

Nuclear Maintenance Applications Center: Heat Exchanger Maintenance Guide



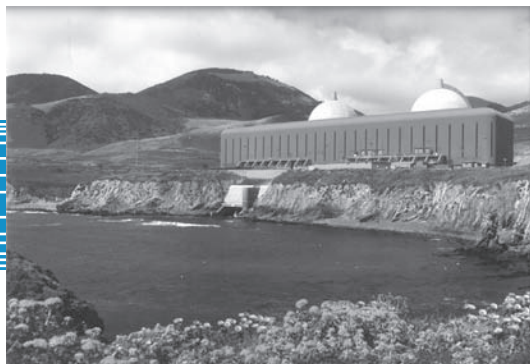
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Nuclear Maintenance Applications Center: Heat Exchanger Maintenance Guide

1018089

Final Report, June 2009

EPRI Project Manager
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This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Nuclear Maintenance Applications Center: Heat Exchanger Maintenance Guide. EPRI, Palo Alto, CA: 2009. 1018089.

PRODUCT DESCRIPTION

This guide provides plant personnel with information on the operation, maintenance, and performance of heat exchangers. The contents of this guide will assist plant personnel in improving heat exchanger reliability, performance, and maintenance practices.

Results and Findings

This technical report provides an overview of system design parameters and familiarizes maintenance and engineering personnel at a nuclear power plant with the components that are contained in various types of heat exchangers and their functions. The focus of the report is providing guidance for performing preventive maintenance on heat exchangers. Troubleshooting guidance is provided for each type of heat exchanger included here.

Challenges and Objectives

The objective of this document is to provide the Electric Power Research Institute (EPRI) members with guidance on proper heat exchanger maintenance. The document revisions include the following:

- Guidance targeted for the audience with less experience and with different experience
- Heat exchanger design and manufacture
- Maintenance guidance for shell-and-tube heat exchangers
- Maintenance guidance for plate heat exchangers
- Maintenance guidance for air-to-water heat exchangers
- Condition monitoring
- Preventive maintenance
- Corrective maintenance
- Troubleshooting

Applications, Value, and Use

This report expands maintenance guidance for both shell-and-tube heat exchangers and plate heat exchangers into one comprehensive report. It also adds maintenance guidance for air-to-water type heat exchangers. The scope of this report includes heat exchangers that can be categorized as low energy, single phase, and water cooled; it excludes phase-change type (that is, condensers, feedwater heaters), high-energy type (that is, moisture separator reheaters, steam generators, feedwater heaters), and air condensers (that is, auxiliary condenser, forced-draft heat exchangers).

EPRI Perspective

Heat exchanger operation and maintenance costs increase as equipment ages. Heat exchanger performance can affect unit reliability and energy costs. This guide provides a comprehensive overview of the equipment practices needed for continued reliable operation.

Approach

The intent of this technical report is to address various engineering, maintenance, and operations issues regarding the preventive and corrective maintenance activities that are typically performed on heat exchangers and how to troubleshoot them. Key suppliers of heat exchangers were solicited for assistance to ensure that the guidance here reflects the latest technologies available in the industry. A Technical Advisory Group was formed that consisted of maintenance and engineering personnel from EPRI Nuclear Maintenance Applications Center (NMAC) utility members. Input was solicited for current maintenance issues for the various types of heat exchangers included in the scope. Experience-proven practices and techniques were identified during this effort and were compiled in this report.

Keywords

Heat exchanger

Maintenance

Performance

Reliability

Troubleshooting

ABSTRACT

This report has been created for the plant heat exchanger engineer. The heat exchangers covered include shell-and-tube heat exchangers, plate heat exchangers, and air-to-water heat exchangers.

An overview of each heat exchanger's design and configuration has been provided for background information.

This technical report provides an overview of system design parameters and familiarizes maintenance and engineering personnel at a nuclear power plant with the components that are contained in various types of heat exchangers and their functions. The topics that are covered include thermal performance, mechanical performance, condition monitoring, preventive and corrective maintenance, and heat exchanger troubleshooting. This guide is a starting point and where more information is required, other industry and EPRI guides have been referenced.

ACKNOWLEDGMENTS

EPRI would like to thank the following individuals who made significant contributions to the development of this report. Their valuable insight and experience were essential in the successful completion of this project.

Dennis Mason (Chairperson)	Duke Energy
Joe Polito	Alfa Laval
Leon Maitre	APV Products
Daniel Hall	APV Products
Tom Mills	Delta T Heat Exchangers
Tim Eckert	EPRI
Fritz Sutor	EST Group, Business unit of Curtiss-Wright Flow Control
Alfred Kong	Ontario Power Generation
Steve Weintraub	Polaris Plate Heat Exchangers, LLC
Thang Dao	South Carolina Electric & Gas
Mike Tulay	Sequoia Consulting Group, Inc.
George Licina	Structural Integrity Associates, Inc.
Iver Jacobson	True North Consulting, LLC

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1

INTRODUCTION AND OVERVIEW

1.1 Introduction and Background

Heat exchangers are used extensively in the power generation industry and can be of various designs and constructions. Their proper operation is essential for reliable power plant operation. Increased awareness of heat exchanger importance at nuclear power plants has led to more maintenance practices used within the nuclear industry

In 1997, EPRI published TR-106741, *Heat Exchangers: An Overview of Maintenance and Operations*. Much of the information contained in TR-106741 is still relevant; however, the guide dealt primarily with shell-and-tube heat exchangers. This document (1018089) serves as a technical update and includes an overall heat exchanger maintenance strategy.

In May 2002, EPRI published 1003470, *Feedwater Heater Maintenance Guide*, which provides coverage of issues that are related specifically to feedwater heaters in much greater detail than the general treatment that was previously included in TR-106741. Accordingly, this document (1018089) will not address feedwater heaters as part of its scope, but refers to 1003470 where appropriate.

1.2 Purpose and Scope of This Report

The objective of this document is to provide EPRI members with guidance on proper heat exchanger maintenance. The document revisions include the following:

- Guidance targeted for the audience with less experience or different experience
- Heat exchanger design/manufacture
- Maintenance guidance for shell-and-tube heat exchangers
- Maintenance guidance for plate heat exchangers
- Maintenance guidance for air-to-water heat exchangers
- Condition monitoring
- Preventive maintenance
- Corrective maintenance
- Troubleshooting

1.3 Scope of Heat Exchangers Included in This Report

As noted in Section 1.1, this report expands maintenance guidance for shell-and-tube heat exchangers, plate heat exchangers, and air-to-water heat exchangers into one comprehensive report. Table 1-1 lists the types of heat exchangers discussed in this report and provides a list of common plant applications for each. The scope of this report includes heat exchangers that can be categorized as low energy, single phase, and water cooled; it excludes phase-change type (that is, condensers, feedwater heaters), high-energy type (that is, moisture separator reheaters, steam generators, feedwater heaters), and air condensers (that is, auxiliary condenser, forced-draft heat exchangers).

Table 1-1
Types of heat exchangers discussed in this report and their plant applications

Types of low-energy, single-phase, water-cooled heat exchangers	Typical plant applications
Shell-and-tube heat exchangers	
Helical	Bearing oil cooler, pump seal cooler, sample cooler
U-tube	Let-down heat exchanger, residual heat removal (RHR), fuel pool cooling, containment spray, main turbine lube oil cooler
Straight tube	Component cooling, stator cooling, diesel generator coolers, hydrogen cooler, lube oil cooler, seal oil cooler, etc.
Plate heat exchangers	
Semi-welded plate	Rare plant applications
Fully-welded plate	Rare plant applications
Gasketed	Can be used for most water-to-water and water-to-oil applications
Air-to-water heat exchangers	Motor cooler, containment air cooler, isolated phase bus cooler, hydrogen cooler, HVAC cooling coils, room coolers, dryers, condensers, vapor recovery coils

Figures 1-1, 1-2, and 1-3 illustrate installations for some of the types of heat exchangers discussed in this report.



Figure 1-1
Component cooling water system heat exchanger



Figure 1-2
Diesel engine jacket water heat exchanger



Figure 1-3
Plate heat exchanger in a plant application

1.4 Glossary of Terms and Acronyms/Abbreviations

1.4.1 Key Definitions

air-to-water heat exchanger – A device with an arrangement of surfaces separating an air stream and a fluid stream to maximize the heat transfer between the two streams.

heat exchanger – A device built for efficient heat transfer from one medium to another, whether the media are in direct contact or are separated by a solid wall so that they never mix.

plate heat exchanger – A device composed of multiple, thin, slightly separated plates that have very large surface areas and fluid flow passages for heat transfer.

shell-and-tube heat exchanger – A device that consists of a series of tubes that contain a fluid that must be either heated or cooled; a second fluid runs over the tubes so that it can either provide heat or absorb the heat required.

1.4.2 Acronyms and Abbreviations

AI – authorized inspector
ASME – American Society of Mechanical Engineers
ASTM – American Society for Testing and Materials
BTU – British thermal units
BWG – Birmingham Wire Gauge
BWR – boiling water reactor
ECT – eddy current testing
EDTA – ethylenediaminetetraacetic acid
ET – electromagnetic testing
HVAC – heating, ventilation, and air conditioning
ID – inside diameter
IRIS – internal rotary inspection system
MHz – Megahertz
MIC – microbiologically induced corrosion
MR – multi-row
MT – magnetic particle testing
NBIC – National Board Inspection Code
NDE – nondestructive examination
NACE – National Association of Corrosion Engineers
NMAC – Nuclear Maintenance Application Center
NRC – Nuclear Regulatory Commission
NTA – trimethylaminetricarboxylic acid
O&M – Operations & Maintenance
OD – outside diameter
OE – operating experience
OEM – original equipment manufacturer
PM – preventive maintenance
PT – dye penetrant testing
PWR – pressurized water reactor
RCM – reliability-centered maintenance
RCP – removable cover plate

RHR – residual heat removal

RVT – remote visual testing

SCC – stress corrosion cracking

SS – stainless steel

SSPC – Steel Structures Painting Council (currently refers to The Society for Protective Coatings)

TEMA – Tubular Exchangers Manufacturers Association

UT – ultrasonic testing

VI – visual inspection

VIAC – visual inspection acceptance criteria

1.5 Key Points

Throughout this report, key information is summarized in “Key Points.” Key Points are bold lettered boxes that succinctly restate information covered in detail in the surrounding text, making the key point easier to locate.

The primary intent of a Key Point is to emphasize information that will allow individuals to take action for the benefit of their plant. The information included in these Key Points was selected by NMAC personnel, consultants and utility personnel who prepared and reviewed this report.

The Key Points are organized according to the three categories: O&M Costs, Technical and Human Performance. Each category has an identifying icon, as shown below, to draw attention to it when quickly reviewing the guide.



Key O&M Cost Point

Emphasizes information that will result in overall reduced costs and/or increase in revenue through additional or restored energy production.



Key Technical Point

Targets information that will lead to improved equipment reliability.



Key Human Performance Point

Denotes information that requires personnel action or consideration in order to prevent personal injury, equipment damage, and/or improve the efficiency and effectiveness of the task.

The Key Points Summary section (Appendix A) of this guide contains a listing of all key points in each category. The listing restates each key point and provides a reference to its location in the body of the report. By reviewing that listing, users of this guide can determine if they have taken advantage of key information that the writers of this guide believe would benefit their plants.

2

HEAT EXCHANGER DESIGN AND CONFIGURATION

The purpose of this section is to provide a primer for plant engineering personnel regarding the basic design, function, and operation of the major types of heat exchangers discussed in this report.

2.1 Shell-and-Tube Heat Exchangers

2.1.1 *General Design Overview*

2.1.1.1 Process-Side System Design

The design of a heat exchanger typically begins with the process-side (or hot-side) system design. For example, closed-loop cooling system design typically results in the establishment of a specific number of heat sources (components generating heat) that need cooling. A specific quantity of closed-loop cooling flow is needed to ensure that an adequate distribution of cooling water is provided to each component being served. Each component needs to receive sufficient flow to meet individual vendor requirements for adequate heat removal and to ensure acceptable outlet temperatures downstream of each component.

The temperature of the cooling water that is delivered to each component is a critical input into the process because it relates to the amount of cooling water that is needed for each component. This establishes the heat exchanger outlet temperature, which becomes the supply header temperature.

Totaling all of the heat loads in the system along with the total system flow rate that will pass through the heat exchanger provides the designer with an estimate of the cooling water return header temperature using a mass and energy balance. This provides the heat exchanger process-side inlet temperature.

The complete thermal specification of the process side of the heat exchanger consists of the following:

- An outlet temperature
- A flow rate
- A required heat load at that temperature and flow rate

Multiple system functions and associated alignments that significantly change any of these inputs typically end up as different modes of heat exchanger operation represented by their own thermal analysis that is contained in a provided vendor data sheet. Maximum process-side temperatures and pressures factor into the heat exchanger's design pressure and temperature from a mechanical design perspective.

2.1.1.2 Cooling-Side System Design

Once the process-side parameters for the heat exchanger are known, the cooling water-side of the heat exchanger can be specified. Several thermal and hydraulic design considerations are involved.

2.1.1.2.1 Supply Temperature Requirements

Cooling water supply temperature is one of the most significant thermal properties for heat exchanger design in that it dictates the thermal capacity of the heat exchanger based on the terminal temperature difference created with respect to the process-side temperature. The cooling water inlet temperature is intimately tied to the design and licensing basis of the plant by the temperature ranges of the cooling water sources. Depending on the type of cooling water sources (for example, lake, river, ocean, or pond), the cooling water temperature has a range of values that can be driven by the seasons of the year as well as the time of day.

The maximum expected temperature of the ultimate heat sink serves as part of the design and licensing basis for the plant and typically becomes the design value for the cooling water inlet temperature for many heat exchangers in the plant. The fact that there can be such wide swings in inlet temperature can create the need for a method of flow control to regulate the cooling capacity of the heat exchanger that is consistent with the process-side temperature requirements.

2.1.1.2.2 Return Temperature Requirements

For a given heat load, the range of outlet temperatures can be estimated based on the range of inlet temperatures and possible flow rates. The maximum allowable outlet temperature includes such considerations as the prevention of two-phase flow (that is, boiling water) and discharge piping mechanical design considerations (for example, thermal expansion, design pressure, and design temperature). Outlet temperature can be regulated to some degree by the selected range of cooling water flow rates as described in the following sections.

2.1.1.2.3 Flow Requirements

Flow requirements are driven by three things:

- Cooling water maximum possible inlet temperature
- Constraints on the cooling water discharge temperature, as described previously
- Required heat removal rate

Issues to consider are as follows:

- Worst-case hydraulic alignments of the system (including undesirable bypass flows)
- Pump degradation
- Variation in ultimate heat sink level
- Pressure loss across the heat exchanger itself

System hydraulics may be further complicated by maintenance and inspection issues such as silting and macrofouling. Fouling considerations are discussed later.

2.1.1.2.4 Differential Pressure Considerations

The system design and licensing basis frequently includes a requirement to keep the cooling water side of the heat exchanger at a higher pressure than that of the process side. Such requirements ensure that any leakage from the one system to the other will be from the cooling water side to the process side of the heat exchanger. This is of particular importance when the process side has the potential to become radioactively contaminated and the cooling system must not allow a discharge path to the environment. A minimum differential pressure (ΔP) requirement complicates the flow control and ultimately limits the range of possible flow rates.

2.1.1.2.5 Shell-Side Design

Shell-side design considerations include the following:

- **Selection of the shell side as the process side or the cooling side** – Typically, the shell side is connected to the system with the cleanest fluid because the shell side is the most difficult to clean. In some cases, the fluid can be from the raw water system.
- **Design temperature and pressure** – The shell-side design temperature and pressure are derived from the fluid system design temperature and pressure for the fluid supplied to the shell. The main outcomes of these inputs are the thickness of the shell and the attached nozzles.
- **Shell size** – The size of the shell depends on the number of tubes and the type of baffling that is selected to create the cross-flow circuit. Size selection takes into account space constraints as well as cost. Efficiency of geometry generally results in longer and narrower heat exchangers. This results in a smaller tube sheet, which can be the most expensive part of the heat exchanger.
- **Baffle spacing** – Baffling directs the shell-side flow over the tubes to create a thermally efficient cross flow. Tighter baffling (closer spacing) usually results in a better overall cross-flow effect. Other benefits of close spacing are higher velocity across the tubes for a given flow rate, which then enhances the heat transfer film coefficient. Mechanically, baffles offer lateral support of the tubes. On the down side, baffling increases hydraulic resistance, which increases the ΔP across the heat exchanger. Such effects must be accounted for in the shell-side system thermal hydraulics analysis.

- **Vibration** – The heat exchanger is a complex compilation of many parts that are subject to a variety of forces. The inherent looseness of the tubes in the tube bundle makes them susceptible to vibration-induced damage. The use of support or baffle plates at predetermined distances ensures a measure of protection against damaging vibration. However, flow-induced vibration at flow beyond what the designer considered could create problems as tubes vibrate in their supports, causing tube fretting at support points, tube erosion, or baffle plate deformation.
- **Component differential pressure (ΔP)** – As noted in the preceding section, some applications include the need to maintain the process fluid at a lower pressure than the cooling water fluid pressure, which dictates a hydraulic constraint for the component in terms of its hydraulic resistance at the design flows.

2.1.1.3 Tube-Side System Design

Tube-side design considerations include the following:

- **Design temperature and pressure** – The tube-side design temperature and pressure are derived from the cooling system design temperature and pressure. The main outcome of these inputs will be specifications for the thickness of the tubing and the channel connections to the shell.
- **Tube material** – The tube material is selected for its corrosion resistance as well as its thermal conductivity and strength. The most important corrosion-resistance considerations are the types of fluid that will exist on both sides of the tube and the kinds of service that the component will be subjected to. When finalizing the number of tubes with respect to the desired surface area, another consideration is the resulting tube velocity for a given tube-side flow rate. The erosion resistance of the tube material can limit the allowable velocity.
- **Tube wall thickness** – Tube wall thickness is determined first by considering thermal considerations and secondly the design operating pressure of the heat exchanger. For a given material selection, the wall thickness becomes a consideration with respect to the desired level of strength. Again, considering the type of service and the amount of corrosion as well as the type of corrosion mechanisms (thinning, cracking, or pitting), a wall thickness is selected that will provide an appropriate level of service life.
- **Tube size** – Tube outer diameter specifies the tube size. In conjunction with the specified wall thickness, the outside diameter specifies the inside diameter. The outside diameter is a key input into the calculation of the heat transfer surface area, and the inside diameter is a key consideration in keeping tube velocity within appropriate limits based on the selected tube material. Tube velocity will be fixed based on the inside diameter and number of tubes for a given flow rate. A tradeoff on tube size becomes apparent as the designer balances area effectiveness (smaller tubes provide greater surface area for a given heat exchanger size) against hydraulic resistance (larger tubes provide less hydraulic resistance on both the tube and shell side of the heat exchanger).
- **Tube pitch** – *Tube pitch* refers to the geometric arrangement of the tubes in the tube bundle as well as the spacing between tubes in the bundle. A compromise between minimizing hydraulic resistance and maximizing surface area in a given heat exchanger shell size drives the selection of an optimum arrangement and spacing.

- **Number of tubes** – Combined with tube size, the number of tubes drives both the available heat transfer area and the tube velocity. The number of tubes can be a source of thermal performance margin if tube plugging has been anticipated. The tube plugging allowance is determined by the purchase specification and can account for 5%–10% of additional area.
- **Tube length** – Tube length is a primary variable for achieving the desired heat transfer when all other tube geometry and tube bundle considerations have been addressed.
- **Tube passes** – Frequently, the need for multiple passes on the tube side stems from the need to keep the tube velocity above minimum acceptable levels for a given number of tubes. In other words, if the desired heat transfer area requires a specific number of tubes in a specified length, the given tube flow rate can be too low. By forcing the given flow rate through half as many tubes and passing it back through the other half, the tube velocity can be doubled and put into a more efficient flow regime. The passes can be achieved with either straight tubes or U-bend tubes. The selection of pass configuration must be weighed against the loss of efficiency. Multiple tube passes are another—often better—way to achieve the desired tube length.
- **Divider plate differential pressure (ΔP)** – The divider plate separates inlet flow from outlet flow in a multi-pass heat exchanger. The plate must be strong enough to withstand the ΔP created by the pressure drop across the heat exchanger, which is a function of the flow rate and the number of available tubes. Plate failure will result in bypass of the heat exchanger tubes and a corresponding reduction in heat exchanger thermal performance.
- **Component differential pressure (ΔP)** – As previously discussed, some applications include the need to maintain a lower shell-side fluid pressure than the tube-side fluid pressure and dictates a hydraulic constraint for the component in terms of its hydraulic resistance at the design flows.

2.1.2 Types and Layout

Figure 2-1 is a schematic drawing of a shell-and-tube heat exchanger as discussed in this report. This is a depiction of a once-through design, but there are other designs as well for this type of heat exchanger. Figure 2-2 shows the shell and rear-end head types for shell-and-tube heat exchangers.

