detonated, the smoke pumped out and the tapered half-round rods removed. The tubes plugged by the explosion plug are filled with the Yorkshire putty while the other tubes are being detonated. This process is repeated on the inlet and the exit end of all the tubes to be plugged.

PSE&G EXPERIENCE

The explosion welded plugs were used for plugging high pressure feedwater heater No. 16 tubes at Hudson Generating Station and No. 17 at Bergen Generating Station.

Since Yorkshire Imperial Ltd. did not have any trained personnel in U.S.A., two technicians were flown in from England both the times.

Hudson Generating Station feedwater heater No. 16 (a vertical head down, high pressure) had a leaking cluster of tubes previously repaired by welding. These tubes were drilled out and holes inspected. Three ligaments were badly damaged and the explosion weld plugging was doubtful and, therefore, rejected. It was considered advisable to use flower plug for the 7-tube cluster having damaged ligaments and the explosion plugs for 2 adjoining failed tubes and the other end of all the failed tubes. All tubes to be plugged were drilled out 6 to 7 inches from the face of the tube-sheet and the tube-sheet hole reamed and cleaned. The tubes were then rolled with mechanical rollers at the back of the tube-sheet and explosion weld plugged near the back of the tubesheet. A total of 11 explosion welded plugs were used and all of them are holding since July 1977. Figure No. 3, Appendix 'C' shows the location of leaking cluster and Photograph No. 7, Appendix 'E' shows the flower plug repair.

Bergen Generating Station feedwater heater No. 17 (a vertical head down, high pressure) developed a bad leak in the ridge of tubes plugged by welding, Figure No. 6 Appendix "B" shows the tube-sheet condition. The following steps were taken to ascertain the conditions of this heater:

The plugged tubes in the leaking ridges were drilled out and inspected. Two ligaments were found damaged due to drilling operation and there were fine hairline cracks in some other ligaments. These ligament cracks were mostly near the face of the tube-sheet.

PSE&G EXPERIENCE (Cont'd)

The two tubes with badly damaged ligaments were plugged by welding hollow plugs and the rest by explosion weld plugging at the back of the tube-sheet. The operation was time consuming and tiring. Figure No. 2, Appendix "C" shows the tubes repaired by Explosion weld plugs.

Four (4) adjacent tubes, which were sound, but needed half-round solid rods for ligament protection, had rolled over welds and were reamed out to fit the protection rods. These four tubes subsequently failed and were plugged by welded plugs. A total of 48 explosion plugs were used, out of which two plugs leaked during the test.

Bergen Generating Station heater No. 17 again developed leaks and it was found that some of the Explosion weld plugged tubes in the ridges were leaking. The cracked ligaments were machined out and special flower plugs welded to seal 72 holes in one ridge and 31 in the other. Photograph No. 7, Appendix "B" show the locations of flower plugs.

FUTURE PLANNING

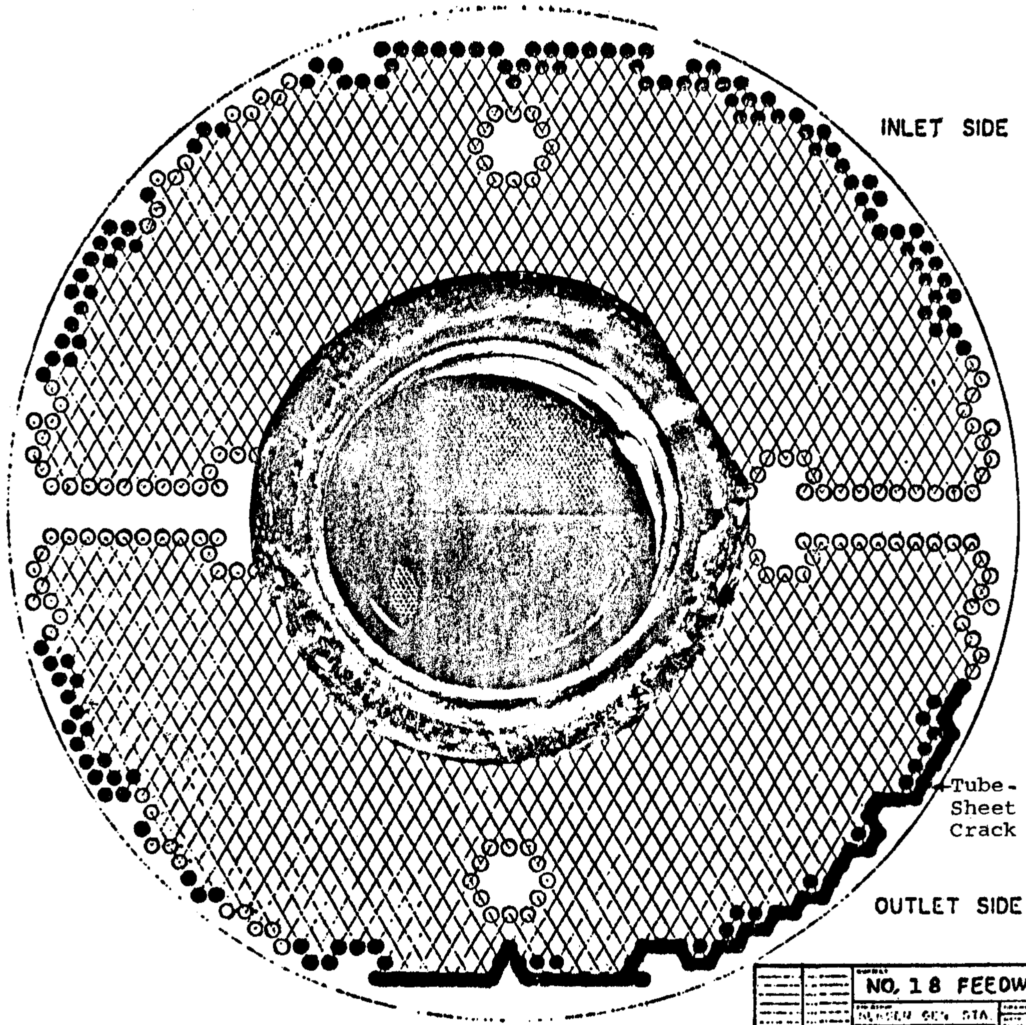
The tube-sheet of No. 18 Feedwater heater removed from Bergen Generating Station is being shipped to ICI Americas, Inc. (Licensee of Yorkshire Imperial) for them to experiment on this tube-sheet and make improvements in their process.

PSE&G has also agreed to allow Foster Wheeler to test their explosion expanded plugs in the test heat exchanger TX-312 Photograph No. 9, Appendix "E" in order to evaluate the plug under actual working conditions.

Southwestern Engineering Company is utilizing explosion expansion technique for expanding tubes and tube-inserts into tube sheet in their shops as well as in the field.

Struthers Wells is experimenting with hydraulically expanding tubes in tube-sheet. This technique has successfully been used in Europe for commercial and nuclear heat exchangers. Hydraulic expansion differs from all other tube anchoring methods in that the tube is plastically deformed simply by means of a pressurized liquid.

We are keeping ourselves abreast with the latest developments and helping the industry to develop the optimum plug. We are using the individual tube tester to test the tubes in the area of failed tubes and have stopped the practice of safety plugging. This procedure will help reduce the clusters and ridges in the tube-sheets.



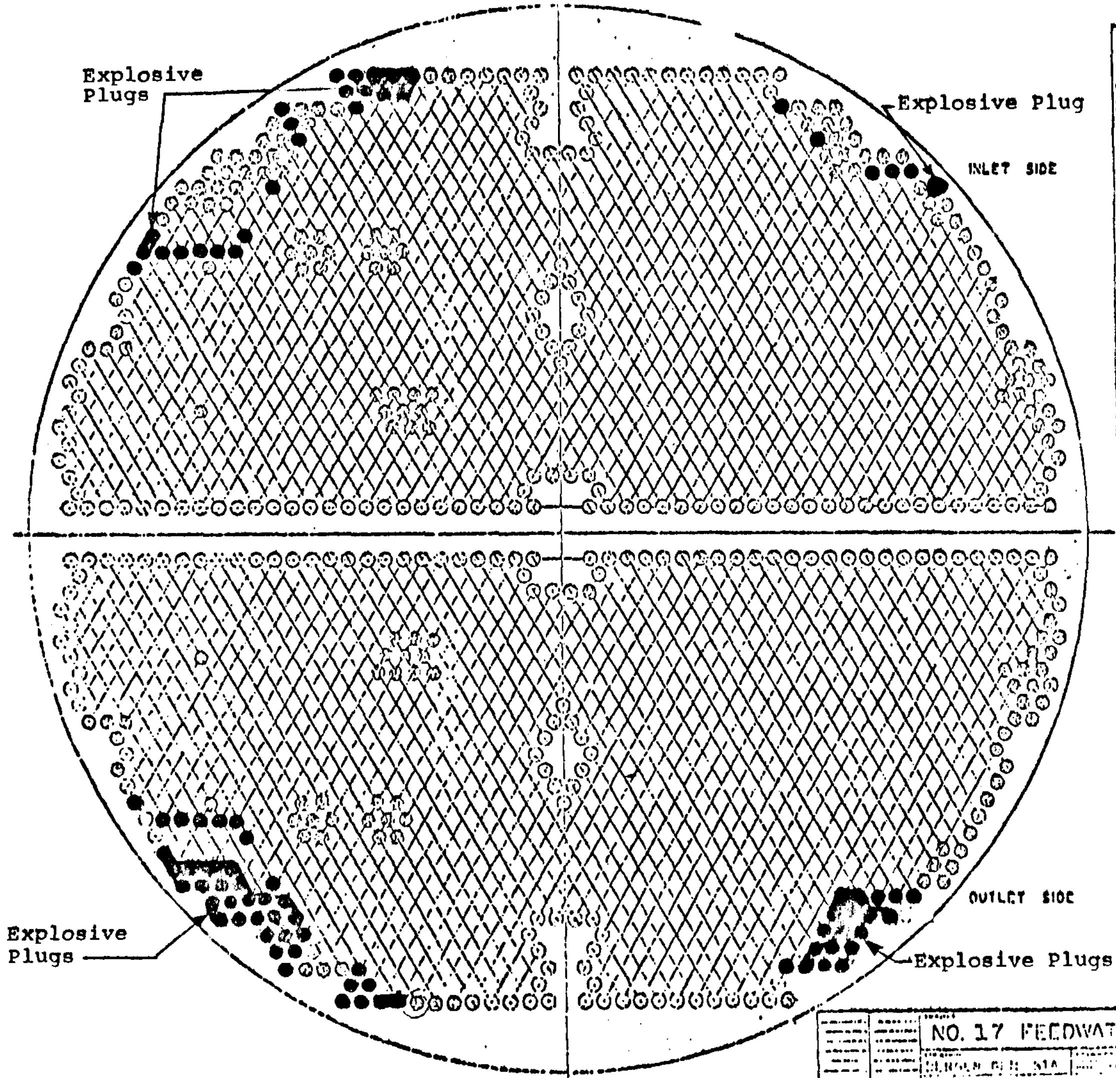
Status of No. 18
Feedwater Heater
before condemnation