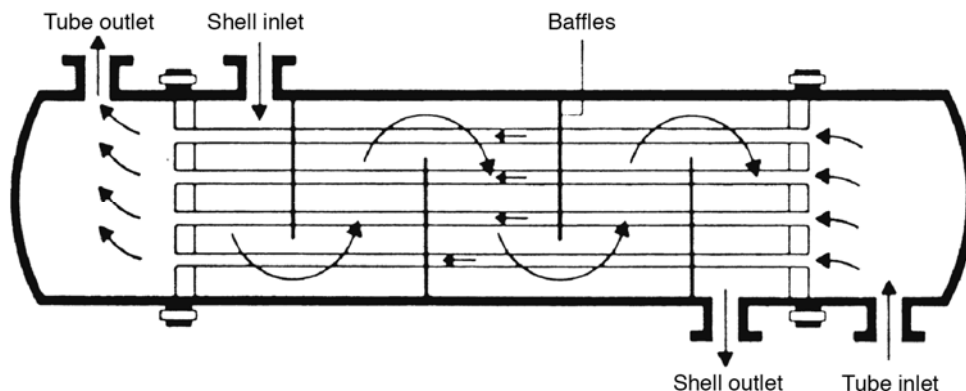


Figure 2-1
Schematic drawing of a once-through shell-and-tube heat exchanger

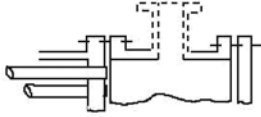
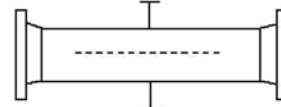
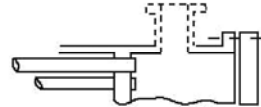
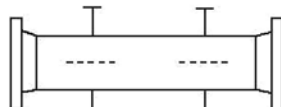
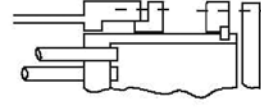
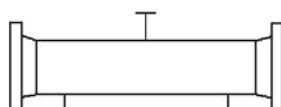
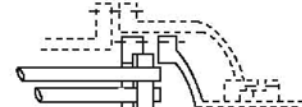
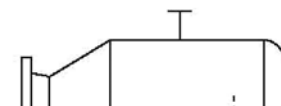
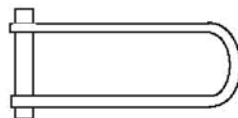
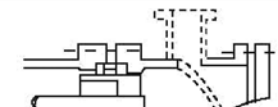
	Shell types		Rear end head types
E	 One-pass shell	L	 Fixed tubesheet like "A" stationary head
F	 Two-pass shell with longitudinal baffle	M	 Fixed tubesheet like "B" stationary head
G	 Split flow	N	 Fixed tubesheet like "N" stationary head
H	 Double split flow	P	 Outside packed floating head
J	 Divided flow	S	 Floating head with backing device
K	 Kettle-type reboiler	T	 Pull-through floating head
X	 Cross flow	U	 U-tube bundle
		W	 Externally sealed floating tubesheet

Figure 2-2
Types and layout of shell-and-tube heat exchangers (from the Tubular Exchangers Manufacturers Association)

2.1.3 Components

The components of a shell-and-tube heat exchanger include the following:

- Shell
- Channel and covers
- Pass partitions, plate and cover (if multi-pass)
- Tubesheet
- Tubes
- Baffle plates
- Nozzles

These components are discussed in detail in the following sections.

2.1.3.1 Shell

The shell of a heat exchanger has the following functions:

- Withstands shell-side pressure
- Contains and directs the flow of shell-side fluid
- Supports the tubes and baffles
- Distributes fluid on the tubes

Heat exchanger supports on the bottom of the shell exterior address the dead weight of the heat exchanger, the operating weight of the fluids, the thermal expansion of the heater, nozzle forces and moments, and restraint during any seismic activity included in the design. On horizontal heat exchangers, one support is fixed on the exterior of the shell to hold that point at a constant position with respect to the building. The second support permits the heat exchanger to grow away from the fixed point. This is done with either guided or unguided wheels, rollers, or a sliding support.

2.1.3.2 Channel and Covers

The channel serves the function of the tube-side fluid inlet for the heat exchanger. It also acts to redirect the flow from one tube pass to the next if a multi-pass design is used. Full-access channels and covers are normally used in low-pressure heat exchangers.

2.1.3.2.1 Full-Access, Low-Pressure

The low-pressure, full-access channel design includes the following:

- Inlet/outlet nozzles
- Vent and drain connections
- Instrument connections
- Safety relief valve connection
- Pass partition plate (if multi-pass)
- Bolting bar (if applicable to the design)
- Partition cover studs and nuts (if applicable to the design)
- Pass partition gasket and cover (if applicable)
- Cover studs and nuts
- Gasket
- Cover

Two examples of the full-diameter bolted and gasketed channel designs, with different pass partition arrangements, are shown in Figures 2-3 and 2-4.

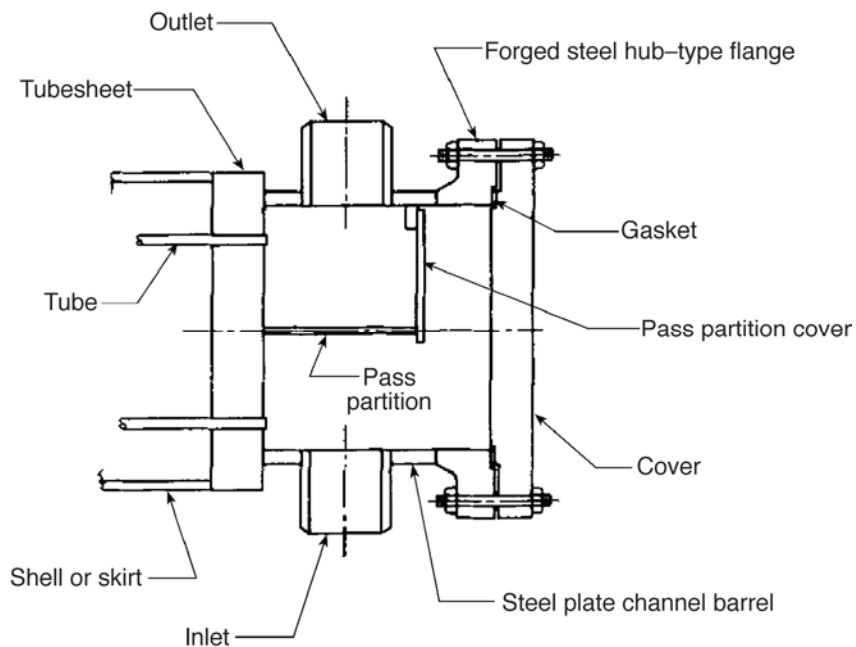


Figure 2-3
Full-access, low-pressure pass partition cover design

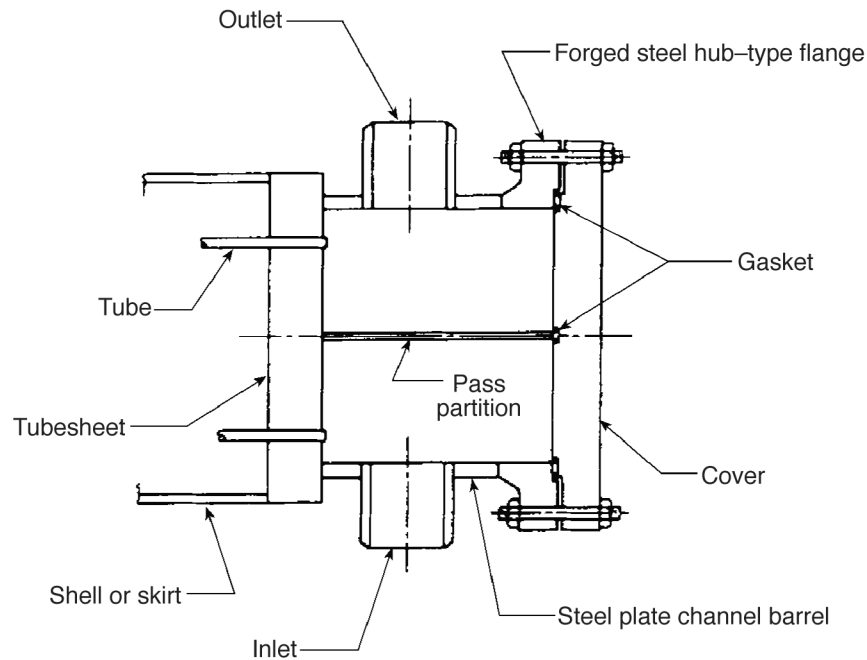


Figure 2-4
Full-access, low-pressure pass partition design

2.1.3.3 Pass Partitions, Plate and Cover

The pass partition separates the fluid in the channel into the various passes where applicable. The pass partition cover can be welded or bolted in the channel or may rely on the channel cover to seal the pass partition in place. There are two types of pass partition designs normally used:

- Welded
- Bolted

2.1.3.3.1 Welded Pass Partition Design

Figure 2-5 illustrates an example of a welded pass partition design.

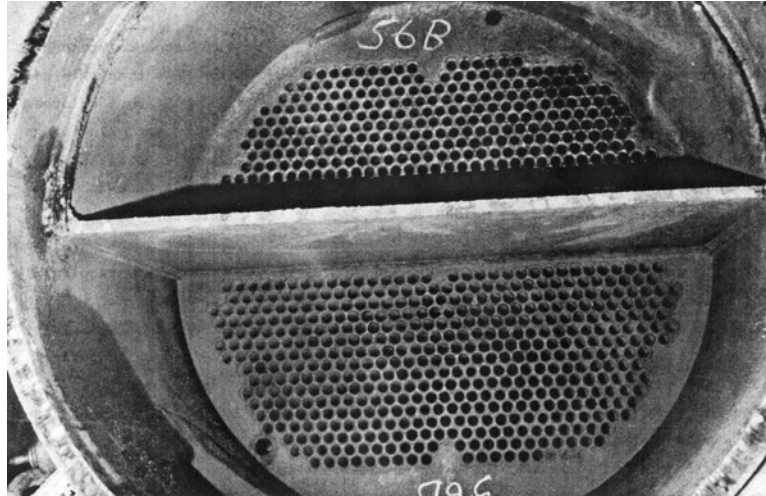


Figure 2-5
Welded partition plate

A welded pass partition plate is most common when access to the heat exchanger is infrequent. The welded plate has a lower failure rate when compared to the bolted pass partition plate design. The welded pass partition design restricts the channel wall from growing in a radial direction as it would under pressure. This design produces a thermal gradient in the channel and channel-to-tubesheet connection, adding additional stress to this area. During operation, one half of the channel is hotter than the other half. The radial growth of the hotter side is greater than the colder side due to thermal expansion resulting in bending stresses at the pass partition weld junction. Over time, cyclic pressure and thermal stresses may lead to cracking around the periphery of the pass partition plate.

2.1.3.3.2 Bolted Pass Partition Design

An alternative to the welded pass partition is the bolted pass partition. This design is shown in Figures 2-6 and 2-7.

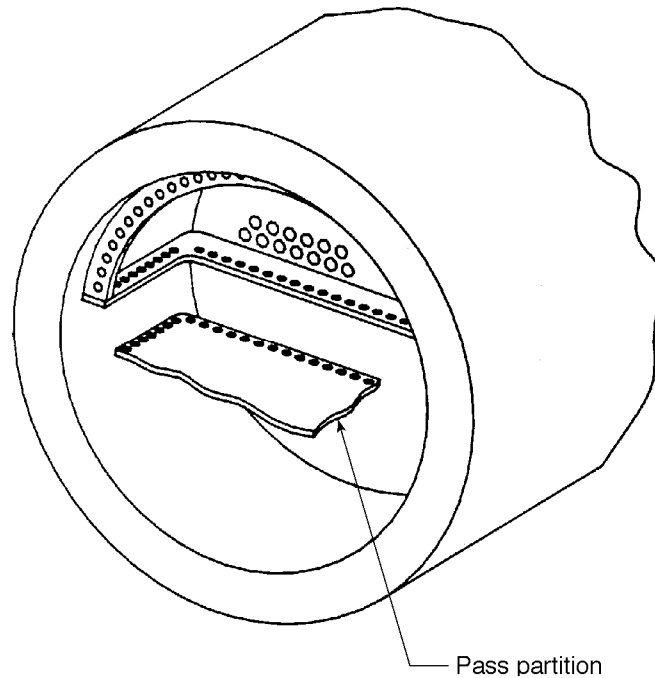


Figure 2-6
Bolted pass partition design

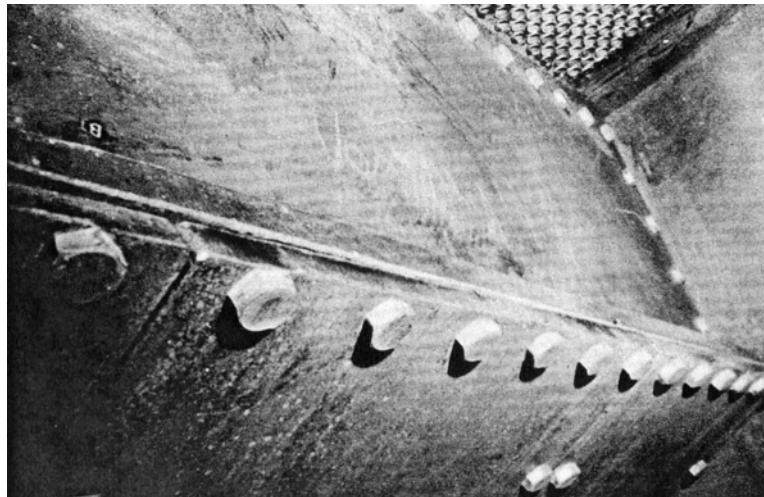


Figure 2-7
Bolted partition plate

The bolted pass partition design is not as restrictive to channel wall growth as is the welded design. However, it is still restrictive because the bolting bars are welded to the channel wall and tubesheet face. This design results in a thermal gradient in the tubesheet connection area. The tubesheet connection radius is used to lower the stress concentrations by providing greater flexibility at the tubesheet-to-channel connection. When a plate or bar is welded along this radius, the flexibility provided by the radius is lost, a notch is created, and stress concentrations are intensified.

Problems can also occur with the welded, circumferential bolting bar used to support the bolted pass partition cover. The channel wall is stiffened locally, which restricts radial growth. Additional stress is also added to the nozzle-to-channel connections because this bar is located very close to the nozzle inside diameter.

The bolted pass partition design is more prone to interpass leakage due to deflection of the channel covers.

2.1.3.4 Tubesheets

The tubesheet is a forged plate with drilled holes for tube placement. Some tubesheets have tube hole grooves that increase the holding force of the expanded tubes. Low-pressure heat exchanger tubesheets are generally carbon steel plate; open cooling water systems often use more corrosion-resistant materials; and the carbon steel tubesheet may have cladding or be coated for corrosion protection.

Tubesheet material can be specified with low nil-ductility (zero-ductility) characteristics so that hydro-testing can be performed without requiring heated test water. The manufacturer's manual should always be checked before performing hydro-testing to ensure that a temperature restriction does not apply.

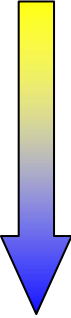
Tubes are usually roller expanded into the tubesheet to a depth that is sufficient to develop a high pullout load, or they may be specified with welded tube-to-tubesheet joints.

2.1.3.5 Tubes

Tube design pressure is required by ASME and other governing codes to be equal to or greater than the maximum normal pressure that will be experienced in operation. Additional guidance regarding tube materials is provided in EPRI report 1014481, *Materials Handbook for Nuclear Plant Pressure Boundary Applications*.

Recommended tube velocities are dependent on water quality and tube material. Normally, for open loop systems (that is, cooling tower, clean river or lake water), it is recommended that, if possible, the water velocity be kept above 3 feet per second (0.91 m/s) to reduce the risk of sedimentation and to minimize bio-fouling on the ID of the tubes. If the water has higher levels of suspended solids, a higher tube velocity should be considered. Depending on the tube material, the velocity should be controlled to avoid erosion. Table 2-1 provides the maximum recommended tube velocities for common tube materials. Figure 2-8 is a picture of a tube bundle at the U-bend.

Table 2-1
Maximum recommended tube velocities

Tube material	Tube velocity		Thermal conductivity
	Feet per second	Meters per second	
Copper	6.0	1.83	Highest  Lowest
Admiralty brass – general service	6.0	1.83	
90/10 Cu/Ni	9.0	2.74	
Carbon steel	6.0	2.74	
70/30 Cu/Ni	9.0	4.57	
304 or 316 stainless steel	12.0	3.66	
304L or 316L stainless steel	15.0	4.57	
Titanium	>15.0	>4.57	

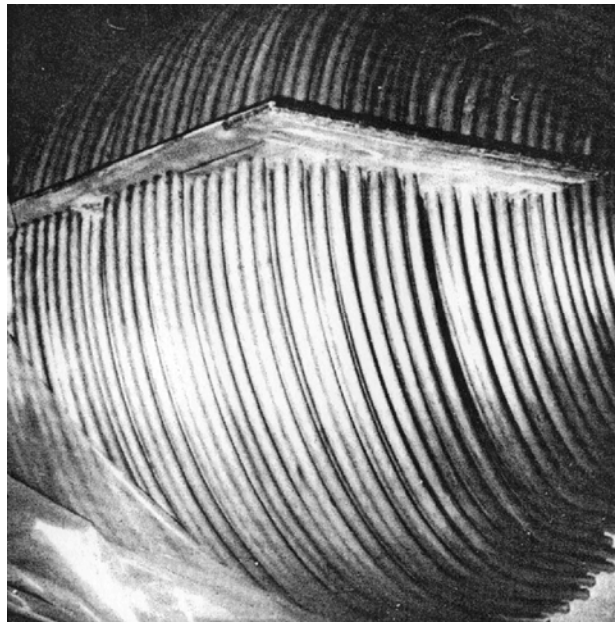


Figure 2-8
Tube support bundle at a U-bend

2.1.3.6 Baffle Plates

Baffle plates provide support for the tubes and direct the flow through the bundle to maximize heat transfer while maintaining shell-side pressure drop within acceptable limits. The type of baffle cut and the spacing are selected during design to balance considerations of space constraints, shell-side pressure drop, heat transfer efficiency, and tube vibration.

Closer baffle spacing provides reduced tube vibration, but increases pressure drop and, if positioned too close together, can reduce thermal efficiency. Longer baffle spacing results in lower pressure drop, but increases tube vibration and, if excessive, can also reduce thermal efficiency. There are various TEMA designs related to shell-side flow configurations that are selected to optimize the design for the application.

2.2 Plate Heat Exchangers

2.2.1 Main Components of the Plate Heat Exchanger and Their Functions

In plate heat exchangers, heat is transferred from one medium to another through thin metal plates, which have been pressed together into a pattern. Figure 2-9 illustrates typical components of a plate heat exchanger.

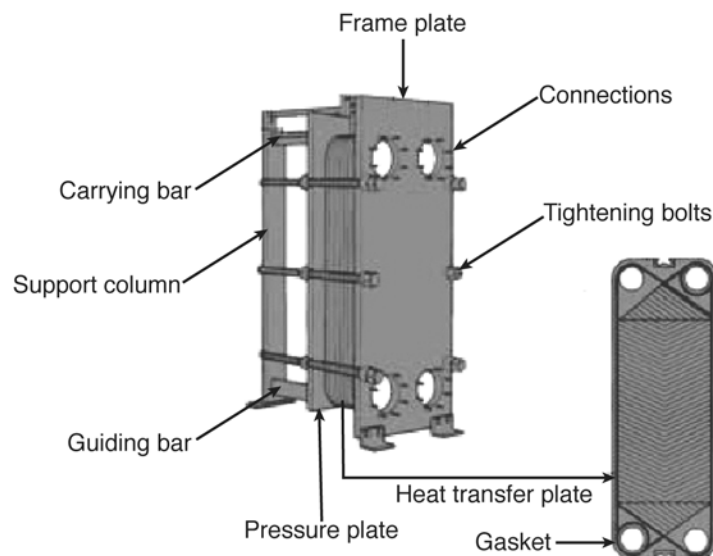


Figure 2-9
Typical plate heat exchanger components

- **Frame plate** – The frame plate is the side of the heat exchanger that connects to the inlet and outlet piping of both the hot and cold fluids. It is the plate used for the pressure plate to squeeze varied numbers of channel plates together in order to achieve the amount of heat transfer required for the application. This item is also known as a *fixed cover*, *stationary cover*, *fixed head*, or *head*.
- **Support column** – This is a column bolted to the floor that supports the carrying bar and guiding bar weight.
- **Stud bolt and connections** – Holes matching the piping lead through the frame plate, permitting the media to enter the heat exchanger. Threaded studs around the holes secure the pipes to the equipment. Depending on the application, metallic or rubber-type linings may protect the edges of the holes against corrosion.
- **Carrying bar** – The plates hang from a carrying bar at the top of the heat exchanger.
- **Guiding bar** – The plates are kept in line by a guiding bar at the bottom of the heat exchanger.
- **Shroud** – This covers the plate pack to protect it from the environment or to protect the environment around a plate heat exchanger from fluid that is contained inside.
- **Tightening bolts** – With a package of thin plates hanging between the frame plate and the pressure plate, tightening bolts are used to press the thin channel plates together and bring them into contact. They are tightened to compress the gaskets enough to seal the narrow passages that have now been formed between the plates.
- **Pressure plate** – The pressure plate is hung on the carrying bar and is moveable, as are the heat transfer plates. In some rare cases, piping may be connected to the pressure plate. This item is also known as a *follower* or a *movable cover*.
- **Plate pack** – Heat is transferred through the surface, except for some small areas near the corners. The number of plates in the heat exchanger is determined by the size of the heat transfer surface required. The heat transfer plates (plate pack) are compressed between the pressure plate and frame plate to form the separate flow paths for the process and service fluids. The corrugated plates are typically formed from metal that is 0.016–0.036 inches (0.4–0.9 mm) thick. Proper plate design and material thickness are determined by ASME Pressure Vessel Code requirements so that the plate pack can withstand the full design pressure.