1,150 Tubes
89 Tubes Plugged
7.7% Plugged

Tube sheet cracking,
as shown to
a depth of ten to
twelve inches.

APPENDIX C
FIGURE NO. 1

NO. 18 FEEDWATER HEATER TUBE SHEET



June 27, 1977 to September 2, 1977

Installed New No. 18 Feedwater Heater.

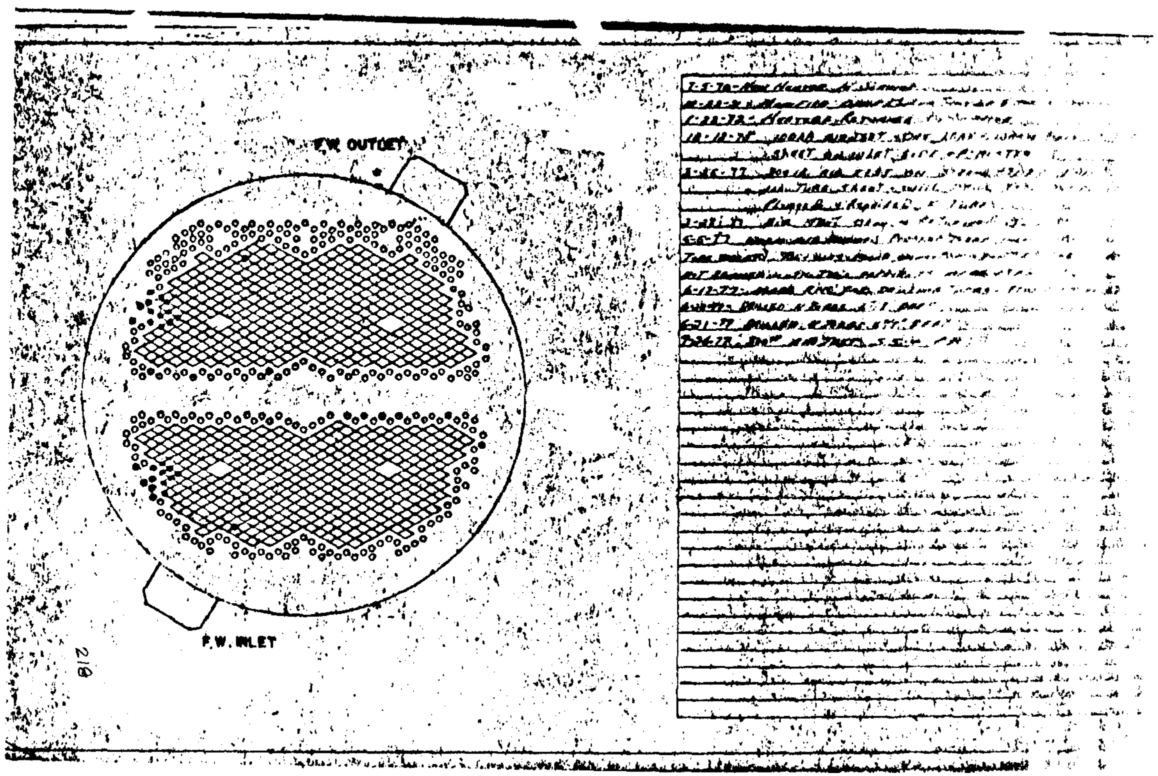
Attempted to arrest tube sheet cracking by utilizing explosive tube plugs developed by an English Firm

Additional 21 tubes plugged.

143 Total Tubes Plugged - 11.4%

APPENDIX C
FIGURE NO. 2

NO. 17 FEEDWATER HEATER



APPENDIX C
FIGURE NO. 3

APPENDIX D
REF. 1

July 2, 1968 R. R. NOE 3,390,721

MULTIPLE HEADER FEEDWATER HEATER

Filed April 22, 1966 2 Sheets-Sheet 2

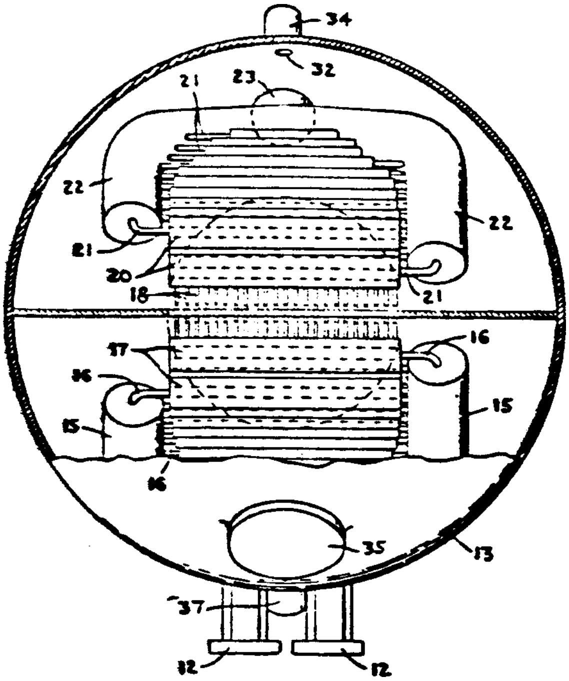


FIG. 4

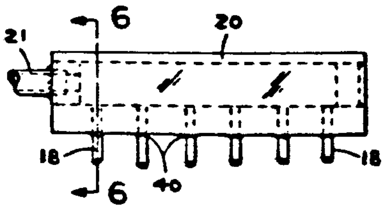


FIG. 5

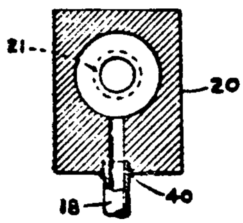


FIG. 6

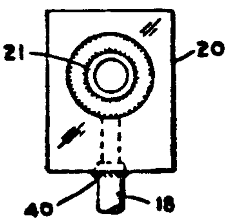


FIG. 7

RENATO R. NOE
INVENTOR.

BY David H. Bobis
Atty

July 2, 1968 R. R. NOE 3,390,721

MULTIPLE HEADER FEEDWATER HEATER

Filed April 22, 1966 2 Sheets-Sheet 1

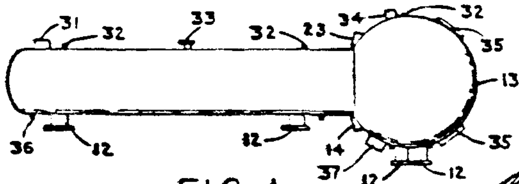


FIG. 1

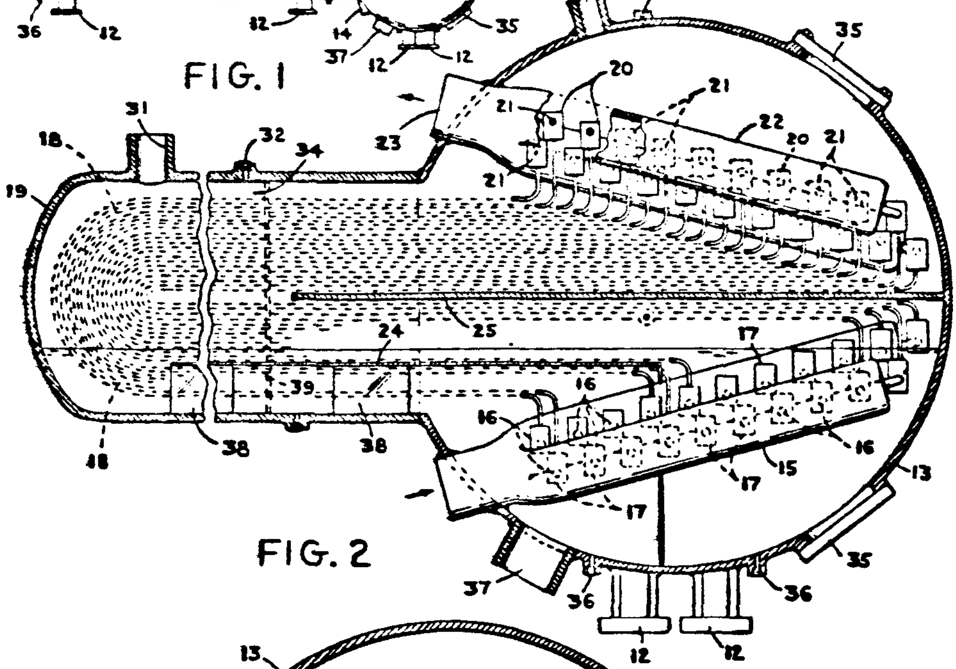
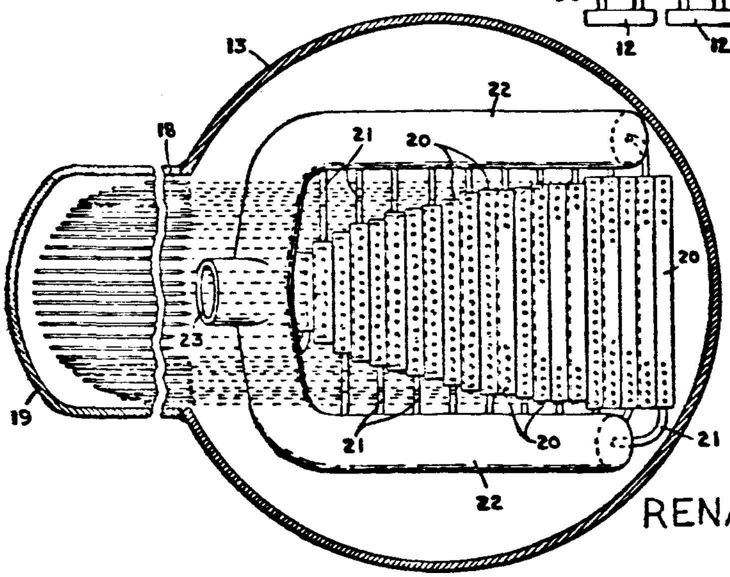