Plate corrugation can be of many types. One pattern, known as *washboard corrugation*, consists of troughs perpendicular to the direction of the liquid flow. These troughs mate with those of the adjacent plate but are kept apart by raised pipes that contact a corresponding point on the adjacent plate, forming flow channels, which results in a ribbon flow path. The gap forming the flow channel typically ranges from 0.150 inch to 0.390 inch (3.8 mm to 9.9 mm), depending on plate design.

The most commonly used plate pattern is the chevron. This design is based on corrugations formed at an angle to the liquid flow that, in combination with plates of opposite or different angles, make contact at the corrugation cross-over points to permit flow between them. This

pattern forms a flow path that is broken into many high-turbulence helical streams. Flow channel gaps on chevron plates typically range from 0.080 inch to 0.433 inch (2.0 mm to 11 mm).

Most applications with clean fluids use chevron plates with flow channel gaps in the lower half of the range (0.080 inch to 0.160 inch [2.0 mm to 4.1 mm]). At the upper end of the range (near 0.250 inch [6.4 mm]), modern wide-gap chevron plates often replace the traditional washboard-style plates because chevron plates can achieve greater mechanical strength and higher design pressure limits with reduced plate thickness and, in turn, a lower cost.

- **Gasket** – Gaskets can be made of various materials, depending on the temperature and corrosiveness of the fluids being handled. For semi-welded plate units, the number of gaskets is reduced by half because sets of two heat transfer plates are welded together on one side. This limits gasket exposure to aggressive chemicals and high temperatures and, where necessary, allows the cost-effective use of elastomers with better chemical resistance. Attachment methods vary between glued and nonglued methods.

2.2.2 Functionality of a Plate Heat Exchanger

Figure 2-10 illustrates the flow pattern for a parallel-flow plate heat exchanger.

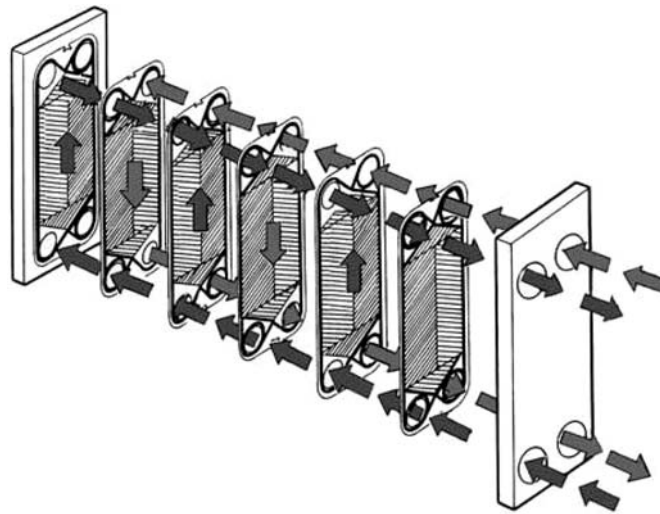


Figure 2-10
Parallel-flow plate heat exchanger

Figure 2-11 illustrates the flow pattern for a diagonal-flow plate heat exchanger. Note that the difference is that the outlet flow is diagonal to the inlet flow when you are looking at an end view of the unit; whereas, on the parallel-flow plate heat exchanger, the outlet flow is directly above/below the inlet flow when looking at an end view of the unit.

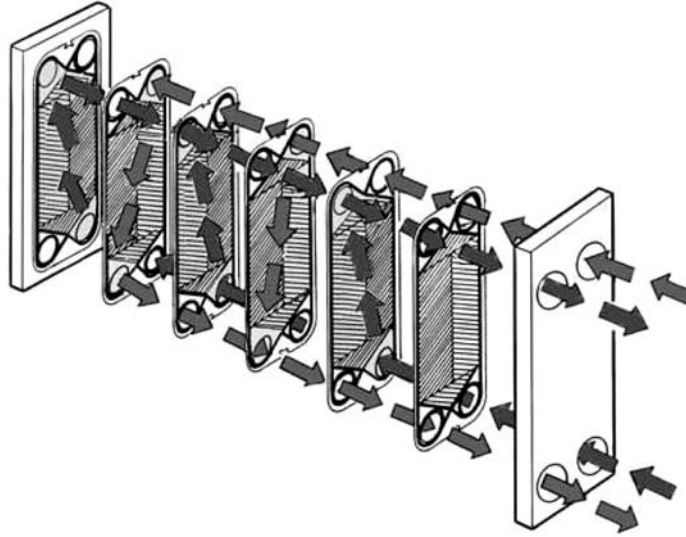


Figure 2-11
Diagonal-flow plate heat exchanger

When a package of plates is pressed together, the holes at the corners form continuous tunnels or manifolds, leading the media (which participate in the heat transfer process) from the inlets into the plate pack, where they are distributed in the narrow passages between the plates.

Because of the gasket arrangement on the plates, and the placing of “A” and “B” plates alternately, the two liquids enter alternate passages, for example, the warm liquid between even-numbered passages and the cold liquid between odd-numbered passages.

The media are separated by the heat transfer plate. In most cases, the liquids flow in opposite directions.

2.2.3 Gaskets

Figure 2-12 illustrates typical configurations for a gasket used in either the parallel flow– or diagonal flow–type of heat exchangers.

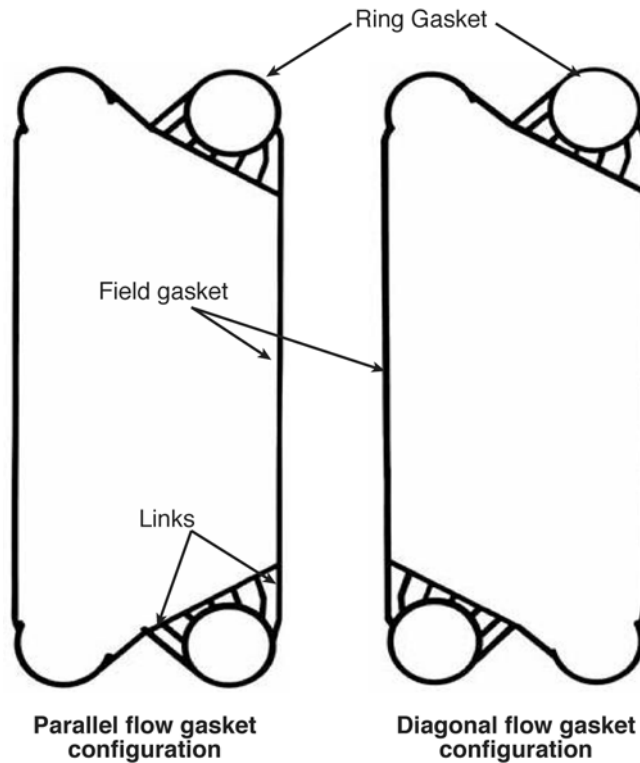


Figure 2-12
Typical gasket configurations

A plate heat exchanger gasket is molded in one piece. The material is normally an elastomer that has been selected to suit the combination of temperature, chemical environment, external environmental conditions (both normal and accident – for example, radiation, temperature, humidity, etc.), and possible other conditions that may be present. The one-piece gasket consists of three parts:

- **Field gasket** – This is the largest part of the gasket that contains the whole heat transfer area with two corners connected to it.
- **Ring gaskets** – These parts of the gasket seal off the remaining two corners.
- **Links** – The links hold the field gasket and two ring gaskets together on larger designs. The links have no sealing function at all. These links may also be referred to as *fingers*. Their purpose is to tie the pieces together and to add support in certain areas. On some plate heat exchangers, the gasket is held in place on the plate by cement or glue.

As already demonstrated, the two media are effectively kept apart by the ring and field gaskets. To prevent intermixing of the media in the corner areas where field and ring gaskets are very close to each other, the link pieces have a number of slots, which opens the area between the field and ring gaskets to atmosphere. Figure 2-13 illustrates the position of these slots.

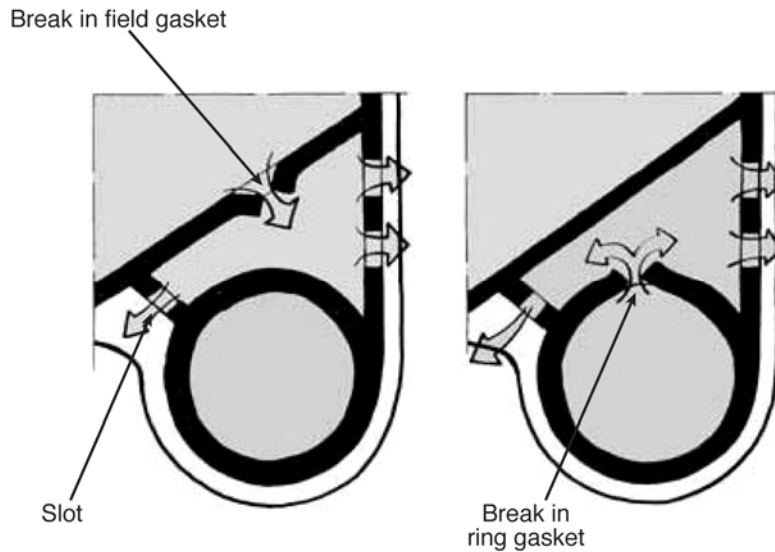


Figure 2-13
Slot configuration

Any leakage of media across either gasket will escape from the heat exchanger through the slots. It is important that these openings are kept clear. If they are not, there is a risk that if a leak occurs in that region of the plate, there might be a local pressure build-up, which could allow one medium to mix with the other. Take care not to cut or scratch the gaskets while handling plates.

2.3 Air-to-Water Heat Exchangers

2.3.1 Description

An air-to-water heat exchanger is an arrangement of surfaces separating an air stream and a fluid stream to maximize heat transfer. The most common air-to-water heat exchanger is the fin-tube heat exchanger, which is often placed directly in an air ductwork, and the fluid side is connected to a hydraulic system. The tubes have the fluid running through them, and the fins on the outside of the heat exchanger create a large heat transfer surface.

Air has poorer heat transfer properties when compared to water. In order to compensate for this discrepancy, the fluid flows inside the tubes, and the fins are placed on the outside of the tubes to create a large heat transfer surface in contact with the air to improve thermal performance. The finned tube bundle of an air-to water heat exchanger is often referred to as a *coil*.

Air-to-water heat exchangers can be used to heat air, cool air, cool and dehumidify air, or to heat or cool fluid with air. Cooling air is the most common application of air-to-water heat exchangers in the power generation industry. In most applications, air is delivered by a fan or blower that is mounted in ducting located upstream or downstream from the heat exchanger or that can be mounted directly to the coil.

2.3.2 Principles

Air-to-water heat exchangers can be characterized as counter flow, parallel flow, or cross flow. Optimum heat transfer is obtained with the counter-flow heat exchanger configuration. The air-to-water heat exchanger is typically designed as a number of connected heat exchangers. When they are connected in series, a counter-flow effect is obtained; when they are connected in parallel, cross-flow characterization is obtained.

2.3.3 Design and Material Variations

2.3.3.1 General

The fin-tube heat exchanger can be varied in size, dimensions, and fin spacing with a combination of construction materials. The tubes and fins may be made of copper, aluminum, steel, and different alloys of these metals, as well as stainless steel and other metals. In some applications, plastics may be suitable, but that is uncommon. Copper tubes and aluminum fins are the most common and economical type of finned tube. The materials have to be carefully selected to avoid corrosion and galvanic action on the fluid side, particularly if open cooling water systems are used. Because water quality varies, the tube material should be selected to suit the specific installation location. Different metals have different thermal conductivities, so the thermal implications should be determined when considering changing tube or fin materials.

2.3.3.2 Fin Types

There are a number of available fin types for air-to-water heat exchangers, each with a unique fin design and attachment method. These fin-type configurations are illustrated in Figures 2-12 through 2-17. Each fin type has advantages and disadvantages in specific applications; consequently, the most appropriate fin selection is dependent on the environment in which it will be applied, the criticality of the installation, the longevity desired, and the maintenance requirements.

2.3.3.2.1 Plate Fin

In the plate fin design, tube holes are pressed in thin sheets of metal, where tubes are inserted and then expanded. This highly efficient fin type provides a very large surface area that helps distribute heat evenly. The fins can be waffled or rippled for greater efficiency. The fin thickness can be varied from thin, in situations where cost is important and cleaning efficiency is not an issue, to thick, in applications where ruggedness and cleaning efficiency are essential. Figure 2-14 illustrates a plate fin design configuration.

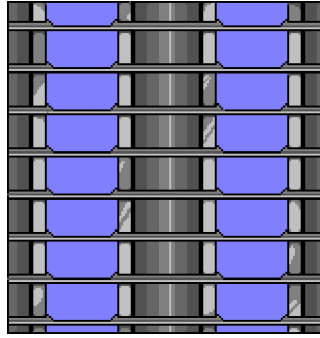


Figure 2-14
Plate fin design configuration

Common applications for the plate fin configuration include HVAC coils, steam coils, air preheaters, air-cooled heat exchangers, transformer oil coolers, motor coolers, and generator coolers.

2.3.3.2.2 Tension-Wound Fin

The tension-wound fin has the fins wrapped tightly around the tube and stapled or welded at the ends to hold the form. These fins are best applied when the fin and tubes are made of the same material. This type of fin is generally used in lighter duty, noncritical applications, where low cost is important and temperature cycling is not an issue. Tension-wound fins can also be solder-coated to help increase corrosion resistance and improve the fin bond to the tube. Figure 2-15 illustrates a tension-wound fin design configuration.

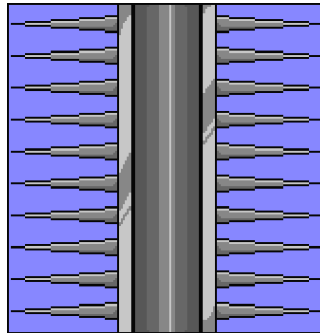


Figure 2-15
Tension-wound fin design configuration

Common applications include HVAC coils.

2.3.3.2.3 “L” Footed Fin

The “L” footed fin has a lip at the base, which is tension wound around the tube. This increases the heat transfer contact area between the tube and the fin and decreases the exposed joint at the fin base. ‘L’ footed fins are better suited than tension-wound fins when the fin and tube are dissimilar metals. Figure 2-16 illustrates an “L” footed fin design configuration.

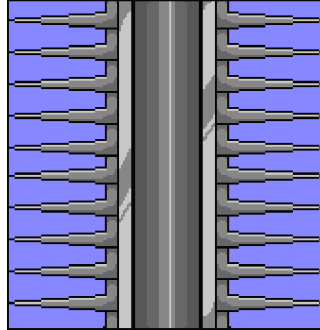


Figure 2-16
“L” footed fin design configuration

Common applications include HVAC coils and steam coils.

2.3.3.2.4 Overlapped “L” Fin

The overlapped “L” fin design has interlocking fins that are wound together to prevent movement and separation. The fin protects the entire tube, so the design works better than the conventional “L” footed fin in applications where corrosion is a factor. Figure 2-17 illustrates an example of an overlapped “L” fin design configuration.

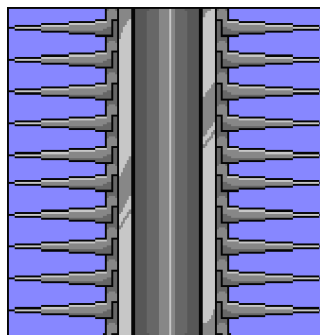


Figure 2-17
Overlapped “L” fin design configuration

Common applications include steam coils and air preheaters.

2.3.3.2.5 *Embedded Fin*

In the embedded fin design, the fin is inserted into a helical groove cut into the tube. The groove is back-filled, which anchors the fin to the tube. The fins can withstand higher temperatures than other designs and are very durable. Embedded fins are best suited for applications that involve high temperatures or thermal cycling and where the fin side will be subjected to frequent cleaning. The tube wall is grooved so a heavy wall tube is required for the embedded fin. Figure 2-18 illustrates an embedded fin design configuration.

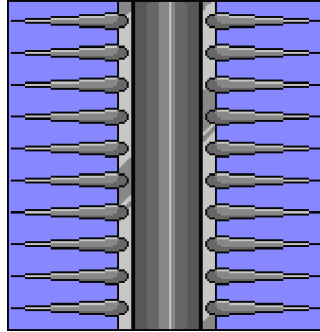


Figure 2-18
Embedded fin design configuration

Common applications include steam coils, air preheaters, and air cooled heat exchangers.

2.3.3.2.6 *Bi-Metal Extruded Fin (Integral Fin)*

Extruded (or integral fins) are created by sliding a liner tube inside a thick-walled tube and then sending this assembly through a rotary press that extrudes the fin from the thick-walled tube in a cold-working process. The outer tube is pressed into a fin pattern, while a mechanical bond is created between the outer (finned) tube and the liner tube. Because the fins are one piece, there is no exposed bi-metal joint at the base of the fin. The liner tube can be chosen to best suit the tube-side fluids since only a small area of the liner tube is exposed to the gas side. Figure 2-19 illustrates an example of a bi-metal extruded fin design configuration.

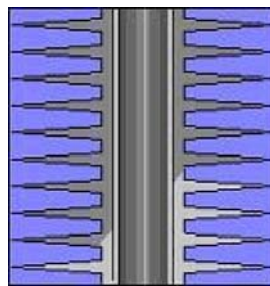


Figure 2-19
Bi-metal extruded fin design configuration

Common applications include steam coils, air preheaters, motor coolers, generator coolers, transformer oil coolers, and air-cooled heat exchangers.

2.3.4 Coil Types

Although the principles of operation are the same, coils can be constructed differently depending on the application and maintenance program for the heat exchanger. The most common type of air-to-water heat exchanger is the multirow design, which often has brazed tube joints and pipe headers and is generally limited to nonferrous tubes. The coil typically has a steel channel frame for rigidity and has U-shaped return bends that are designed to direct water flow to achieve the required pass arrangement. The tube side of the multirow coil design is not accessible and can be cleaned only chemically. Figure 2-20 illustrates an example of the multirow air-to-water heat exchanger.



Figure 2-20
Multirow-type air-to-water heat exchanger

Another type of heat exchanger design has a removable cover or end plate, which allows access to the tubes for cleaning or inspection and has welded headers. The coil generally has steel channel-side casings attached to tubesheets to form a rigid frame. Common tubesheet materials include steel, stainless steel, brass, and copper-nickel. The tubes are typically roller-expanded into the tubesheet, and a welded header (including pass partitions) is bolted or welded to the tubesheet. The tubes can be seal or strength welded to the tubesheets if the application demands additional leak protection. A cover plate is bolted to the header, “sandwiching” the header between the cover plate and the tubesheet. Figure 2-21 illustrates an example of an air-to-water heat exchanger with a removable end plate.

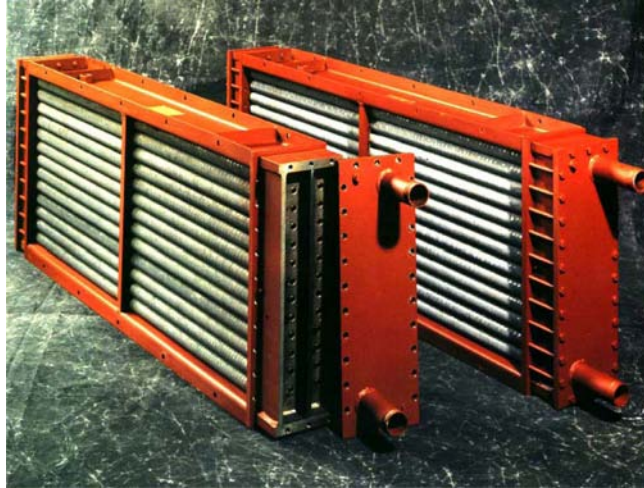


Figure 2-21
Air-to-water heat exchanger with a removable end/cover plate

Figure 2-22 shows an exploded view of an air-to-water heat exchanger with removable end covers.

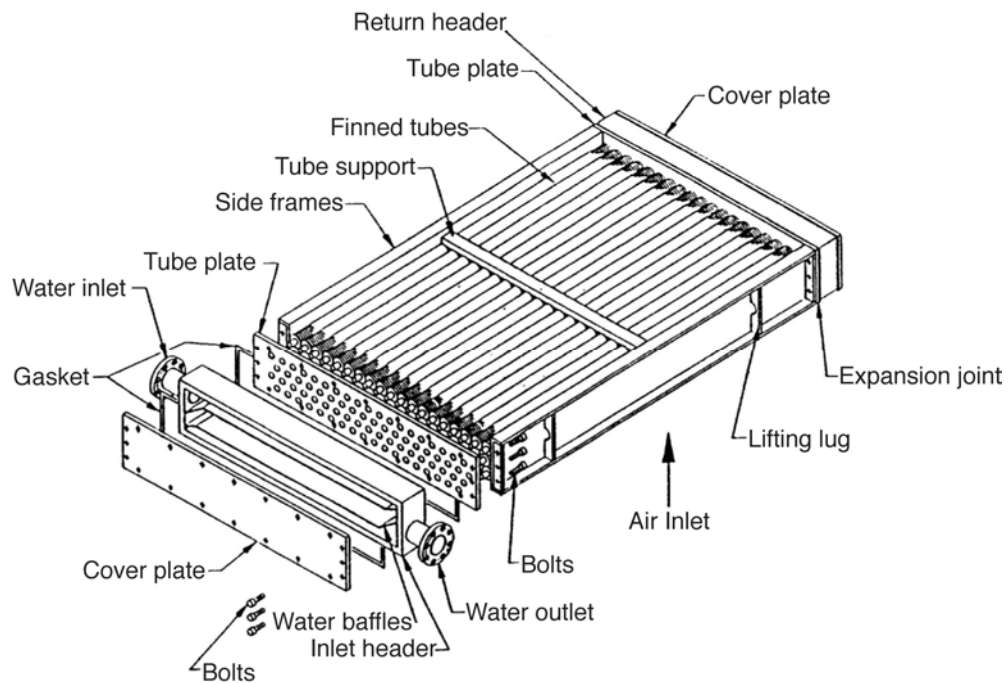


Figure 2-22
Air-to-water heat exchanger with removable end/cover plate (exploded view)

Common nomenclature used to describe an air-to-water heat exchanger is as follows:

- **Tube face** – The number of individual tubes in the cross-section of the duct (also called *tubes per row*).
- **Face width** – The dimension of the heat exchanger in the direction of the tube face (inside the casings).
- **Face length** – The length of the individual tube exposed to the air stream between the tubesheets. This value can be an actual number or a nominal length. (also called *nominal length* or *finned length*).
- **Rows** – The number of tube faces of tubes that the air flows over, perpendicular to the duct cross-section.

Figure 2-23 illustrates how an air-to-water heat exchanger is configured.

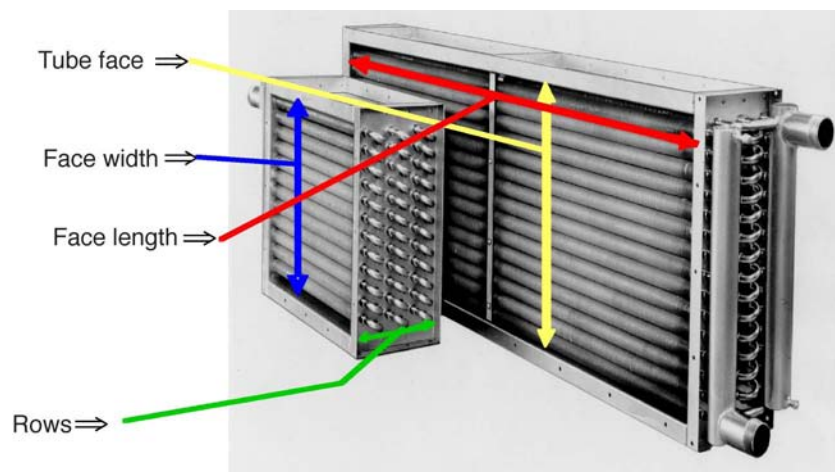


Figure 2-23
Typical heat exchanger nomenclature

2.3.4.1 Circuiting

Circuiting describes the path that the water travels through the coil in relation to the number of rows and the tube face. Figure 2-24 illustrates four rows of tubes in a four-pass, single-velocity, full-circuit arrangement.

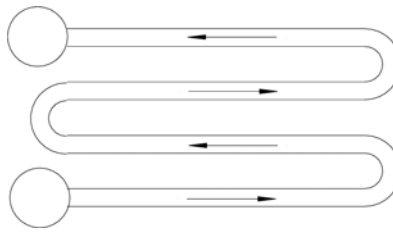


Figure 2-24
Four-pass, single-velocity, full-circuit arrangement

Figure 2-25 illustrates four rows of tubes in a two-pass, half-velocity, double-circuit arrangement.

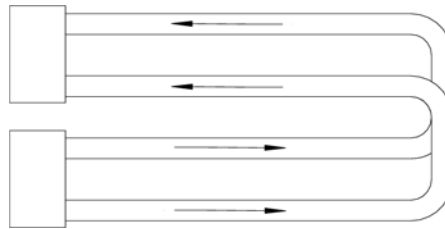


Figure 2-25
Two-pass, half-velocity, double-circuit arrangement

If only half of the tubes in the face are fed, the water makes eight passes through a four-row coil and is called *double velocity* or *half circuit*. If only a third of the tubes in the face are fed, the water makes 12 passes through a four-row coil and is called *triple velocity* or *1/3 circuit*. The circuiting is chosen to maintain a suitable water velocity in the tubes while meeting the heat transfer performance with the available water flow.

2.3.5 Thermal Design Considerations

In most common applications of air-to-water heat exchangers, the air-side thermal requirements control the design. Typically, the air flow and temperature requirements are dictated by the process, the fluid flow, and the temperature available within the plant. The size and configuration of the heat exchanger are a result of satisfying the space requirements and meeting the allowable pressure drops on both the air side and fluid side of the heat exchanger.

2.3.5.1 Approach Temperatures

In an air cooling application, the most economical design will result from the highest fluid flow rate possible and the coldest water temperature available.

2.3.5.2 Sensible Cooling and Dehumidifying

When moist air is cooled below its dew point, the moisture in the air is condensed out as liquid. The phase change of the moisture from gas to a liquid (latent heat) produces heat energy that is transferred to the cooling water. When the air is cooled to a temperature above the dew point, no moisture condensing occurs, and that is considered sensible cooling. When calculating the total heat load of an air cooling application, both the sensible heat load and the heat of condensation must be considered.

2.3.5.3 Fin Spacing

Using larger gaps between the fin tubes reduces the pressure drop and potential for air-side fouling; however, the effective heat transfer surface area of the exchanger is reduced.

2.3.5.4 Air-Side and Tube-Side Velocity

The air-side velocity (referred to as *face velocity*) is a function of the coil face size and the air flow. Most water-to-air heat exchanger applications involve low-pressure air in a duct; the velocity is not usually high enough for concern when there is no condensing on the air side. Face velocity should be above 200 feet per minute (1 m/s) to be in the turbulent flow regime. For sensible cooling, where no moisture will be condensed from the air stream, the face velocity would normally be kept below 1500 feet per minute (457 m/min); however, some applications and fin types can handle higher velocities. In cooling applications where there will be moisture condensed from the air stream, the face velocity should be kept below 500 feet per minute (152 m/min) to reduce moisture droplets being picked up by the air/steam and deposited downstream (moisture carryover). Recommended tube-side velocity guidance is provided in Section 2.1.3.5.

2.3.6 Mechanical Design Considerations

In order to develop specific mechanical design criteria for an air-to-water heat exchanger, some fundamental installation, operation, and maintenance details need to be understood:

- Is the heat exchanger accessible for cleaning, repair, and replacement?
- Will the heat exchanger be prone to tube-side or air-side fouling?
- Will the heat exchanger be prone to tube-side or air-side corrosion?
- Is the heat exchanger critical to an important process?
- Will the heat exchanger be exposed to vibration, seismic loads, or piping or ducting loads?

2.3.6.1 Tube Material

Typically, water quality is the main criterion for the tube selection; however, the tube joint at the header or tubesheet should also be considered in order to ensure a long lasting joint that is not susceptible to galvanic corrosion.

2.3.6.2 Access to Tubes

Throughout the operating life of an air-to-water heat exchanger, access to the tubes might be required for tube cleaning, tube inspection (including video probe and eddy current), tube repair, or tube plugging. Removable cover plate– (RCP-) type coils provide access to the tubes; however, the initial cost of a RCP-type coil is generally higher than a multirow (MR) coil of the same duty. Consideration should be given to the accessibility of the coil and the cost of accessing the coil in order to service or repair tubes. Coils for which tube access should be considered are the following:

- Coils with a high replacement cost where plugging tubes would provide some life extension
- Coils with a high replacement cost or any coil where eddy current testing is part of the maintenance program
- Coils that are prone to fouling and are accessible for cleaning
- Coils in a critical process that cannot be brought down, unplanned, long enough to change the coils
- Coils in a critical process where there is no redundancy or ability to continue the process if a coil is lost

2.3.6.3 Return Bend/Water Box Design

Maintaining water velocity within appropriate limits throughout a coil is important, and consideration should be given to more than just the tube velocity. The return bend design (in an MR coil) and the header or water box design (in an RCP coil) can affect localized velocity at a critical point within a coil.

2.3.6.3.1 *Return Bends*

Return bends are particularly vulnerable points in a multirow coil. At the return bend, the water makes a 180° turn and, therefore, can be more erosive at the bend due to the tangential flow. To make matters worse, because the return bend is bent from a tube, the outer edge of the tube thins as a result of the bending process, so there is less material on the outer edge of the bend to resist erosion.

To reduce the impact of erosion, the return bend should be designed as a smooth radius of 180° rather than a 90° bend followed by a flat section followed by another 90° bend. The smooth bend minimizes the local wall thinning, which can be a susceptible point for erosion, and it reduces the abrupt tangential flow of the water, which can also encourage erosion as shown in Figure 2-26.

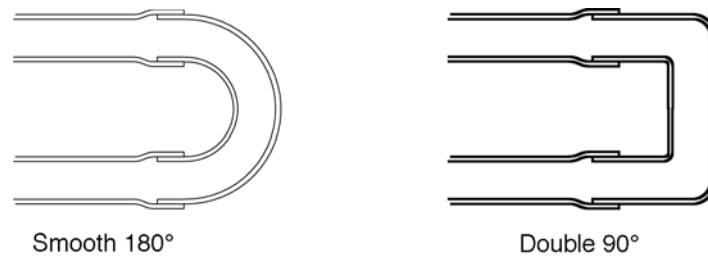


Figure 2-26
Tube bend arrangements

Size-to-size return bends should be used rather than return bends with a smaller outside diameter than the tube inside diameter (ID). Manufacturers can cut corners by using return bends that slide inside the tubes. This type of construction is suitable for a commercial grade or light industrial coils, but it is not recommended in power plant applications. The inside diameter of the ID-type return bend can be significantly less than the tube, resulting in a higher water velocity at the return bend, which increases the propensity for erosion. The size-to-size return bend has the same flow area of the tube; therefore, the water velocity does not increase at the return bend. Figure 2-27 illustrates two types of return bend configurations.

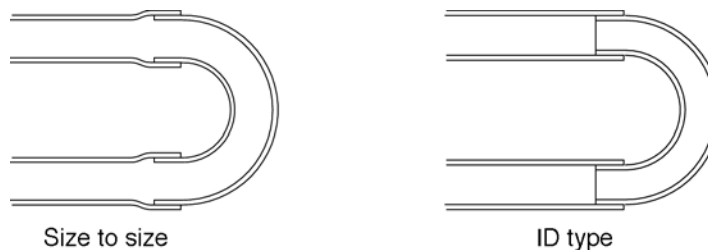


Figure 2-27
Return bend configurations

2.3.6.3.2 Header or Water Box design

The component that distributes the water to the individual tubes in a fin-tube heat exchanger is called a *header*, *manifold*, or *water box*. In the case of a multirow coil, the header is typically a pipe, but it sometimes is rectangular tubing. The header for a removable cover plate-type coil is typically a welded fabrication that is rectangular in shape.

If the tube velocity is within an acceptable range for a multirow coil, the water velocity through the header is typically within a reasonable range as well because the pipe diameter will be sized based on the appropriate nozzle velocity.

The design of rectangular header of a removable cover plate coil must consider the water velocity in each chamber of the header. The circuiting of this header will determine the pass partition locations to direct the water flow. It is important that the layout and flow area in these pass partition chambers is designed so that the water velocity does not increase in the header where erosion can take place or decrease to the point where sedimentation will occur.

2.3.6.3.3 Fin Design

The fin type selected for use in air-to-water exchangers should be based on a balance of durability, maintainability, longevity, and economics. The contributing factors to determine the relative importance of each of these factors is dependent upon the application of the heat exchangers. At the beginning of Section 2.3.6, key factors to consider for the mechanical design of fin-tube heat exchangers are discussed. These same factors should be applied to the selection of the fin type, as shown in Table 2-2.

Table 2-2
Fin-type selection factors

	Extruded aluminum fin	0.010" thick aluminum plate-fin	0.020" thick aluminum plate-fin	0.010" thick applied aluminum
Resistance to bending	Excellent	Fair	Excellent	Fair
Low-pressure cleaning	Excellent	Good	Excellent	Good
High-3pressure cleaning	Excellent	Poor	Good	Poor
Fin/tube contact (effectiveness)	Excellent	Good	Good	Poor
Fin/tube contact (mechanical longevity)	Excellent	Good	Good	Fair
Fin/tube contact (protection from exposure)	Excellent	Good	Good	Poor
Handling of thermal cycling	Good	Fair	Fair	Fair
Handling of differential thermal expansion	Good	Fair	Fair	Good
Handling of tube vibration	Fair	Good	Good	Fair
Fin spacing options (fins per inch)	Fair	Good	Good	Excellent
Fin thickness options	Poor	Good	Good	Good
Fin height options	Fair	Poor	Poor	Good
Tube pitch/row pitch options	Excellent	Fair	Fair	Excellent
Enhancement options	Poor	Excellent	Excellent	Poor
Temperature limit	450°F	350°F	375°F	250°F

1 inch = 25.4 mm

$C = (°F - 32) \times 5/9$

2.3.6.3.4 Structural Design

Local regulations might require that air-to-water heat exchangers in specific services be rated to particular seismic loads.

Flow-induced vibration is generally not a concern for air-to-water heat exchangers because the air density and velocity difference between the air side and water side dampen any vibration concern. For annular fin-tube heat exchangers that are installed on rotating equipment such as generators, motors, and compressors, attention should be given to the location of the tube supports so that they are not placed in nodal points that can amplify harmonic vibrations generated by the rotating equipment. Calculations can be performed to place the tube supports at a location along the tube so that resonant frequencies are avoided.

3

HEAT EXCHANGER THERMAL PERFORMANCE

This section provides an overview of thermal performance issues associated with heat exchangers. The thermal performance of a heat exchanger is affected by the system operating temperature, flow, and heat load, as well as fouling impairment of heat transfer surfaces and bypass flow around the heat exchanger. Many factors can account for unexpected or insufficient performance. Problems that affect heat exchanger thermal performance are most often experienced with open cooling water systems. Closed loop cooling systems experience relatively infrequent heat exchanger thermal performance issues with the use of clean, treated water.

This section focuses on common issues that can cause reduced thermal performance of a heat exchanger, as well as potential problems associated with operation of a heat exchanger outside its intended operating range. This section also focuses on the following common causes of thermal performance degradation:

- **Fouling** of heat transfer surfaces in excess of design allowances. (Biological or chemical sources as well as loss of heat transfer surface area due to tube blockage.)
 - Reduced flow to the heat exchanger due to internal heat exchanger problems such as macrofouling debris block or restrict flow at the tubesheet or in tubes.
 - Microfouling (either biological or chemical) results in reduced heat transfer capability
- **Improper installation** of the tube bundle, piping connections, or end covers of multipass heat exchangers resulting in lost or ineffective tube surface area
- **Bypass flow** such as partition plate leaks or shell-side deterioration of the tube bundle components
- **Improper venting** that causes air to be trapped inside the heat exchanger

Other considerations that could affect heat exchanger thermal performance are the following:

- **Reduced flow** to the heat exchanger due to system problems external to the heat exchanger (that is, pump degradation, increased system hydraulic losses, strainer fouling, valve lineup, bypass or system boundary valve leakage, etc.)
- **False indication** due to incorrect or out-of-calibration instrumentation (for example, pressure, temperature, etc.)
- **Changes in overall system operation or design** from the original design conditions that change heat exchanger operating characteristics and thermal performance, for example, system operation changes resulting from power uprates, increased temperature of cooling water, and/or replacement of major system components

When the heat exchanger is experiencing insufficient cooling without evidence of unusual fouling, the initial inspection should focus on the system operation including flows, temperatures, and pressures. The flow alignments and the piping to the heat exchanger are checked for correctness. Similarly, pressures and temperatures are compared to procedures and technical specifications such as the heat exchanger data sheet.

3.1 Shell-and-Tube Heat Exchanger Performance

3.1.1 Fouling

This section introduces you to the various types of fouling. The information presented here is generic and will be cross-referenced as appropriate in Sections 3.2 and 3.3, which address plate heat exchangers and air-to-water heat exchangers.

There are two primary types of fouling seen in heat exchangers, macrofouling and microfouling. Table 3-1 describes the various forms of fouling most common with heat exchangers and their causes.

Table 3-1
Types of fouling and their causes

Type of fouling	Reference	Causes of fouling
Macrofouling	3.1.1.1	Seaweed Wood chips/fibers Mussels Barnacles Rocks Foreign material Degraded and detached coatings Component parts
Microfouling	3.1.1.2	
Sedimentation		Corrosion products Metal oxides Silt Alumina Diatomic organisms and their excrement
Scaling and incrustation		Calcium carbonate Calcium sulfate Silicates Phosphates
Biological growth – slime		Bacteria Nematodes Protozoa

3.1.1.1 Macrofouling

Macrofouling can cause significant flow blockage and reduction in flow through some of the tubes without deposition of a film that impedes heat transfer. The major effects of macrofouling are a decrease in flow and blockage of tubes, effectively removing the tube surfaces from active heat transfer duty. Macrofouling can be caused by biological matter or debris inside the heat exchanger.

Biological macrofouling can be due to organisms that are present in the system or heat exchanger without causing excessive pressure drop or other symptoms while they are alive; however, an event such as chemical treatment or thermal shock may cause large numbers of shells and byssal threads (from zebra mussels) to release and subsequently rapidly accumulate on tubesheets, which may become an acute problem. Conditions that support macrofouling are also likely to be conducive to microfouling biological growth.

Possible internal sources of debris and foreign materials are from the system itself in the form of delaminated coatings or liners from pumps, piping, or intake bays. Other internal debris sources include corrosion nodules or tubercles that have released from the piping system, as well as failed component parts such as rubber valve seat liners. External sources of debris could include non-organic items such as rocks, dirt, and tools inadvertently left in the heat exchanger.

3.1.1.2 Microfouling

Microfouling can severely degrade heat exchanger thermal performance due to very high thermal resistances of the slime layer on the tubes, which may not cause notable changes in heat exchanger flow or pressure differential. The microfouling can also be damaging to heat exchanger metals (with the exception of the most resistant alloys or materials) via waste byproducts, under-deposit corrosion, or related corrosion dynamics.

3.1.1.2.1 Sedimentation

Sedimentation is the deposition of suspended matter from the fluid to the heat exchanger surfaces. It is a potential problem in open cooling water systems, particularly once-through systems. It varies according to water quality, flow rate, the geometry of the unit, and its piping. Sedimentation is primarily controlled by keeping the fluid velocity high.



Key Technical Point

Sedimentation is a seasonal occurrence at many plants if cooling water flow is throttled or bypassed when water temperatures are low, which results in low tube velocities and the subsequent settling of suspended materials.

3.1.1.2.2 *Scaling and Incrustation*

When the solubility limit of a solution is exceeded, for example, based on elevated tube wall temperature, solids plate onto the tube wall. When the solubility limit is exceeded by the concentration of a solute, crystallization also occurs, for example, the evaporation of water in a cooling tower with a concentration of impurities. Typically, the resulting scale deposits cause significant thermal performance losses and are hard to clean, requiring strong chemicals or mechanical cleaning. The susceptibility to scaling is highly dependent on the water quality (mineral content) of the cooling water source.

3.1.1.2.3 *Biological Growth*

The presence and growth of bacteria, algae, mussels, and other biological organisms in the fluid and heat exchanger components is a serious occurrence in open cooling systems. The water quality and flow most often dictate the rate of fouling. Figure 3-1 illustrates an example of biofilm fouling in a heat exchanger



Figure 3-1
Biofilm fouling in a heat exchanger

While biofouling is most often associated with open cooling water systems, particularly once-through systems, problems with microfouling have occurred in lube oil systems due to excessive water intrusion (such as in turbine seal oil with water introduced from gland steam) as well as closed loop systems. Both of these issues are discussed in operating experience (OE) databases that are readily available through industry sources.

3.1.2 Improper Installation

Smaller multipass heat exchangers often include divider or partition plates that are integral to the heat exchanger cover/head/end bell. This design relies upon proper rotational orientation of the heads to align the divider plates that separate the tubes for each pass, but the incorrect orientation of the head may not be apparent after reassembly. Incorrect orientation of the heat exchanger head during reassembly can result in loss of thermal performance due to isolating some tubes/passes from the cooling water flow. Improper gasket placement or gasket slippage/shifting during installation activities can also result in obstructed tubes and/or bypass flow.

Removable tube bundle designs may also be orientation-specific due to the baffle plate arrangements relative to the shell inlet/outlet nozzles. A tube bundle could be inadvertently rotated 180 degrees during reinstallation, which can result in thermally inefficient portions of the tube bundle.

Piping connections for small bore lines, particularly tubing connections, could inadvertently be reversed, which could also result in less efficient heat exchanger operation (that is, parallel flow).

3.1.3 Bypass Flows

3.1.3.1 Partition Plate Failures

Reduced thermal performance might be due to leaks through or across partition plates. The problem can be determined only with a visual inspection. A decline in heat exchanger capacity can be detected, but it will be generally attributed to fouling before an inspection can be performed. Most multipass heat exchangers rely on the cover to compress and seal the partition plate gasket versus the use of a separate internal bolted/welded pass partition cover. Normally, an exchanger cover has enough bolts to seal the peripheral flange area, but due to bowing of the cover from “flange rotation,” it may not seal the pass partition gasket area.