FIG. 2



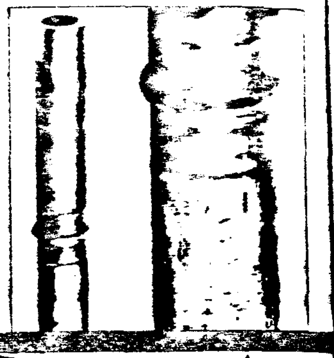
RENATO R. NOE
INVENTOR

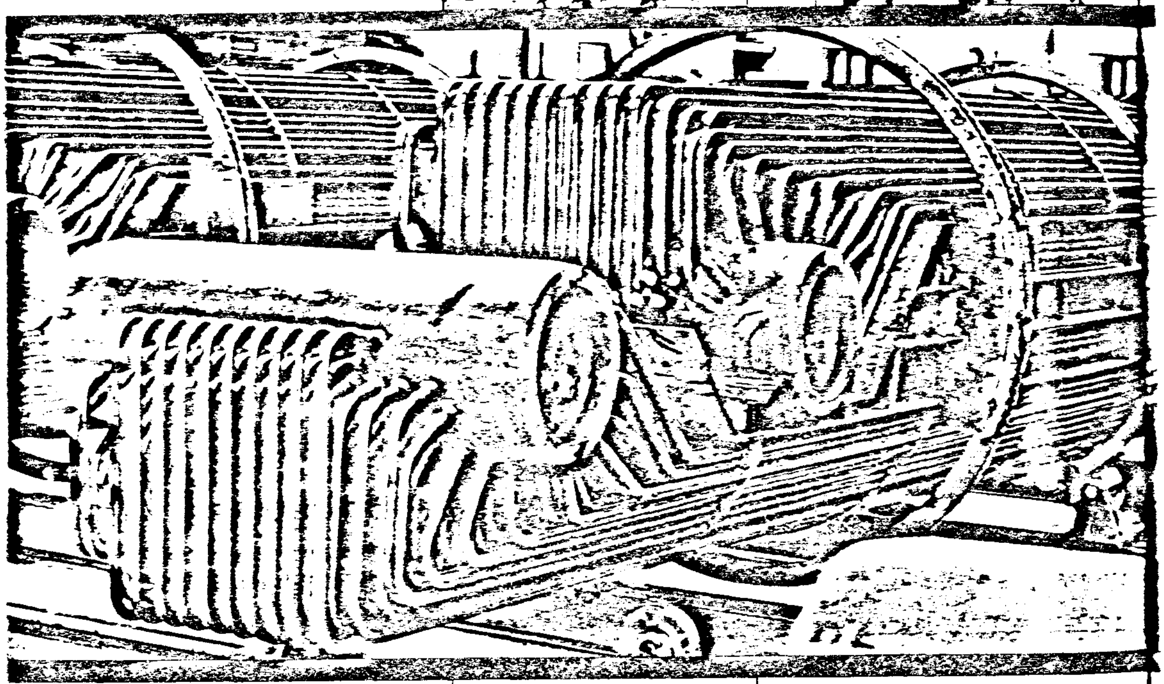
BY Daniel H. Bobis
Atty

FIG. 3

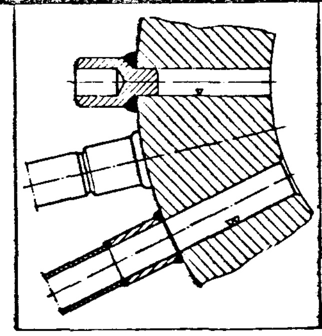
High pressure feedwater heaters of header type

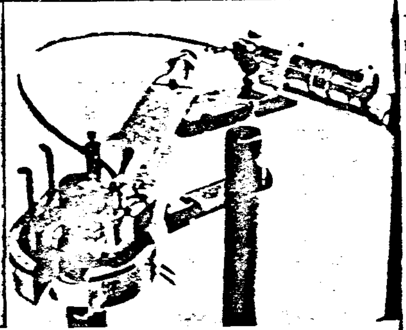
Heaters according to this design can be built in any size desired. CASS has been building feedwater heaters of header type since 1950. More than 400 units were in successful operation by beginning of 1974.