3.1.3.2 Partition Plate Gasket Failure

The most common failure mechanism for gaskets installed in heat exchangers is a loss of physical properties due to poor design, aging, changes in water chemistry, or physical damage incurred during maintenance of internal elements/subcomponents. Loss of physical properties can include cracking, embrittlement, and loss of elasticity or durometer hardness. Any of these failure mechanisms can result in leakage.

Gaskets at the pass partitions can sometimes be dislodged if an excessive difference in pressure develops between two passes. If tubes become plugged from a sudden influx of debris, pressure will build up in the first pass of the exchanger, often resulting in the pass partition gasket being “blown out.”

3.2 Plate Heat Exchanger Performance

3.2.1 Fouling

The fouling mechanisms described in Section 3.1.1.1 are also applicable to plate heat exchangers. The pattern of the plate material for a plate heat exchanger provides strength and rigidity and increases the rate of heat transfer; however, deposits on the wall surfaces can cause the heat transfer rate through the wall to be severely reduced. The corrugation on the heat transfer plates induces highly turbulent flow. The induced turbulence resists, but does not eliminate, the formation of deposits on the plate surface.

Deposits and fouling consist of materials that have a much lower thermal conductivity than the metal plate and can reduce the overall heat transfer rate. The fouling and deposits in the heat exchanger can then lead to corrosion occurring under the deposit.

To maintain adequate flow and heat transfer through the plate heat exchanger, pressure drops should be kept as close as possible to the design value. As the flow area decreases, for a given volumetric flow rate, pressure drop increases. To maintain the desired flow through the reduced open area in the heat exchanger, more energy must be expended and subsequently causes a pressure drop.

An indication of fouling or clogging occurring includes the following:

- Decreased thermal performance (desired temperatures are not maintained)
- Increased pressure drop and or reduced flow on either the cold side or hot side



Key Technical Point

The flow passages in plate heat exchangers are normally smaller than the tube ID of shell-and-tube heat exchangers and, thus, are more susceptible to fouling without adequate filtration present.

3.2.2 Improper Installation

While not considered a common problem, improper stacking or sequencing of the plates during reassembly can result in reduced thermal performance. Improper reassembly, such as the incorrect number of plates in a given pass arrangement, could result in reduced flow passages, causing an elevated differential pressure and/or reduced flow through the heat exchanger.

3.2.3 Bypass Flow

Bypass flow can result when a gasket seal is broken, punctured, or cracked. This may be caused by debris impact, corrosion, or water hammer.

3.3 Air-to-Water Heat Exchanger Performance

3.3.1 Fouling

The fouling mechanisms described in Section 3.1.1 are also applicable to air-to-water heat exchangers. It is important to check the operating flows and temperatures to confirm that they are within the design range when reduced thermal performance is suspected.

Possible causes of reduced thermal performance in air-to-water heat exchangers are the following:

- Plugged or fouled tubes on the water side.
- Plugged or fouled fins. This provides a thermal barrier and also increases pressure drop, which can reduce the air flow.
- Reduced system flows on the air or water side.
- In the case of air-cooled fluid coolers, where ambient air is blown over a coil to cool the fluid inside, obstructions around the heat exchanger can limit performance. Hot discharge air can reflect off walls or other equipment, causing this hot air to be recirculated back through the air intake and raising the cooling air temperature. Air-cooled fluid coolers are also sized to consider an ample supply of cooling air. Once installed, often other equipment, walls, or barriers restrict the supply of cooling air. Equipment installed close to air-cooled fluid coolers can generate heat that can locally raise the temperature of the cooling air.

The effects of fouling on heat transfer are best illustrated using typical heat exchanger parameters. Air-to-water heat exchangers typically have overall heat transfer coefficients ranging from 5–20 BTU/hr-ft²-°F (28.39–113.56 W/m² K). The lower heat transfer coefficient is caused by the poor heat transfer properties of air, which controls the heat balance. Due to the large difference in surface area in contact with the air relative to the surface area in contact with the water, the effect of fouling factors applied to the air side of an air-to-water heat exchanger has a minimal effect on the overall heat transfer coefficient under most conditions.

3.3.2 Improper Installation

Waterboxes can be subject to the same types of assembly and reinstallation errors seen on shell-and-tube heat exchanger heads, as discussed in Section 3.1.2.

3.3.3 Bypass Flow

Bypass flow in a removable cover plate coil is similar to bypass flows for shell-and-tube heat exchangers, which is discussed in Section 3.1.3. Bypass flow may be due to leakage past partition gaskets on removable cover-type coils. It may also be due to failed or improperly installed air dams around cooling coils.

3.3.4 Fin Bond Loss

Some fin types can lose the contact with the tube over time through thermal cycling. Different fin types have different temperature limits. If the temperature limit is exceeded, loss of contact between the fin and tube may result.

4

HEAT EXCHANGER MECHANICAL PERFORMANCE

This section provides an introduction to various mechanical failure mechanisms that can occur in the types of heat exchangers discussed in this report.

4.1 Overview of Failure Mechanisms Associated with Heat Exchangers

Table 4-1 provides an introduction and overview of failure mechanisms and their applicability to the three general types of heat exchangers discussed in this report. A discussion of each failure mechanism is provided in the sections noted in the table.

Table 4-1
Applicability of failure mechanisms to various types of heat exchangers

Failure mechanisms	Section with general guidance	Sections with special issues discussed		
		Shell and tube	Plate	Air to water
Corrosion	4.1.1	X	X	X
Erosion	4.1.2	X	X	X
Vibration	4.1.3	4.2.1	4.3.1	4.4.1
Gasket failure	4.1.4	X	4.3.2	X
Bolting failure	4.1.5	X	X	X
Plug failure	4.1.6	X	N/A	X
Tube impingement	4.1.7	X	N/A	X
Cracking or degradation of coatings	4.1.8	X	N/A	X
Thermal stresses	4.1.9	X	4.3.3	4.4.2
Expansion joints	4.1.10	X	N/A	N/A
Hydraulic shock	4.1.11	X	4.3.4	X

Note: An X indicates that the heat exchanger type is susceptible to the failure mechanism noted. Special issues associated with various failure mechanisms are noted in the column appropriate for each type of heat exchanger.

4.1.1 Corrosion

Open cooling water systems are more susceptible to corrosion due to differences in water quality when compared to a closed cooling water system that has chemistry controls.

4.1.1.1 General Corrosion

General corrosion is the uniform loss of a metal surface caused by a chemical or electrochemical reaction. Average corrosion rates are measured in thousandths of an inch (0.001 inch = 25 μm) per year, and the metal life expectancy can be predicted. Predicted general corrosion is the source of corrosion allowances for components.

General corrosion is responsible for the greatest destruction of metal by weight, but it is not as insidious as other types that lack uniformity and predictability. General corrosion attacks are the most evident in carbon steel, but they also occur to a lesser degree in nonferrous metals and stainless steels. General corrosion does not often result in the need for heat exchanger repair because open cooling water system design normally specifies corrosion-resistant materials, coatings, and/or sufficient corrosion allowances to address general corrosion.

4.1.1.2 Galvanic Corrosion

Galvanic corrosion occurs from a potential difference between two dissimilar metals, for example, steel and copper. The farther apart the metals are in the galvanic series, the greater the potential generated and the greater the corrosion effect. Galvanic corrosion should always be a consideration when a heat exchanger is retubed. Figure 4-1 is an example of severe galvanic corrosion of a Muntz metal tubesheet following retubing of a condenser with 6% molybdenum stainless steel tubes.

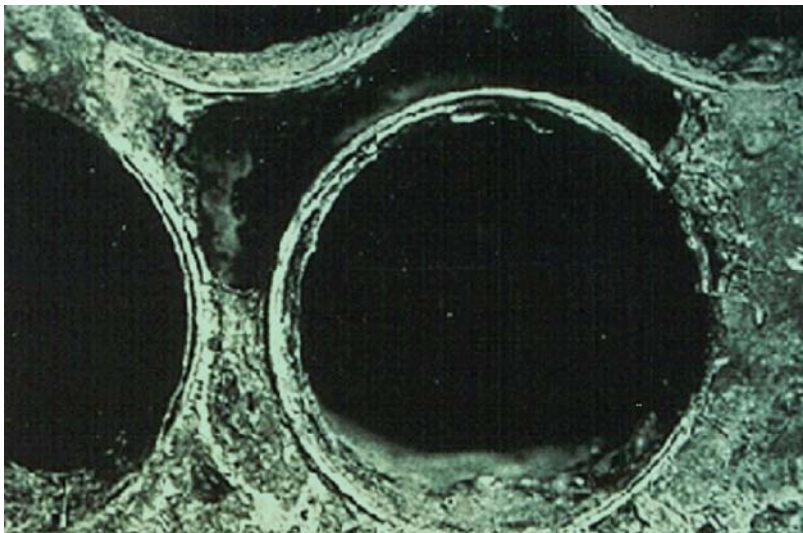


Figure 4-1
Severe galvanic corrosion of a Muntz metal tubesheet following retubing of a condenser with 6% molybdenum stainless steel tubes

4.1.1.3 Crevice Corrosion

A localized corrosion attack begins in crevices, fissures, or other confined mechanical interfaces where differences in oxygen concentration exist in the occluded zone. The overall electrochemical reaction involves the dissolution of metal and the reduction of oxygen to hydroxyl ion.

Crevice corrosion attack occurs in many media, although it is most intense in halogen/halide environments. It often requires a long incubation period to develop; however, once the corrosion starts, it proceeds at a rapid rate.



Key Technical Point

Crevice corrosion is one of the most common degradation mechanisms for stainless steels, particularly in open loop systems.

4.1.1.4 Pitting Corrosion

Pitting corrosion is similar to crevice corrosion in that a local anodic site (the type of site where metal dissolution occurs) stays as an anodic site so that the remainder of the surface can support metal dissolution reactions. In addition, the inside of the pit will often develop very different water chemistry than the bulk water (that is, outside the pit), which makes the pitting process autocatalytic. Pitting can be extremely localized and produces destruction of the metal by local penetration, even when the overall weight loss of metal may be small or nearly undetectable. Most pits develop and grow downward from horizontal surfaces in the direction of gravity. Fewer pits develop on vertical surfaces. Rarely do the pits grow upward, opposing gravity.

Similar to crevice corrosion, pitting requires a long incubation period to develop. Once started, the pit can penetrate the metal at a very rapid rate. Low fluid velocities and/or stagnation are conditions are associated with pit development.

Typically, pitting of austenitic stainless steel tubes occurs by a concentration of chloride ions under deposits or within crevices. Chloride ion-induced pitting of austenitic stainless steels is an infrequent event in fresh water applications.



Key Technical Point

Because seawater contains substantial chlorides (approximately 19,000 ppm), seawater-cooled plants are more prone to experience pitting in austenitic stainless steel tube materials than freshwater-cooled plants.

Examples of corrosion pitting damage are shown in Figures 4-2 and 4-3.

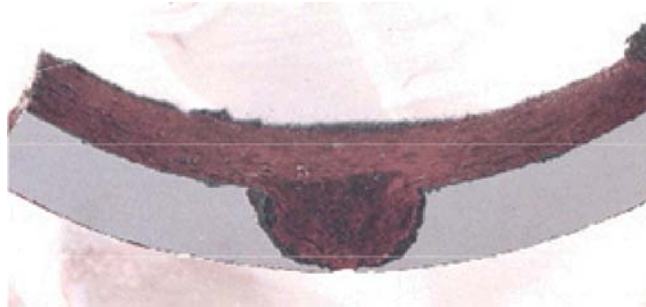


Figure 4-2
Pitting corrosion damage of carbon steel

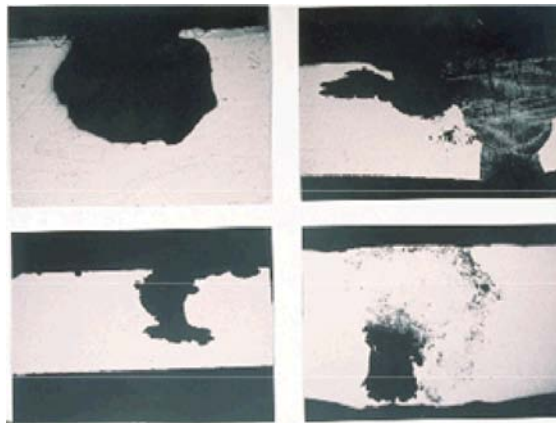


Figure 4-3
Pitting corrosion damage of stainless steel

4.1.1.5 Intergranular Corrosion

Localized attack at and adjacent to grain boundaries in a metal with relatively little corrosion of the grains is known as *intergranular corrosion*. The result is disintegration of the alloy and/or loss of strength. Sensitization, described below, is a common precursor to intergranular corrosion attack in stainless steels. Exfoliation is a common form of intergranular corrosion of copper-nickel alloys.

Sensitization of stainless steel occurs when the alloy is heated or cooled slowly through the temperature range of 900–1500°F (482–816°C), either during a heat treatment or during welding. In this temperature range, the chromium-rich carbide precipitates to a degree directly related to the carbon content, temperature, and duration of exposure. The precipitation results in the depletion of chromium near the grain boundary. The chromium-depleted zone deteriorates because it does not contain sufficient corrosion resistance in many environments. This sensitization creates miniature galvanic cells that further enhance attack.

**Key Technical Point**

Exfoliation is a special form of intergranular corrosion attack that is characterized by elongated grain attack on a plane parallel to the rolled or extruded surface. This results in a characteristic delamination or peeling of the metal strata. Susceptible alloys other than aluminum and magnesium are the 70/30 and the 80/20 copper-nickel alloys. The 90/10 copper-nickel alloy is immune.

Another form of intergranular corrosion attack is known as *weld decay*. This corrosion failure takes place in or near the heat-affected zone where sensitization occurred.

4.1.1.6 Stress Corrosion Cracking

Stress corrosion cracking can be defined as a catastrophic metal failure promoted by the interaction of tensile stresses, time, and the environment. Chloride stress corrosion cracking is of particular concern in units with austenitic stainless steels. These steels are susceptible to cracking when under stress in the presence of high temperature, oxygen, and chlorides.

The chloride ion is the most prevalent corrodent capable of producing stress corrosion cracking in stainless steels. Other environmentally critical stress corrosion factors are fluid temperature, conductivity, pH, and dissolved oxygen concentration. Stress corrosion cracking of admiralty brass tube material has been reported in open cooling water systems with high chlorine halogens from biocide treatment or shock treatments.

**Key Technical Point**

Stress corrosion failures of Monel 400 tubing have occurred in a few applications, primarily at U-bend locations. The susceptibility to stress corrosion can be eliminated by properly heat treating U-bends to sufficiently relieve the residual stress produced by tube bending.

Stress corrosion cracking failure can be from operational stresses or from stresses built in during manufacture. Figures 4-4 through 4-6 show stress corrosion tube failures in two different low-pressure heat exchangers. In both cases, residual stresses from heat manufacturing were considered to be the source of the stress that contributed to the stress corrosion cracking.

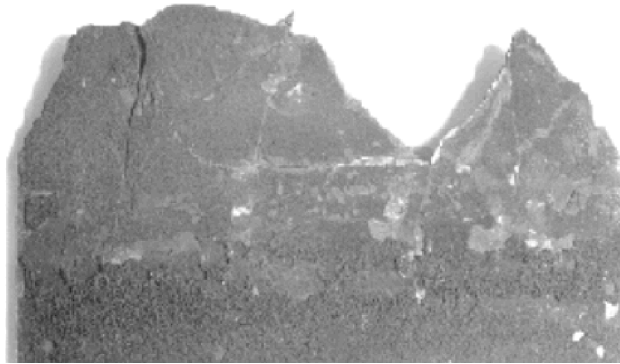


Figure 4-4
Stress corrosion cracks in stainless steel tubing

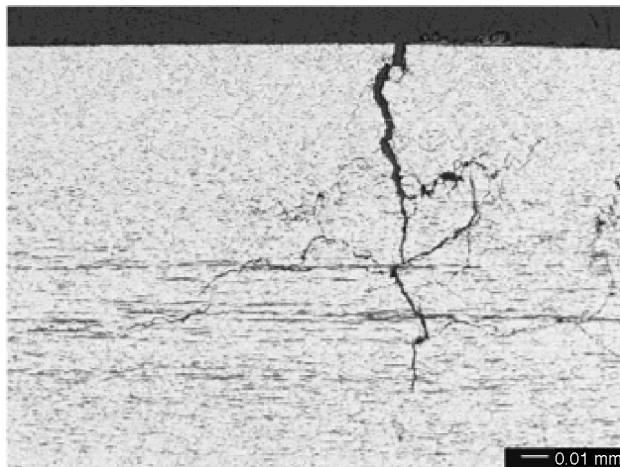


Figure 4-5
Stress corrosion cracks in stainless steel tubing

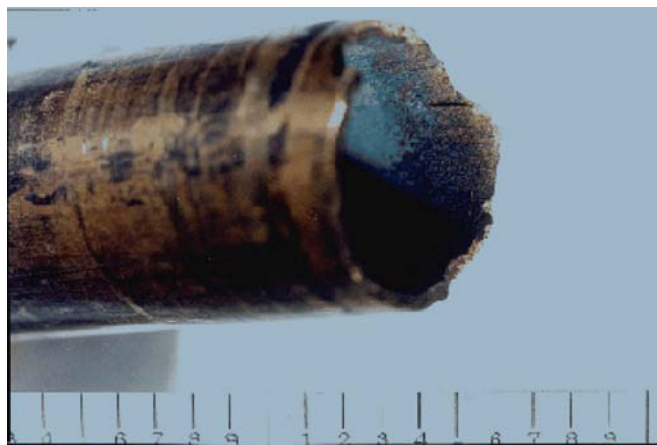


Figure 4-6
Stress corrosion cracks in brass tubing

4.1.1.7 Microbiologically Induced Corrosion (MIC)

Microbiologically induced corrosion (MIC) is an interaction between corrosion processes and microbiology. Biofilms, comprised of bacteria, algae, fungus, etc., can produce localized environments that are very different, and in many cases much more aggressive, than the bulk environment or environments that would result from a geometric crevice. As a result, MIC can initiate and proceed very rapidly.

4.1.2 Erosion

Three types of erosion discussed in this section are the following:

- Tube inlet erosion
- Tubesheet erosion
- Impingement erosion

4.1.2.1 Tube Inlet Erosion

Tube inlet erosion is a form of erosion-corrosion. In low-energy heat exchangers, this failure mechanism primarily affects copper alloy materials.

A visual inspection from the inlet tubesheet will indicate if tube inlet erosion is present. Examples of tube inlet erosion are shown in Figures 4-7 and 4-8. Although the indications should be most prominent on the inlet pass, it is advisable to look also at the condition of the outlet pass.

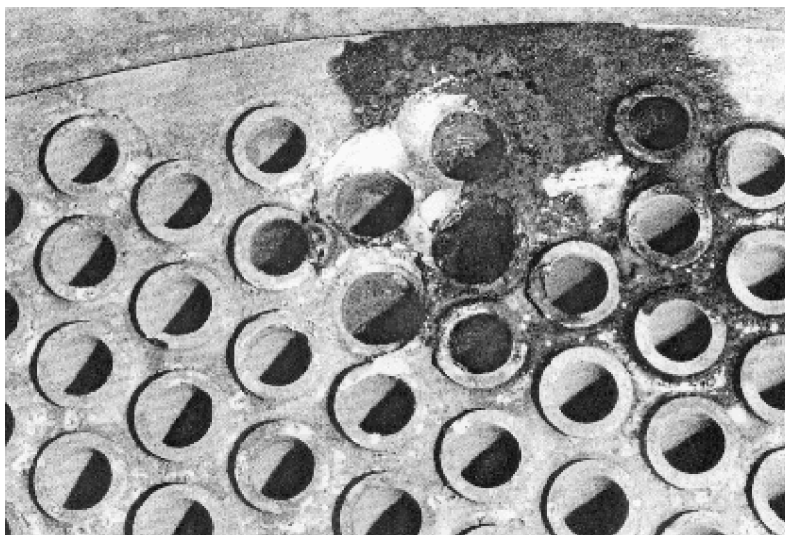


Figure 4-7
Tube inlet erosion



Figure 4-8
Horizontally cut tube ID, tube inlet erosion



Key Technical Point

Tube inlet erosion is particularly intense within the first several inches (25–100 mm) of the tube. A borescope inspection of the first 6 inches (15 cm) of a random number of inlet end tubes should be made if tube inlet erosion is suspected or likely. This allows for early detection of erosion symptoms such as excessive metal polishing or wear. If erosion is detected, it is recommended to inspect farther down the tube (10 inches [250 mm]) to the end of the damage.

Common root causes of problems related to heat exchanger erosion-corrosion are the following:

- Heat exchanger design
- Abnormal operation
- Water quality (especially suspended solids)

4.1.2.1.1 Heat Exchanger Design

Material selection is the most significant design consideration in erosion-corrosion problems. Other significant design considerations are the location, orientation, and geometry of the inlet piping. A short distance between the inlet pipe connection and the inlet tubesheet (<5–6 inches [13–15 cm]) promotes susceptibility to tube inlet end erosion-corrosion. If the orientation directs the flow toward the face of the tubesheet at close range, erosion-corrosion attack on the tubes can be severe. If the inlet piping makes a sharp turn before coming into the channel barrel, as in a 90° elbow, the turbulence of this incoming water may cause tube inlet erosion. The deterioration of the metal can be severe. The face of the tubesheet should be overlaid with erosion-resistant material, and the tube material selected should be erosion resistant. Erosion-resistant coatings can also be used. Inlet nozzle flow diffusers can reduce turbulence in this area.

For welded tubesheet joints, the weld rollover at the tube entrance should not create an orifice effect that could worsen the inlet erosion problem. Tubes that protrude from the face of the tubesheet can generate local eddy effects that create abnormal erosion-corrosion problems. Where tube protrusion does exist, consider trimming the excess tube ends to provide a smooth, flat surface condition.

4.1.2.1.2 Abnormal Operation

High water velocity is a significant cause of inlet end erosion. Susceptibility to inlet end erosion-corrosion can be reduced by following current industry guidelines for optimizing tube velocity. Acceptable tube velocities in raw water cooling systems can also negatively impact the amount of suspended solids and sediment in the water, potentially causing erosion damage even if tube velocities are within industry standards.



Key Technical Point

Every time a tube is plugged, the velocity through the remaining tubes is likely to increase in both the plugged heat exchanger and other heat exchangers in the system. As more tubes need to be plugged, check to ensure that velocities do not go above design conditions for the tube material.

4.1.2.1.3 Water Chemistry

Water chemistry can affect erosion of certain heat exchanger components. The water chemistry is often controlled through existing plant programs, which are outside the scope of this report. Additional guidance regarding water chemistry can be found in the following EPRI technical reports:

- *Closed Cooling Water Chemistry Guideline, Revision 1: Revision 1 to TR-107396, Closed Cooling Water Chemistry Guideline, 1007820*
- *Service Water System Chemical Addition Guideline, TR-106229*

4.1.3 Vibration

4.1.3.1 Overview of Vibration

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

Tubes will be excited and will vibrate at all frequencies. However, when the tube is excited to its natural frequency, depending on the tube geometry, tube material, flow rate, and fluid densities, the amplitude of vibration will increase very dramatically. Excitation at the natural frequency and harmonics (multiples of the natural frequency) must be avoided.

Damage results only if the amplitude of the tube vibration is sufficient to cause any of the following:

- Stresses in the tube or tube joint that exceed the endurance limit for fatigue failure (typically at tubesheets)
- Collision between adjacent tubes
- Fretting wear between the tube and the tube support plate

If a group of tubes fails simultaneously, vibration-related fretting or mid-span collisions might be causing the damage. A complete analysis of the failure location can determine the cause of failure.

As a preventive measure, heat exchangers can be accessed to determine which ones are more susceptible to tube vibration damage for the purpose of identifying shell-side flow rate limitations in operating procedures. The section titled “Flow Induced Vibration” in *Standards of the Tubular Exchanger Manufacturers Association* (TEMA) provides calculations and parameters for the basis of such an assessment. The manufacturer’s drawings for the tube bundle details and the heat exchanger specification sheet are the base documents to support the assessment.

4.1.3.2 Common Tube Damage from Vibration

There are three common forms of vibration-related tube damage:

- Fretting
- Collision
- Cracking

Fretting, also called *chatter*, is the most common form of vibration tube damage found mostly in feedwater heaters. It occurs at the support plates or baffles. The tube may wear either 180° or 360° around the circumference. The most common occurrence is the 180° wear, especially in the bundle periphery and windows.

The support plate or baffle may also wear, causing increased tube hole size in the baffle. The tube hole wear and the tube wear increase the clearance between the tube and support plate/baffle, which reduces damping and increases tube vibration. The rate of fretting degradation increases exponentially.

If the tubes deflect enough, they collide with each other. This collision usually occurs at the mid-span between support plates or baffles. The mid-span is the point of greatest deflection. It is uncommon to find collisions at points other than the mid-span.

The tubes wear at the points of collision. Collision-induced tube wear can create a through-wall failure. A fatigue crack induced by the stress riser from the tube wear is the more typical form of tube failure.

Cracking failures from high-cycle fatigue occur mostly at rigid attachments such as tubesheets and supports and at stress risers.

4.1.4 Gasket Failure

The most common failure mechanism for gaskets installed in heat exchangers is loss of physical properties due to aging, changes in water chemistry, or physical damage incurred during maintenance. Loss of physical properties can include cracking, embrittlement, and loss of elasticity or durometer hardness. Any of these failure mechanisms can result in leakage. Figure 4-9 illustrates the effects of a gasket failure.



Figure 4-9
Effects of a gasket failure in a heat exchanger

4.1.5 Bolting Failure

The most common failure mechanism for bolting is cracking, often caused by thermal or fatigue stress. Bolts may also exhibit shear failure if they are not tightened to the prescribed torque.

4.1.6 Plug Leakage or Failure

Tube plugs can develop leaks due to loosening, cracking, or becoming dislodged. Cracking and embrittlement of nonmetallic plug materials can result from aging of the elastomeric materials. Tube plugs installed on degraded tube ID surfaces, such as when tube inlet erosion is present, may achieve only minimal sealing that is subsequently lost due to differential thermal expansion or pressure changes when heat exchangers are placed in and out of service. Dislodged plugs most commonly result from improper installation techniques.

4.1.7 Tube Impingement

Tube impingement is the physical deformation of the tube geometry when particles of foreign material of sufficient size impinge upon either the outer or inner walls of the tube resulting in dents or, in some extreme cases, tears in tube walls.

4.1.8 Cracking or Degradation of Coatings

Coatings provide corrosion protection for piping materials, most often by providing a barrier between the environment and the metal. In some cases (for example, coated carbon steel in seawater or brackish water service), the coating permits the use of a material for a heat exchanger that would not have been used if it were in direct contact with the environment. In all environments, corrosion can start at areas of coating failure and, in some cases, as in the case of coated carbon steel exposed to seawater, can proceed very rapidly.

Not all coatings are impervious to water migration and, thus, will degrade over time. For example, epoxy coatings applied to internal components of heat exchangers crack, flake, and subsequently detach from the metal surface. Over time, cracked epoxy coatings can lead to corrosion of the underlying metal surface and possibly the slow accumulation of bio-films. Both mechanical and environmental effects will also influence coating life.

The failure of a coating can contribute to system damage, for example, through blockage of piping or heat exchangers. Ideally, when a coating degrades, it will fail in small pieces rather than in large sheets, but when a coating is degraded, further investigation is required to assess the condition of the underlying material and to evaluate how the damaged coating may impact other equipment.

Additional guidance regarding coating failure mechanisms is provided in EPRI report 1003102, *Guideline on Nuclear Safety-Related Coatings, Revision 1 (Formerly TR-109937)*.

4.1.9 Thermal Stresses

TEMA E (fixed tubesheet) designs are susceptible to thermal stresses, especially with temperature cycles. The tubes are held between the tubesheets and have no opportunity to expand or contract. Unless evaluated by the heat exchanger manufacturer in the original design, it is a good practice to limit the difference between the inlet shell-side and tube-side fluid temperatures to less than 100°F (38°C) for safe operation. A U-tube bundle can better handle temperature-induced thermal stresses, and the manufacturer can provide these limits. In most cases the inner tubes, having the smallest bend radius, experience the highest stresses.

The slots in the heat exchanger shell supports accommodate expansion and contraction of the shell. The bolts must have some looseness to allow the supports to slide in the slots. Provisions for expansion of the nozzle piping must also be maintained.

4.1.10 Expansion Joints

A shell-side expansion joint absorbs thermal stresses in a fixed tube bundle. The vendor is the best source for information and experience. Thin-walled joints are fragile, damaged easily, and often not repairable and must be replaced. Thick-walled joints are only slightly more repairable.

In general, the root cause for the failure must be identified. Causes range from fatigue to excessive pressure to erosion and are taken into account to effect a lasting repair or replacement. There are several methods to replace an expansion joint, but all are costly efforts. At all times, protect a joint from harm. Small dents and defects decrease the remaining life of the joint.

4.1.11 Hydraulic Shock

Hydraulic shock is the term used to describe the momentary pressure rise in a piping system that results when liquid flow is started or stopped quickly. This pressure rise is caused by the momentum of the fluid; therefore, the pressure rise increases with the velocity of the liquid, the length of the system from the fluid source, or with an increase in the speed with which it is started or stopped. Hydraulic shock can occur when valves are opened or closed quickly or when pumps start with empty discharge piping. Hydraulic shock can occur if a high-speed wall of liquid (from a starting pump) hits a sudden change of direction, such as an elbow. The pressure rise created by the hydraulic shock is added to the fluid pressure existing in the piping system and, although only momentary, can be enough to cause damage to certain heat exchanger components and parts.

4.2 Specific Failure Mechanisms in Shell-and-Tube Heat Exchangers

4.2.1 Vibration

Vibration problems are common to shell-and-tube heat exchangers, but a properly designed heat exchanger that is operated within the original design limits established in the specification or by the manufacturer can normally avoid destructive vibration problems. Vibration damage is often a function of tube position in the bundle. For example, a U-tube bundle can experience problems at the U-bends. A primary source for allowable vibration information is available from the TEMA Standards. Several types of tube damage are caused by vibration. If tubes collide repeatedly, the tube walls show wear. Figure 4-10 illustrates an example of tube failure in a component cooling water heat exchanger.

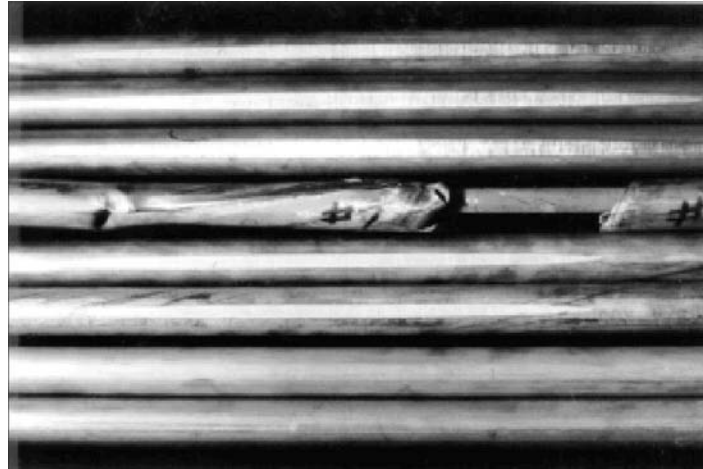


Figure 4-10
Tube failure in a component cooling water heat exchanger

Another typical failure is tube wall wear from contact with the support plate hole. Another vibration indicator is fatigue failure of the tube near the tubesheet joint. Tube movement at the tubesheet hardens the tube material and increases its susceptibility to stress corrosion cracking. Simultaneously, residual rolling stresses are reduced, weakening the tube-to-tubesheet joint. In a welded joint, vibration can damage the weld, and cracks can continue through the tube and into the tubesheet.

Shell-side flow reduction, if possible, will reduce the severity of tube vibration problems.

Mechanical fixes involve forcing wedges between susceptible tubes (staking) or wiring groups of tubes together to stiffen the tube bundle. This may require cutting into the shell and performing a weld patch repair if the tube bundle is not removable.

4.3 Specific Failure Mechanisms in Plate Heat Exchangers

The most common failure mechanism associated with plate heat exchangers is leakage. Leakage can be caused in a plate heat exchanger by any of the following circumstances:

- Gaskets that have become damaged, torn, brittle, hard, or dried out
- Excessive localized corrosion of the plates
- Physical damage to the plates that prevents a tight seal between plates
- Object/debris inadvertently trapped on the gasket
- Water hammer (spikes in operating pressure)
- Other transient operating conditions

4.3.1 Vibration

Plate heat exchangers can handle some vibration, but excessive vibration could cause damage to the plate material. Most liquid applications will not cause vibration problems. When vapor or steam is used, velocities in the port and channels need to be considered for proper design. The manufacturer of the heat exchanger should be consulted when vapor or steam is present.

4.3.2 Gasket Failures

In a plate heat exchanger, the seal between plates is achieved by a gasket around the perimeter of the plate and a double gasket around the two through ports. Pressure pulsations, cuts, debris, cracks, improper assembly, and operating outside design conditions can all result in gasket leaks. These leaks can develop over time or be catastrophic in nature. A severe leak can reduce thermal performance of the heat exchanger. Due to the nature of the design of a plate heat exchanger, any failure in a gasket will cause a visible leak.

4.3.3 Thermal Stresses

Plate heat exchanger designs are not very susceptible to thermal stresses because the plates are separated by elastomeric gaskets that have the ability to expand and contract, which limits thermal stresses. When an application involves thermal cycling, a gasketed plate heat exchanger is more reliable than welded technologies.

4.3.4 Hydraulic Shock

The plates in a plate heat exchanger are very susceptible to hydraulic shock caused by the transfer of pressure pulsations by the system pumps. These pressure pulsations can cause fatigue failures and gasket extrusions. It is recommended that pressure dampening devices be used in the pipeline to minimize this effect.

4.4 Specific Failure Mechanisms in Air-to-Water Heat Exchangers

4.4.1 Corrosion

Corrosion can lead to fouling, which is a common failure mechanism in air-to-water heat exchangers. Crystallization is one of the most common types of fouling in air-to-water heat exchangers. Salts present in natural waters have a lower solubility in warm water than cold. Therefore, when water is heated during the cooling process (particularly at the tube wall), these dissolved salts will crystallize on the surface in the form of scale. The most common solution to minimize this type of fouling is to reduce the temperature of the heat transfer surface, which often decreases susceptibility to precipitation, or consider water treatment.

The types of fouling most often encountered in air-to-water heat exchangers and their causes are listed in Table 4-2.

Table 4-2
Types of fouling and their causes

Type of fouling	Causes of fouling	Area affected by fouling
Crystallization	Salts commonly present in natural waters	Tube wall
Sedimentation	Silt, sand, and rust suspended in fast moving water, dropped out in low flow or "dead" areas of the heat exchanger	Headers and sometimes tubes
Biological organic growth	Bacteria Nematodes Protozoa	Selectively attack particular metals
Gross fouling	Seaweed Wood chips/fibers Mussels Barnacles	Manifold
Corrosion	Oxide layers or rust residue	Tubes and headers
Freezing	The water is cooled by ambient air	Tubes

4.4.2 Vibration

Flow-induced vibration is generally not a concern for air-to-water heat exchangers because the air density and velocity difference between the air side and water side dampen any vibration concern. For annular fin-tube heat exchangers that are installed on rotating equipment such as generators, motors, and compressors, attention should be given to the location of the tube supports so that they are not placed in nodal points that can amplify harmonic vibrations generated by the rotating equipment. Calculations can be performed to place the tube supports at a location along the tube so that resonant frequencies are avoided.

4.4.3 Thermal Stresses

The construction and operating temperatures of fin-tube heat exchangers limit the thermal stress concern to tube expansion only. Multirow coils are constructed with return bends similar to U-tube type shell-and-tube heat exchangers and, therefore, can accommodate thermal expansion of the tubes.

The tubes in a removable cover plate-type exchanger are fixed to tubesheets at each end; therefore, provision for thermal expansion must be allowed for in the structural side casings of the coil.

5

HEAT EXCHANGER PERFORMANCE MONITORING

5.1 Selection Criteria for Heat Exchanger Performance Monitoring

The following criteria provide a technical basis and rationale for identifying a set of heat exchangers to include in a performance monitoring program. As noted in the following sections, performance monitoring (that is, on-line operational monitoring) is a key activity that is integral to preventive maintenance for all of the types of heat exchangers discussed in this report. The criteria are listed in order of increasing restriction, so that after applying the last criterion, a reasonable and manageable set of heat exchangers should remain.

5.1.1 *System Function*

If the heat exchanger is served by an open-loop service water system and serves an active safety function or an operationally critical function, it should be selected. If closed loop system chemistry monitoring indicates the presence of bio-fouling, then heat exchangers performing an active safety function or operationally critical function served by the closed-loop system should also be selected.

5.1.2 *Component Categorization*

If, in addition to the system function criterion, the heat exchanger performs a safety-related function, it should be selected. The licensee should also consider including heat exchangers that have been categorized as critical equipment in accordance with industry-recognized equipment categorization guidelines.

5.1.3 *System Configuration*

If, in addition to the previously discussed criteria, there is more than one heat exchanger in parallel and they are all subjected to the same service conditions (that is, all the same flow rates, none stagnant for long periods of time, etc.), then only one of the heat exchangers needs to be selected for initial performance monitoring. For heat exchangers in series, the first one in the series should be selected for initial performance monitoring because it would be expected to collect the majority of deposits. The other heat exchangers, however, should be rotated through the performance monitoring program so that all heat exchangers are eventually monitored.

5.2 EPRI Heat Exchanger Performance Monitoring

EPRI report NP-7552, *Heat Exchanger Performance Monitoring Guidelines*, lists several methods to evaluate the in-line thermal performance of heat exchangers. The document presents the details of each method and explains their strengths and weaknesses for determining the overall thermal performance of heat exchangers.

6

PREVENTIVE MAINTENANCE ACTIVITIES

Preventive maintenance (PM) tasks are performed on a time or interval basis to avoid unacceptable equipment degradation or equipment failure. PM performs maintenance tasks on a planned rather than a reactive basis and avoids the losses associated with unplanned downtime. The penalty of PM is that some tasks are performed that are unnecessary and costly.

6.1 General Preventive Measures to Mitigate Failures in Heat Exchangers

6.1.1 *Preventive Practices to Mitigate the Effects of Erosion-Corrosion*

The following PM practices may stop or slow the erosion-corrosion process:

- Use thin wall tubular sleeves made of an erosion-corrosion-resistant material to mitigate inlet end erosion-corrosion. The sleeves are cut to a length that covers all eroded portions of the affected tubes. The sleeves are inserted into the tube inlet ends and rolled or explosively expanded along their full length. All sleeves should be tapered at the downstream end to prevent the formation of a turbulence-inducing step that could promote erosion-corrosion at the downstream sleeve-tube interface. Figure 6-1 shows an incorrectly installed insert.

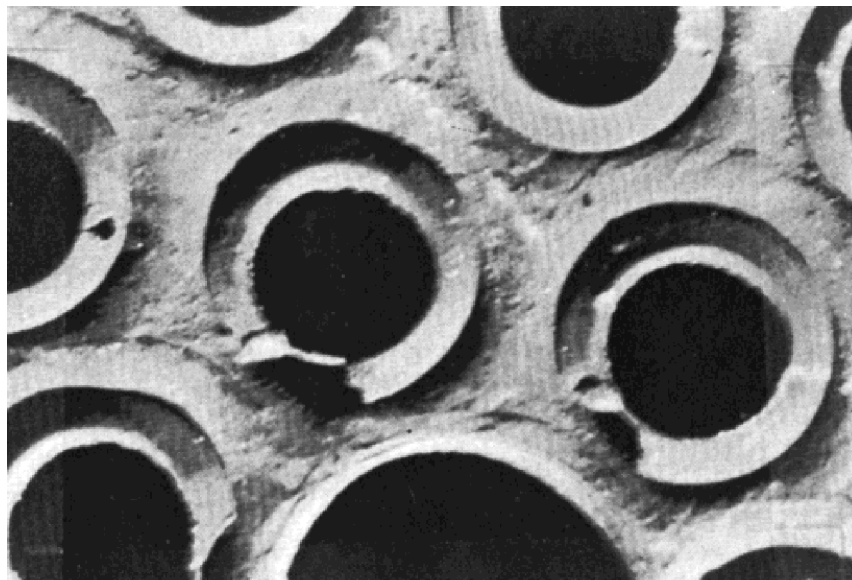


Figure 6-1
Tubesheet damage from incorrect tube insert installation

- Add flow diffusers on the inlet pass to minimize turbulence in the tube entrance area.
- Maintain good plugging records, and evaluate affected heat exchangers at appropriate intervals to determine if plugging will cause excessive velocity.
- Do not plug adjacent to a failed tube without checking for actual need. An adjacent tube that has been severely damaged due to secondary impingement from the failed tube can be detected by eddy current testing.
- When plugging a tube, use extra care to ensure that adjacent tubes are not damaged in the process.
- Remember that coatings can also provide improved resistance to inlet end erosion



Key O&M Cost Point

Effective preventive maintenance strategies to mitigate the effects of erosion-corrosion in the heat exchanger can prolong the life of the heat exchanger and its components in the system.

6.1.2 Preventive Practices to Mitigate Fouling Corrosion and Erosion Control

Steps to minimize biofouling, corrosion, and erosion degradation are varied. With water as the fluid stream, the tube-side velocity should be maintained at a minimum of three feet per second (0.9 m/sec) to reduce biofouling and silting. A regular mechanical cleaning schedule should be evaluated since complete cleaning is impossible because some organisms remain to grow again. Biocides such as chlorine, hypobromous acid, hydrogen peroxide, and others can be dispensed as part of an overall water treatment program. Environmental restrictions and waste disposal issues must be taken into consideration in most water treatment programs. Nonchemical treatments such as thermal shock may also be used.

Cathodic protection minimizes galvanic reactions and can reduce general corrosion and pitting corrosion. The anodes are placed in strategic locations, but it can take several attempts to locate the best positions. As a measure of success, the anode life is trended; it may last months or years, depending on the corrosion mechanism, placement, water quality, and turbulence. Anodes must be periodically inspected and replaced when depleted. Also, a protective coating, such as paint or cladding, can minimize galvanic corrosion. To retard fouling and prevent tube blockage, remove the corrosion products by mechanical cleaning in combination with chemical inhibitors. It is important to adhere to the vendor's instructions when employing chemical additives.

As part of a monitoring program, fluid properties are sampled. Specific testing checks water hardness, pH, and sediment in addition to measuring chemical composition, corrosion products, suspended particles, and biological contents. The data are compared to water quality standards for the plant.