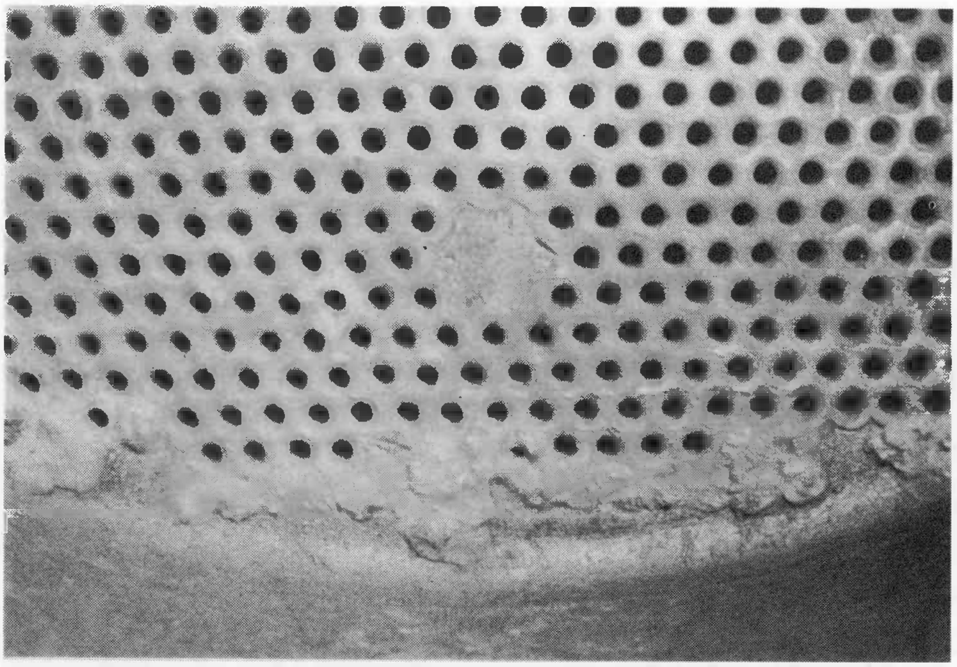




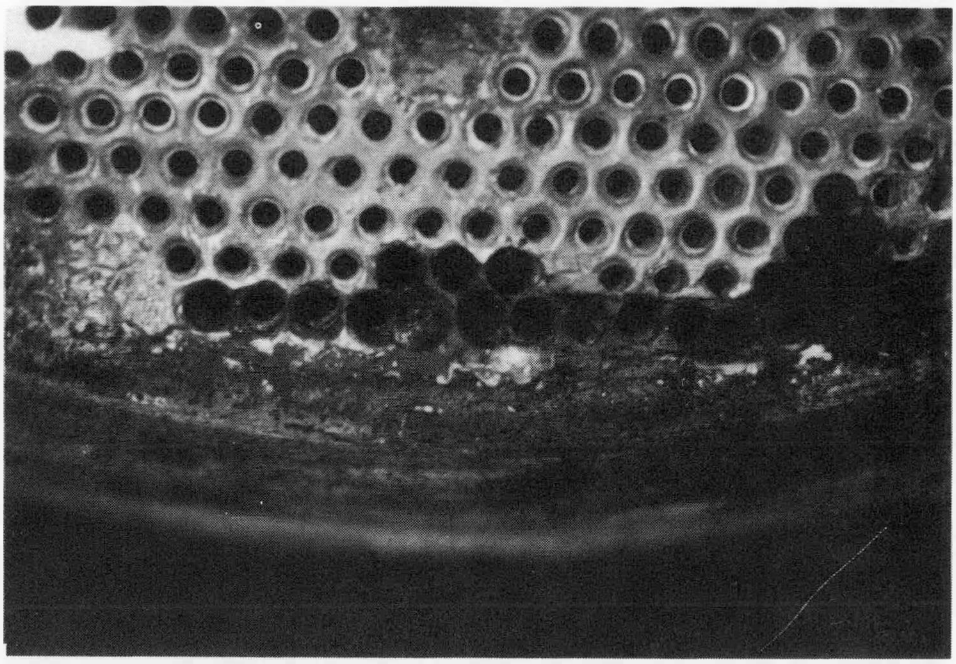
High pressure heaters for a feedwater capacity of 2,000 tons/hour (as typically used for a plant with a turbine output of 680 MW) reach unit weights up to 110 metric tons. This high pressure feedwater heater is a cylindrical vessel with two dished ends and with integrated desuperheating, condensing and sub-cooling sections. The internal tube bundles of different shapes are carefully attached and connected to the inlet and the outlet headers.