6.2 Shell-and-Tube Heat Exchangers

6.2.1 Introduction to Shell-and-Tube Heat Exchanger Preventive Maintenance

PM activities typically performed for shell-and-tube heat exchangers include the following:

- Internal visual inspection
- NDE (including eddy current testing, ultrasonic testing, radiography, liquid penetrant testing, and magnetic particle testing)
- Performance/functional testing (including pressure leak testing)
- Cleaning of tube bundles (including flushing, tube brushing, and chemical cleaning)
- On-line operational monitoring (for example, water chemistry, corrosion, bio-film monitors, thermography)

Table 6-1 provides an overview of PM activities appropriate for shell-and-tube heat exchangers. The table lists the failure mechanisms, the resulting condition, and locations where failure mechanism may occur. The table also states which maintenance activities would typically be the primary means of identifying each type of failure and which would be the secondary means.

Table 6-1
Primary (P) and secondary (S) PM activities for shell-and-tube heat exchangers

Failure mechanisms	Produces	Inspection location	Internal visual inspection	NDE	Functional testing	Cleaning	On-line operational monitoring
Sedimentation	Sedimentation	Channel, tubes	P	NA	NA	S	S
Scaling	Scale	Tube internal surface	S	NA	P	S	P
Corrosion	Cracks, holes, pits	Tubes	S	P	NA	S	S
		Channel and tubesheet	P	S	NA	S	NA
Biofilm	Slime	Tube internal surface, channel, tubesheet	S	NA	S	S	P
Macrofouling	Foreign material	Tubesheet	S	NA	P	S	P
Erosion	Metal loss	Tube inlet	S	P	NA	NA	NA
		Partition plate	S	NA	P	NA	P

Table 6-1 (continued)
Primary (P) and secondary (S) PM activities for shell-and-tube heat exchangers

Failure mechanisms	Produces	Inspection location	Internal visual inspection	NDE	Functional testing	Cleaning	On-line operational monitoring
Vibration	Cracks, tube and baffle wear	Tubes, tubesheet	S	P	NA	NA	NA
Gasket failure	Material loss, degradation, hardening, leakage	Partition plate gasket, channel closure gasket	P	NA	NA	NA	S
Bolting failure	Loose bolts, missing bolts, leakage	Partition plate, channel cover	P	NA	NA	NA	S
Plug failure	Missing plug, tube leaks	Tubesheet	S	NA	NA	NA	P
Tube impingement	Cracks, dents, metal loss, holes, foreign material	Tube internal surfaces and tube ends/external surfaces	S	P	NA	S	NA
Flow obstruction and blockage	Flow obstruction and blockage	Tubesheet, tubes	P	NA	S	S	P
Cracking or degradation of coating	Corrosion	Tubesheet, waterbox, tubes	P	NA	NA	NA	NA

6.2.2 Internal Visual Inspection

A thorough visual inspection is a valuable tool in a heat exchanger maintenance program. The examination is not limited to heat exchanger components. Color photographs and surface contaminant sampling provide information during inspection. A borescope is helpful to examine inside heads and tubes. More recently, video probe systems using a small camera attached to a flexible probe tip have been successfully used. The image is transferred to a viewing monitor and can be recorded. The flexible nature of the probe allows for inspection of remote areas and U-bends. This type of inspection can identify pitting, corrosion, corrosion byproducts, fouling, and debris.

Direct visual examination of a heat exchanger is limited to channels, pass partition plates, covers, and the tubesheet face. Shell-side inspection without shell removal is limited to the exterior shell, nozzles, and internals that are accessible by piping into the shell side and using a borescope to view the interior.

The inspection areas and associated tasks listed below are for inspection when the channels are opened. The existing condition of the equipment might dictate that additional or fewer tasks should be implemented. The guidelines of what to look for and what to document in the selected areas are listed below:

- **Tube inlets** – For heat exchangers with copper alloy tube material, check for signs of erosion in the tube inlets. Use an internal micrometer to establish baselines and quantify wall thinning. Check any sleeves for expansion and erosion between the sleeves and tubes. Start with the peripheral tubes and the tubes surrounding plugged tubes, and check randomly located tubes. Perform a borescopic inspection on a representative sample of tubes.
- **Tube-to-tubesheet joint and ligaments** – Check tube joints for signs of cracking. Use shell-side air tests to locate leaking holes and cracks. Use dye penetrant tests to quantify surface weld cracks.
- **Tubesheet** – Determine the seal integrity of existing tube plugs. Look for any signs of leakage or partial plug failure. Verify the tube plug map. Examine the cladding around the tube welds and the periphery of the tubesheet for defects. If cracking is indicated, perform dye penetrant examination.
- **Pass partition** – Check for erosion, cracking, distortion of the pass partition plate, and weld cracking/failure at the periphery of the plate. Plate integrity must be maintained to ensure that there is no leakage between the passes resulting in partial heater bypass. Inspect the channel and tubesheet weld connections, cover, cover bolts, nuts, and the cover-to-plate sealing surface.
- **Channel/cover** – Check internal surfaces for signs of corrosion damage and the channel-to-tubesheet welds for cracks. Note any cracks in welds or in the tubesheet-to-channel transition. If cracking is indicated, use dye penetrant testing. Look for gouging or other damage to gasketed surfaces.
- **Shell internals** – When access to the shell side exists, inspect for loose, missing, or damaged fasteners. Inspect for evidence of damage to the impingement plates, erosion/corrosion on the baffle plates, and vibration damage on the OD of the tubes.

Appendix B of this report provides visual inspection guidance and an example of an inspection data sheet that can be used when performing a visual inspection on a shell-and-tube heat exchanger. The example is provided only for illustrative purposes and should be modified accordingly to meet the needs of your facility. Implementation of this guidance, however, can ensure that a common approach is taken to the inspection of heat exchangers. The guidance contained in Appendix B is based on EPRI report 1003320, *Supplemental Guidance for Testing and Monitoring Service Water Heat Exchangers*.



Key O&M Cost Point

A borescope is a valuable tool to use during visual inspections to access areas of the heat exchanger that cannot normally be seen by the inspector.

6.2.2.1 Remote Visual Testing

Because of the complex geometry and welded construction of a heat exchanger, direct visual inspection or observation of internals with the naked eye is not practical. The NDE techniques might determine the failure mechanisms, but might not determine the root cause of the failure. Remote visual testing (RVT) has proven valuable as a complementary testing technique in support of NDE and in root cause determination.

RVT technology is currently based around three different viewing tools for recording/documentation. The relative success or failure of a given inspection is dependent on the proper choice of the RVT tool. The tools are the following:

- Borescope
- Fiberscope
- Photographic equipment

6.2.3 Nondestructive Examination

Nondestructive examination (NDE) is a valuable technology to evaluate the structural integrity of heat exchanger components. The results are used to improve maintenance programs and trend life expectancy. A short summary of each NDE method is given here. Figure 6-2 illustrates typical tube degradation that can be noted from such an examination.

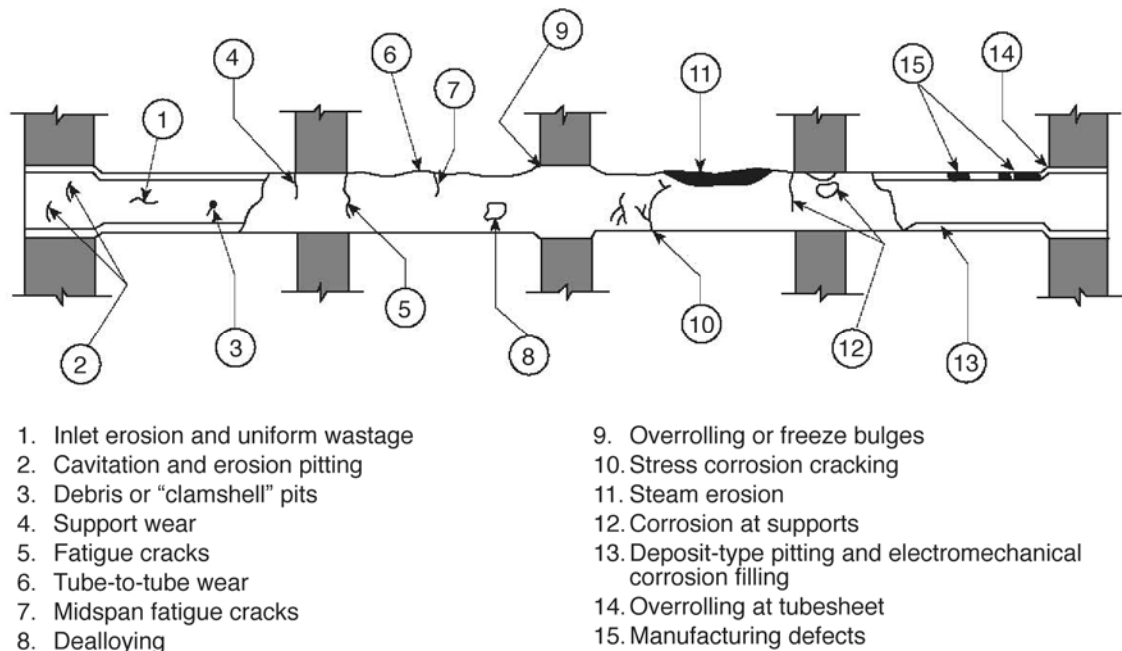


Figure 6-2
Typical heat exchanger tube degradation

Several NDE methods are used to perform a complete heat exchanger inspection. Accurate diagnoses are dependent on selecting the proper NDE technique or combination of techniques. The following are commonly used NDE techniques:

- Ultrasonic testing (UT)
- Magnetic particle testing (MT)
- Dye penetrant testing (PT)
- Electromagnetic testing (ET)

Destructive failure analysis is sometimes needed to determine or verify the failure mechanisms found in the heat exchanger.

6.2.3.1 Ultrasonic Testing

Ultrasonic testing (UT) is a nondestructive examination method that measures the time and sound path between an entry point of the material and the back reflection. Interpretation of the back reflection results in the accurate identification of wall thickness and material defects such as pits and cracks.

UT can be used to identify weld defects, cracks, etc., in pressure vessel components. However, surface NDE methods are less expensive. UT is particularly valuable in determining wall thickness in shells where internal erosion has occurred.

UT for wall thickness measurement has become extremely accurate in the last few years because of higher frequency (>20 MHz) transducers and digital microprocessor-based instruments. UT thickness measurements can be easily calibrated for any material over any reasonable thickness (0.020–0.250 inch [0.51–6.4 mm]) and is accurate when the material's acoustic velocity is known.

UT can discriminate between inside and outside diameter tubing metal loss and between gradual thinning, step-type fretting, or localized corrosion. One system that is used in the inspection of heater tubes is called the internal rotary inspection system (IRIS). UT is not affected by attachments external to a tube, such as support plates or corrosion products.

The disadvantages of using UT are as follows:

- The testing is slow.
- The testing makes only point line measurements.
- The testing requires experienced operators.

6.2.3.2 Magnetic Particle Testing

The magnetic particle testing (MT) method is used in the detection of surface and shallow subsurface flaws such as cracks, forging laps, and nonmetallic inclusions in magnetic materials. A major advantage of MT over other surface testing methods is that the surface does not have to be smooth and clean. In addition, the MT technique offers high sensitivity.

MT operates on the principle that induced magnetic lines of force, produced by the activation of an electromagnetic yoke placed on the equipment, will be interrupted by a defect. The defect causes leakage of the magnetic flux lines into the air at the location of the defect. Application of fluorescing magnetic particles suspended in a fluid will collect around the defect, fluoresce, and outline the defect. The defect is observed with the use of a black light.

6.2.3.3 Liquid Penetrant Testing

Liquid penetrant testing (PT) is a surface flaw inspection method. It can be applied to both magnetic and nonmagnetic materials for the detection of surface cracking and surface laps.

The surfaces to be tested must be thoroughly cleaned and relatively smooth (250 rms or better). PT sensitivity is good, but less than the MT method.

The PT method operates on the principle that a flaw open to the surface will, by capillary action, absorb colored dye that is applied to the flawed surface. After a soaking time of approximately 10 minutes, the dye is thoroughly removed and the surface dried. Then a light application of white powder is sprayed on the surface. The outline of the flaw can be seen as the white powder blots the dye out of the flaw.

6.2.3.4 Electromagnetic Testing

Assessment of the condition of heat exchanger tubing to determine remaining service life must be performed repeatedly, and the technique used must provide a high degree of confidence in the accuracy of the results. In addition, the inspection data must be repeatable so that rates of tube degradation can be determined through periodic inspections during planned outages. Only the electromagnetic testing (ET) techniques meet these criteria.

Selection of the most appropriate ET techniques is dictated by the magnetic properties of the tube material. The testing technique for nonmagnetic alloys (304 SS) is eddy current testing (ECT). Pulsed ECT has been used to determine shell thickness. Full-saturation ET, partial-saturation ET, remote-field testing ET, and flux leakage are tests used for the inspection of magnetic alloys.

6.2.3.4.1 Eddy Current Testing of Heat Exchanger Tubes– Overview



Key Technical Point

The most commonly used NDE technique for determining the condition of installed tubes is eddy current testing (ECT). It is fast, repeatable, good for baseline screening, and accurate in sizing known defects. However, ECT is operator dependent. Quantification of certain types of defects is sometimes difficult, and other NDE methods may be needed in conjunction with ECT.

Eddy current testing (ECT) employs an internal probe specifically designed for the tube inside diameter and the material being tested. The probe consists of an alternating current coil that establishes an electrical field that produces a field of eddy currents in the tube. Tube wall flaws such as wall thinning, cracks, or pits interrupt this field, and the interruptions cause an impedance change in the coil.

Some of the advantages of eddy current examination include the following:

- Relatively fast. For tubing inspections with a high digital sample rate, test speeds of up to 260 inches per second (6.6 m/s) can be achieved.
- Good sensitivity to material property changes (physical/chemical) of the test object.
- Good sensitivity to surface cracks.
- Easy configuration and application for automated examination.
- Easy storage of data for past and future review and comparison (useful for data trending).

Some of the limitations of eddy current examination include the following:

- Eddy currents are affected by the presence of flaws and variation of material properties, such as conductivity, permeability, geometry, etc.
- Eddy currents are influenced by flaw orientations that make the testing directional.
- The sensitivity level for flaw detection is not uniform throughout the test piece. Optimum detection occurs at the test surface closest to the test coil and decreases exponentially below the surface. The depth of penetration is a function of the frequency of the input energy.
- Credible eddy current signal interpretation requires a high level of operator training and awareness.

Because conventional eddy current testing cannot be performed on magnetic tubing material, there are several alternative eddy current tests that can be performed:

- Full-saturation
- Partial-saturation
- Remote-field
- Flux leakage

6.2.3.4.2 Tube Sampling Scheme



Key Human Performance Point

A basic objective is to optimize the tube sampling plan by using a combination of targeted and random sampling to minimize the risk of potential tube failures. A general approach is to test the peripheral tubes, the tubes surrounding plugged tubes, and then a random selection of tubes.

After the tube sampling scheme is determined, the current numbering pattern of the tubes needs to be followed. The degraded tubes selected in the tube sampling plan can be tested and trended to assess the damage-specific growth rate. See Section 7.1.3 on tube plugging guidance.

6.2.3.4.3 On-Site Inspection Activities

Before the start of the examination, all relevant documents, including personnel certification, ECT equipment calibration records, and prepared examination plans for each component should be reviewed and approved. To allow for data comparison, it is important for the vendor to use the tube numbering system that was outlined in the examination plan.

6.2.3.4.4 Post-Inspection Activities

After the inspection activities are completed, an in-depth analysis of test results for immediate remedial actions and for planning future inspection activities must be conducted. Specific utility engineer responsibilities include the following:

- Obtain test results.
- Prepare a list of tubes to be plugged.
- Identify candidate tubes, if applicable, for tube pulls and destructive analysis.
- Implement recommendations for mitigation of observed damage, heat exchanger repair, or heat exchanger replacement.
- Estimate the remaining heat exchanger operating life based on the current and prior test results. Plot the number of tubes plugged versus time (semi-log scale). Look for a sharp increase in the number of tubes plugged to determine if rapid failure is imminent.



Key Technical Point

After the final NDE report has been received, you are strongly urged to record the latest ECT information in a database. This would help you monitor heat exchanger conditions and estimate remaining operating life. Depending on economic and operational factors, it might be necessary to re-evaluate the established plugging criteria because they ultimately affect the remaining heat exchanger operating life.

6.2.3.5 Component Testing

6.2.3.5.1 *Channel and Tubesheet Area*

Internal visual testing is a viable technique for inspecting the channel and tubesheet area. MT and LT should be used to examine the partition welds, nozzle welds, and the channel-to-tubesheet radius if evidence of cracking was noted during visual inspections. UT can be used to determine the channel thickness.

Minor surface cracks might not be identified by the examiner. Therefore, MT or PT of partition welds and the channel-to-tubesheet radius should be performed if evidence or history of cracking exists. Because the tubesheet and channel materials are normally magnetic, MT is usually preferred.

UT for the thickness of the channel can be performed. UT flaw analysis of cracks emanating from the inside (for example, cracks in the channel radius) is difficult to evaluate. This difficulty is a result of the following:

- The thickness of the channel
- The need to remove insulation
- The need for extremely good surface preparation
- The varying surface geometry of the channel (which may be a series of welded plates or a forging)

6.2.3.5.2 *Shell and Nozzle Area*

Visual testing, UT, or ECT can be used to inspect the shell and nozzle areas of the heat exchanger.

UT for thickness measurements is easy to perform and can be streamlined if digital display UT equipment is used. Indications of shell wall loss should be verified with UT equipment of the cathode ray tube type. Laminations on older shells are common and must be identified as laminations and not shell wall loss.

6.2.4 Performance/Functional Testing

6.2.4.1 Pressure Leak Testing

To identify leaks in a heat exchanger or to verify the results of other nondestructive testing, leak checking by pressurizing the heat exchanger shell with air or water (hydro) as the test medium can be a useful tool. It must be considered a supplement to other forms of examination because only a pressure boundary with a through-wall defect will be identified by leak testing under moderate test pressures.

An alternative to pressurizing is to pull a vacuum on the heat exchanger, and monitor pressure. This is a superior method due to the fact that the vacuum is insensitive to ambient conditions. Regardless, any pressure monitoring requires anywhere from several hours to one day or more for a meaningful test to observe a pressure change in the presence of small leaks. An accurate pressure instrument is vital, as is an ambient temperature record.

A common problem with leak checking occurs when heat exchanger isolation valves do not seal or isolate completely. In this instance, proper leak checking is impossible, and the defective valves must be replaced or bypassed.

Pressure testing is sometimes used as a PM tool, but it is normally a poor tool to use for some of the reasons noted, primarily that it detects only existing through-wall leaks. If you have an adequate monitoring and PM program for your heat exchangers, then you should know that you have leaks through means other than performing leak tests. Pressure or vacuum leak testing are commonly used in conjunction with corrective maintenance.

6.2.4.1.1 Tube Wall Leakage Detection

Tube wall leak tests commonly used in conjunction with corrective maintenance follow:

- **Industrial tube tester device** – Tube wall leaks can be found using a tube test device that pressurizes (100 psig or 51.7 cm of Hg) each tube and uses a gauge to monitor for a drop in pressure on the tube. The device has a rubber seal, and it takes about 1 minute per tube to perform the test. One significant drawback is that tiny leaks can go undetected. When searching for these smaller leaks, keep in mind that in any test where the gas pressure is monitored over an extended time, the pressure can fluctuate several psi (kPa) with changes in room temperature. With small leaks, any positive pressure method may be undesirable.
- **Individual tube hydro-test** – When ECT detects cracking indications, an individual tube hydro-test of suspect tubes is useful in determining the pressure-retaining capability of a tube when making plugging evaluations. If an identified cracking flaw does not propagate to failure when subjected to hydro pressure under the tube yield strength, based on ASME Code allowable stresses, then plugging the tube might not be warranted at that time. Only personnel or contractors with experience in this type of hydro testing should be used. Also, note that hydro testing is not effective in exposing incipient leaks in tubes with only indications of pitting due to the high strength shouldering effect around the pitted surfaces.
- **Shell pressure test** – Place gas pressure on the shell side; cork all the tubes on both ends; and observe which corks pop out. As a precaution, a transparent, protective shield must be fixed between the observer and the tubesheet to avoid injury resulting from escaping corks or other plugs.

For smaller leakages, one tube end is blocked with a rubber stopper, and the other end is fitted with a single-hole stopper with a small section of flexible tubing through it. The free end of the tubing is inserted into a vessel of water. If a leak exists, the escaping gas is forced into the tubing, and bubbles are visible in the water vessel. The procedure is repeated for every tube. This is a time-consuming exercise and can take many minutes per tube or days to complete the entire bundle. This method is advised only when other methods of detection have failed to identify leaks.

- **Ultrasonic leak detection** – Relatively small tubing leaks have been successfully detected with an ultrasonic device that senses compressed air leakage within a tube. Compressed air passes through the tube wall perforation and creates turbulence. The turbulence has strong ultrasonic components, which are heard through headphones and seen as intensity increments on the meter. For a shell-and-tube heat exchanger, the test conditions have the shell pressurized with air, and physical access is given to the tubesheet. The hand-held device is placed across the tubesheet, and the audible signal leads to the source of the leakage.