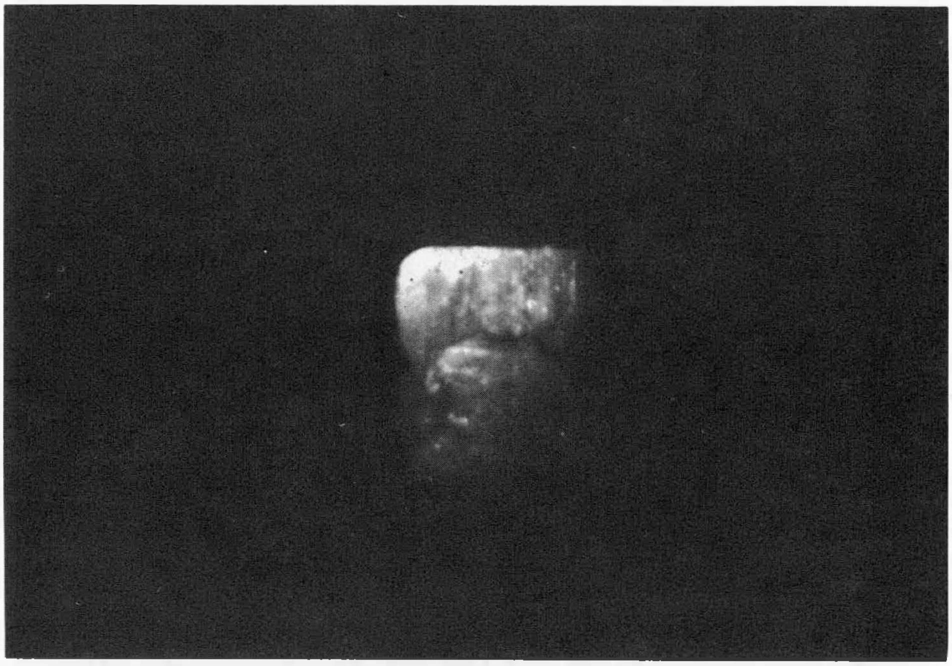


PHOTOGRAPH NO. 1
NO. 18 FEEDWATER HEATER, BERGEN GENERATING STATION
TUBE-SHEET FACE SHOWING WELDED PLUGS RIDGE



PHOTOGRAPH NO. 2
NO. 18 FEEDWATER HEATER, BERGEN GENERATING STATION
TUBE SHEET WITH WELDED PLUGS RIDGE GROUND OFF
AND DRILLED FOR TUBE SHEET INSPECTION

APPENDIX E

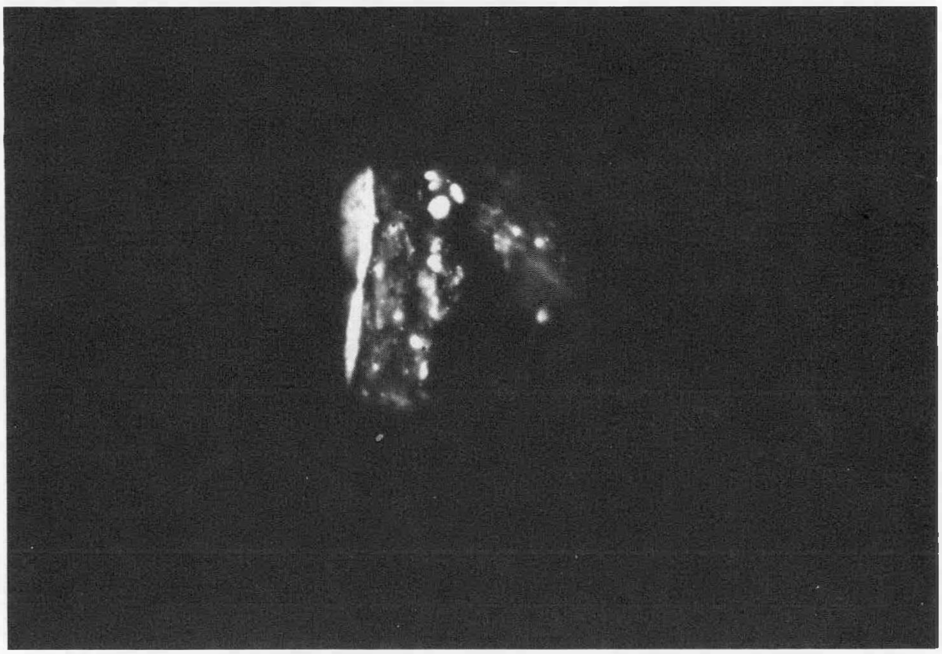


PHOTOGRAPH NO. 3
NO. 18 FEEDWATER HEATER, BERGEN GENERATING STATION
CRACKED TUBE-SHEET LIGAMENT AS SEEN WITH FIBER OPTIC BOROSCOPE

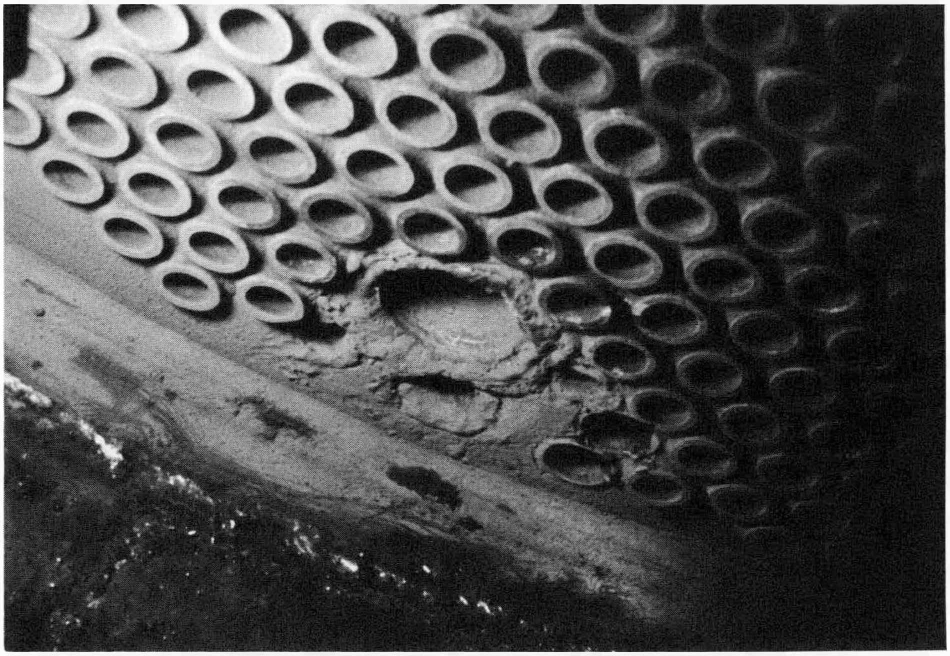
PHOTOGRAPH NO. 4
NO. 18 FEEDWATER HEATER, BERGEN GENERATING STATION
BACK OF TUBE-SHEET SHOWING CONTIGUOUS LIGAMENT CRACKS

APPENDIX E

PHOTOGRAPH NO. 5
ADJACENT TUBE FAILURE DUE TO
IMPINGEMENT FROM FAILED TUBE



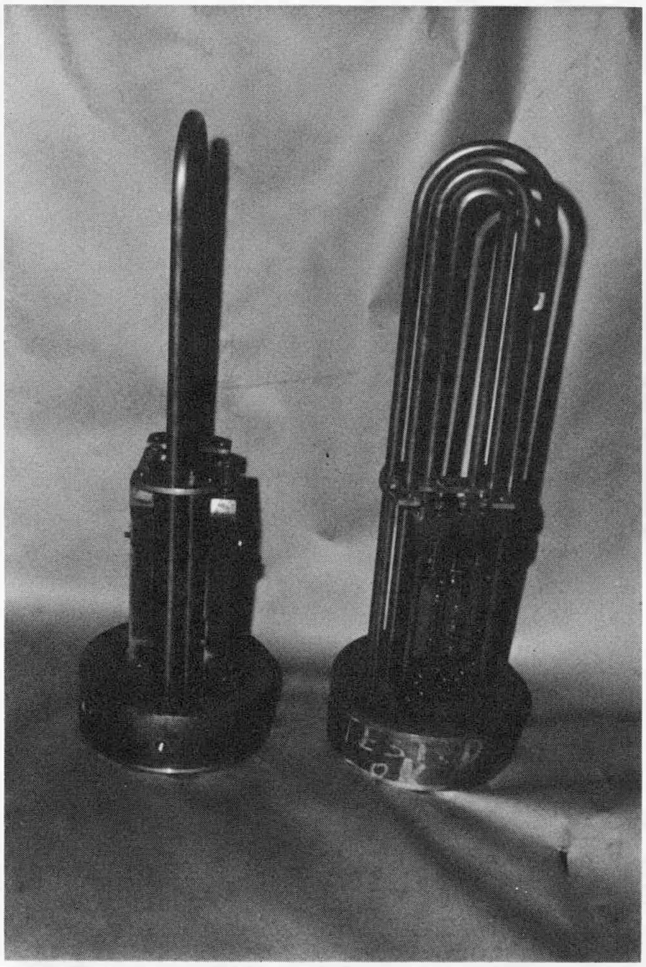
PHOTOGRAPH NO. 6
TUBE TO TUBE-SHEET WELD FAILURE AT THE
FACE OF THE TUBE-SHEET



PHOTOGRAPH NO. 7
NO. 16 FEEDWATER HEATER, HUDSON GENERATING STATION
A FLOWER PLUG IN PLACE

PHOTOGRAPH NO. 8
TUBE FAILURES DUE TO STEAM IMPINGMENT

APPENDIX E



PHOTOGRAPH NO. 9
TX-312 TEST HEAT EXCHANGER TUBE-BUNDLE
AND COUPON CASSETTES