6.2.4.1.2 Shell-Side Leakage Detection

For shell-side leaks, apply pressure to the shell side, and spray a bubble solution on suspect areas including major seams such as the tubesheet-to-shell weld. To improve the test, use a tracer gas in place of air with a detector designed for the particular gas used for the test. Upon pressurization, examine the exterior of the heat exchanger. Note that some detectors (halogen-type) react to chemicals naturally present in the heat exchanger (fluids, contaminants, and so on) and can yield false readings. It might be possible to calibrate out the false signals; however, in some systems, an inert tracer gas (helium, for example) must be chosen.

6.2.4.1.3 Tube-to-Tubesheet Joint Leakage Detection

To detect tube joint leaks, fill the shell side with water under pressure with the heads off, and view the tubesheets for leakage of water. An alternative is to pressurize the shell side with gas and brush a bubble solution on the joints; small bubbles identify leaks that can be repaired. Unfortunately, a joint leaking into the shell side from the tube side is not easily seen or detected because of the limited access to the shell side of most heat exchangers.

6.2.4.1.4 Test Pressures

It is best to leak check with water, when practical. With compressed gas (pneumatic test), keep in mind the high amount of stored energy in the compressed gas and the dangers inherent in this method. When testing, excessive gas pressures are unnecessary; 5–50 psig (2.6–26.0 cm of Hg) are usually adequate. Another guideline would be 15% of design pressure or 1.5 times the operating pressure, up to 50 psig (26.0 cm of Hg). When pressurizing the tube side, be sure that all existing tube plugs are securely in place; otherwise, the plugs can be expelled with potential harm to personnel and damage to equipment.

Always stay below the design rating of the unit. Never use 1.5 times the design pressure as given in the ASME Section VIII Code. This is intended only for new construction.

Another potential failure encountered while pressure testing is brittle fracture. To avoid this phenomenon, never pressure test cold metal. ASME Section VIII defines acceptable temperatures, but, in general, if it feels cold to the touch, it is too cold to test.

6.2.5 Cleaning

6.2.5.1 Cleaning (Nonchemical)

Cleaning should include the following tasks:

- Evaluate the type of fouling that has occurred.
- Determine the appropriate cleaning method or process that provides the best results and limits damage to the tubes.

6.2.5.2 Tube Bundle Cleaning

For tube bundles that are removable from the heat exchanger, tube bundle cleaning is an option to improve heat exchanger efficiency. The interiors of U-tubes and finned tubing are difficult to clean, but plain, straight tubes are cleanable by mechanical, hydraulic (hydro-blasting), and chemical means and can be inspected throughout their entire length. Available tools include pigs and scrapers, sponge balls, hydro-lazing and chemical methods. Note that in many cases U-tube and integral (extruded) finned tube (with an ID contraction in the finned region) bundles can be cleaned with grit-coated balls that readily traverse U-bends and small ID reductions, although they are not as effective as other scrapers and methods applied to straight tubes for harder deposits.)

On the shell side, a large, 90-degree tube pitch facilitates cleaning. A 1/4-inch (6.5-mm) wide space between tubes must be present for a hydraulic cleaning of a tube bundle. Otherwise, the pressurized water cannot penetrate the bundle's interior. For this reason, a triangular tube pitch is harder to clean than a square one. A hydro-blasting pressure of 8,000–10,000 psi (550–690 bar) is typical but can range up to 18,000 psi (1240 bar).

For fixed tubesheets, chemical cleaning is usually the only alternative unless clean-out ports are provided on the heat exchanger. In the instance of floating head units, the bundle can be chemically cleaned while in the shell or the bundle can be removed and washed mechanically, chemically, or hydraulically as long as the tube pitch provides a minimum of 1/4-inch (6.5-mm) empty spacing.

Thermal stresses and potential detrimental effects on heat exchanger components need to be considered when performing hot steam hydraulic cleaning. The possible effects include tubesheet bending and tube bowing. Similar guidance holds for U-tubes with the added complication of access to tube surface within the U-bends.

In all bundle installations and removals, adhere to the vendor's instructions for pulling, pushing, and supporting; otherwise, the bundle or shell can become damaged.

6.2.5.3 Flushing

It is usually desirable to clean a heat exchanger without disassembly. Often cleaning is achieved by first flushing the unit. Flushing is performed on the shell side or tube side when water is the system fluid. For adequate velocity and turbulence, flush with 5–10 ft/sec. (1.5–3.0 m/sec) water on the tube side. Less velocity is required on the shell side. (The minimum would be 1.25 times design flow for either tube side or shell side.)

When cleaning a series of heat exchangers in the same system, begin at the heat exchanger farthest from the pumps and at the highest elevation, and work toward the pumps. In this way, debris has an opportunity to exit the system immediately through clean piping, instead of building up as would occur if flushing began at the pumps.

For persistent deposits, a back flush with water and compressed air or nitrogen (50 psig or 260 cm of Hg, minimum) may be more effective than a water flush alone since the gas provides turbulence to scrub the heat transfer surfaces. This method is not likely to be effective at addressing hard scale deposits and is likely to provide only temporary reductions in biological fouling unless combined with improved chemical treatments to reduce new growth.

6.2.5.4 Tube Cleaning

Automatic cleaning machines, down to 1/2 inch (12.0 mm) tube ID, are easily obtained, but smaller tubes can call for manual brushing. Access to both ends of the tubes is recommended to fully flush debris from the tubes.

For brushing soft copper tubes, exercise caution when using hard coated brushes or cleaning balls. Additionally, extreme care should be taken when cleaning brass tubes with metal tube scrapers. Scratches in the tube wall could result from the metal scrapers, and these scratches tend to preferentially corrode due to an upset in the tube surface oxide protective layer, leading to a pitting corrosion concern. In general, the choice of brush is dependent on the fouling encountered and the tube material. When in doubt, first try the procedure on a sample tube, and verify that base metal is not being damaged or removed by the proposed procedure. Tube brushing is limited to straight tubing. U-bends are not cleaned by mechanical brushing, but can be traversed by grit-coated cleaning balls. Figure 6-3 and 6-4 illustrate stainless steel tube fouling before brushing and the same tubes after brushing, respectively.



Figure 6-3
Stainless steel tube fouling before brushing

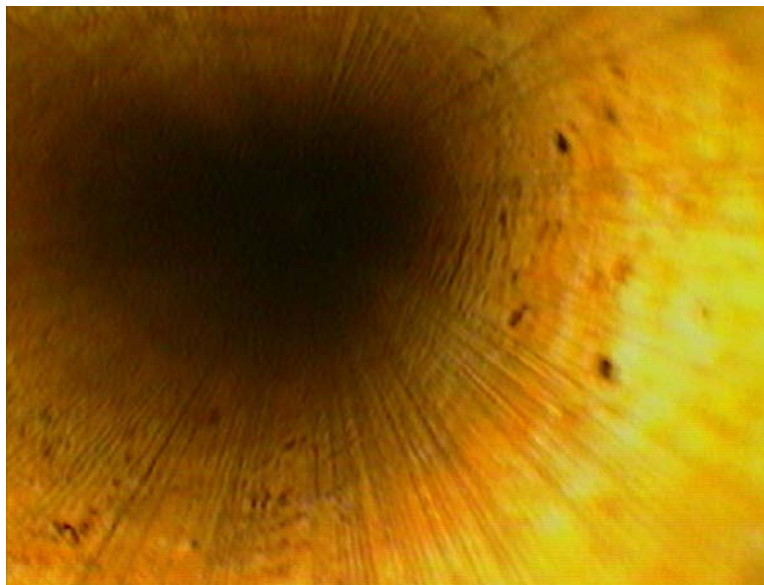


Figure 6-4
Stainless steel tube after brushing

When using individually shot tube brush cleaners, accountability of the brushes or balls must be maintained to ensure that no brush cleaners are left in tubes that could result in adverse system operational problems due to foreign objects in the system. This particular problem is more sensitive when accounting for large numbers of brush cleaners in heat exchangers that contain thousands of tubes. One solution to this problem is to use a mechanically rotated brush attached to a cable that is fed down each tube. Hand feeding the cable and brush through the tubes can be time consuming, but low cost equipment is available that automatically feeds a cable-attached rotating brush down through a tube and back at an efficient speed.

6.2.5.5 Chemical Cleaning

If flushing and mechanical means are not sufficient, chemical cleaning becomes an option. This is especially true for maintenance on the shell side, which cannot be brush cleaned. It is imperative to follow the vendor's instructions when employing a chemical cleaner. The use of a pulsing pump is helpful due to the agitation in the heat exchanger, which scrubs the surfaces and facilitates cleaning. Always locate a filter or strainer to collect the debris from a cleaning process; heat exchangers are collection points for debris, and broken-off corrosion products can lodge in tubes or other system components.



Key Technical Point

Whenever acids are used, they must be properly inhibited to eliminate or minimize the removal of base metal.

Proper metal passivation is required after cleaning. When considering chemical methods, environmental and waste disposal issues are important and add significant costs to the processes. Certain vendors offer on-site tube bundle chemical cleaning with mobile trailer vats that completely contain the cleaning apparatus hardware and resulting solution waste. These mobile units are fitted with pumps, heaters, spray nozzles, and all other necessary cleaning equipment to ensure uniform thorough cleaning of exposed tube surfaces.

6.2.5.6 Cleaning Frequency

A cleaning schedule is based upon the specific application and operating experience of the plant. Each heat exchanger might have its own maintenance schedule. Fouling can be trended, but it is speculative to project too far in the future because fouling mechanisms and rates are often not well understood. Maintenance is coordinated with outages as appropriate. Documentation of conditions before and after cleaning serves as a guide to future maintenance and performance evaluation.

More attention should be given to intermittent-use heat exchangers. These may be more susceptible to fouling and corrosion, depending on water quality and treatment. The optimal solution is to rotate all the heat exchangers of a particular system during actual operation. However, if this is not practical, a flushing or cleaning schedule should be established that is based on the fouling tendency for each unit and system and is in accordance with current industry best practices.

6.2.6 On-Line Operational Monitoring

6.2.6.1 Chemistry Monitoring and Operator Rounds

Chemistry monitoring and operator rounds are an important activity in the operation and maintenance of cooling systems.

Operator rounds can include activities such as detecting unusual noises or external leaks and monitoring operations parameters, water levels, and drain flow for heat exchangers.

6.3 Plate Heat Exchangers

6.3.1 Introduction to Plate Heat Exchanger Preventive Maintenance

PM activities typically performed for plate heat exchangers include the following:

- Internal visual inspection
- Cleaning (including soft brush, pressure sprayer, and chemical cleaning)
- On-line operational monitoring

Plate heat exchangers, are subject to degradation and eventually require some form of maintenance to ensure continued performance and to extend operating life. The common problems are performance degradation (for example, due to fouling and clogging) and mechanical failures (for example, internal and external leakage).

The components of a plate heat exchanger that normally require maintenance or replacement are the plates and gaskets. Clean plates ensure proper thermal performance and can be chemically cleaned to remove scale buildup and other deposits. Damaged plates can be replaced. Gasket lifetime depends on process variables such as changes in operating temperature, differential pressure, compatibility with the fluids involved, and the environment external to the plate heat exchanger. Gaskets are subject to physical aging and chemical deterioration—swelling, shrinking, hardening, losing their sealing force, cracking, and blowout.

Table 6-2 provides an overview of PM activities appropriate for plate heat exchangers. The table lists the failure mechanisms, the resulting condition, and failure locations of each mechanism. The table also depicts which maintenance activities would typically be the primary means of identifying which type of failure and which would be the secondary means.

Table 6-2
Primary (P) and secondary (S) PM activities for plate heat exchangers

Failure mechanisms	Produces	Inspection location	Internal visual inspection	Cleaning	On-line operational monitoring
Sedimentation	Sedimentation	Bottom of the plate, top corners of the field gaskets	S	S	P
Scaling	Scale	Raw water side of the plates	S	S	P
Corrosion	Cracks, holes, pits	Plates	S	S	P
Biofilm	Slime	Plates	S	S	P
Macrofouling	Foreign material	Plates	S	S	P
Erosion	Metal loss	Plates, inlet and outlet nozzles	P	S	NA
Vibration	Cracks	Plates, inlet and outlet nozzle liners	P	S	S
Gasket failure	Material loss, degradation, hardening, leakage	External leakage of shell	S	S	P
Bolting failure	Loose bolts, missing bolts, leakage	External leakage of shell	S	NA	P
Flow obstruction and blockage	Flow obstruction and blockage	Plates	S	S	P

6.3.2 Internal Visual Inspection

Internal visual inspections are primarily useful for identifying evidence of erosion or vibration-induced cracks around the plate and the inlet and outlet nozzles. Visual inspections can also identify evidence of scaling on the plates, corrosion (cracks, holes, or pits) of the plates, biofilm on the plates, or flow obstruction and blockage around the plates. Visual inspections should be performed to identify external leakage caused by either gasket failure or bolting failures.

Aside from periodic visual inspections, PM for a plate heat exchanger generally consists of cleaning for different types of fouling and on-line operational monitoring.

6.3.3 Cleaning Activities to Remove Fouling

Section 3.2 discussed various types of fouling and their causes that are typical for plate heat exchangers. Based on these types of fouling, take care to ensure that the appropriate cleaning methods are used.

The following are three different methods of mechanical cleaning after opening the plate heat exchanger:

1. Soft brush and running water – Remove minor fouling safely with a soft brush and running water, as shown in Figure 6-5. Take special care to avoid gasket damage. Dry surfaces with a cloth or rinse them with clean water before reinstallation.

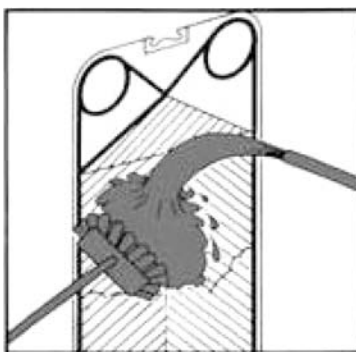


Figure 6-5
Cleaning with soft brush and running water

2. High-pressure sprayer – Figure 6-6 illustrates the use of a high-pressure sprayer (typically less than 4000 psi [276 bar]) to remove significant amounts of fouling.

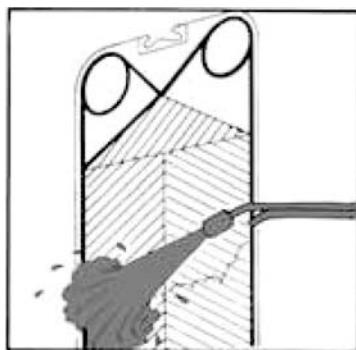


Figure 6-6
Cleaning with a high-pressure hose

Care should be taken to ensure gaskets are not damaged when using a high-pressure sprayer, avoid spraying directly on the gaskets.

3. Chemical cleaning – Chemical cleaning by utility personnel is not recommended and should be performed only by experienced personnel. Table 6-3 describes the types of chemicals suitable for cleaning various types of fouling:

Table 6-3
Chemical cleaning of plate heat exchangers

Chemical cleaning compound	Type of fouling		
	Scaling and incrustation	Sediment	Biological growth - slime
Nitric acid	X	X	X
Sulfamic acid	X	X	X
Citric acid	X	X	X
Phosphoric acid	X	X	X
Complexing agents (EDTA, NTA)	X	X	X
Sodium polyphosphates	X	X	X

Note: Work closely with a chemical cleaning vendor to select the optimum chemical process for the given fouling and to ensure compatibility with heat exchanger materials.

Under no circumstances should hydrochloric acid be used with stainless steel plates, and under no circumstances should hydrofluoric acid be used with titanium plates. Water of more than 300 ppm chlorine cannot be used for the preparation of cleaning solutions.

It is very important for carrying bars and support columns made of aluminum to be protected against chemicals. The addition of surfactants can improve the cleaning effect on the sedimentary type of fouling. Maximum concentrations should not exceed 4% by weight, and typically maximum temperatures should not exceed 140°F (60°C).

Care should be taken to coordinate closely with an appropriate chemical vendor when establishing these limits on concentration and temperature to ensure that they are suitable for the type(s) of scaling, sediment, and biological fouling conditions combined with heat exchanger materials of construction.

6.3.4 On-Line Operational Monitoring

On-line operational monitoring should identify pressure drops or pressure spikes and any changes in heat transfer. Monitoring the pressure drop through the plate heat exchanger can provide an indication of fouling and can provide an indication of a major flow obstruction or blockage around the plates. Monitoring and subsequent changes in the pressure differential can lead to discovery of external leakage, which can be caused by bolting or gasket failures.

6.4 Air-to-Water Heat Exchangers

PM activities typically performed for air-to-water heat exchangers include the following:

- Internal visual inspection
- NDE (including eddy current testing, ultrasonic testing, radiography, liquid penetrant testing, and magnetic particle testing)
- Performance/functional testing (including pressure leak testing)
- Cleaning of tube bundles (including flushing, tube brushing, and chemical cleaning)
- Cleaning external heat transfer surfaces
- On-line operational monitoring (for example, water chemistry, ΔP , and temperature)

Table 6-4 provides an overview of PM activities appropriate for air-to-water heat exchangers. The table lists the failure mechanisms, the resulting condition, and failure locations of each mechanism. The table depicts which maintenance activities would typically be the primary means of mitigating each type of failure and which would be the secondary means.

Table 6-4
Primary (P) and secondary (S) PM activities for air-to-water heat exchangers

Failure mechanisms	Produces	Inspection location	Internal visual inspection	NDE	Functional testing	Cleaning	On-line operational monitoring
Sedimentation	Sedimentation	Channel, tubes	S	NA	NA	S	P
Scaling	Scale	Tube internal surface	S	NA	P	S	S
Corrosion	Cracks, holes, pits	Tube	S	P	NA	NA	S
		Channel and tubesheet	P	S	NA	NA	NA
Biofilm	Slime	Tube internal surface	NA	NA	S	S	P
Macrofouling	Foreign material	Tubesheet	S	NA	P	S	P
Erosion	Metal loss	Tube inlet	S	P	NA	NA	NA
Vibration	Cracks	Tubes, tubesheet	P	S	NA	NA	NA
Plug failure	Missing plug, tube leaks	Tubesheet	S	NA	NA	NA	P

Table 6-4 (continued)
Primary (P) and secondary (S) PM activities for air-to-water heat exchangers

Failure mechanisms	Produces	Inspection location	Internal visual inspection	NDE	Functional testing	Cleaning	On-line operational monitoring
Tube impingement	Cracks, dents, metal loss, holes, foreign material	Tube internal surfaces and tube ends/external surfaces	S	P	NA	NA	NA
Flow obstruction and blockage	Flow obstruction and blockage	Tubesheet, tubes	S	NA	S	NA	P
Cracking or degradation of coating	Corrosion, foreign material, flow obstruction and blockage	Tubesheet, waterbox, tubes	P	NA	S	NA	S

Note: Internal visual inspection and NDE activities of the tube ID are feasible only for air-to-water heat exchangers with a waterbox design, which facilitates the removal of the head.

6.4.1 Cleaning the Fin Side of the Air-to-Water Heat Exchanger

Take care when cleaning the fin side so as not to deform or crush the fins. Brush light residue in small areas. If the fins are strong and thick enough, use high-pressure air, steam, or water to clean around the fins. In most fin-tube heat exchangers, the tubes are typically in a triangular pitch so the pressure washing nozzle should be directed on a 45° angle. If possible, flush the fins in both directions, beginning from the air outlet side. Use chemicals if they are compatible with the process, fin material, and debris. Coordinate with the manufacturer to ensure that proper cleaning solutions are used.

6.4.2 Cleaning the Water Side of the Air-to-Water Heat Exchanger

A multi-row type of air-to-water heat exchanger can be chemically flushed. Clean the tubes with manual or rotary brushes if the cover of the heat exchanger is removable. Some cover-plate designs incorporate hinges for easy access. Additional guidance is provided in Section 6.2.5 of this report for tube cleaning.

7

CORRECTIVE MAINTENANCE

7.1 Repairs to Shell-and-Tube Heat Exchangers

The ASME “U” stamp covers only new construction; the National Board Inspection Code (NBIC) is recognized by most jurisdictions as the document to follow for repairs and alterations of pressure vessels, including heat exchangers. Any repairs or alterations are under the jurisdiction of the locality that is ultimately responsible. The National Board is not responsible for work; it acts on behalf of ASME and promotes and sets uniformity of rules, trains and certifies inspectors, and registers pressure vessels.

The “R” (for Section VIII vessels) or “NR” (Section III heat exchangers) stamp is usually necessary for alterations and for repairs when welding is performed. If welding is not done during a heat exchanger repair, the repair facility does not need to hold approved ASME Code stamps.

It is wise to discuss the work plan with the authorized inspector (AI) prior to initiating changes. The construction repair must comply with the edition of the ASME Code that was current at the time of the original construction or any later edition up to the current one if the design features are applicable to later editions.

Repairs and alterations can be conveniently grouped into three categories: major repair, minor repair, and alteration. For a major repair, an identical (or better) replacement component should be selected. The original ASME-stamped design conditions remain. Examples of this type of work include the following:

- Replacement involving welding of a major component such as a head, shell, tubesheet, etc.
- Replacement of a large nozzle or port similar to the nozzles already on the unit
- Weld repair of flanges
- Weld repair of major seams in shells and heads

A minor (routine) repair is the same as a major repair except that a vessel “R” stamp is not required at the end of the repair, but a repair report (R-1 form) must be issued. The AI must concur that the repair is of a routine nature. Selected examples of this type of repair are the following:

- Weld build-up in wasted regions
- Weld addition of a corrosion-resistant overlay

- Retubing with seal welds, using the same type of tube material/size
- Small diameter nozzle or flange replacements similar to those already on the unit
- Weld seal of gauge openings or drains
- Nonpressure part replacements, such as partition plates, legs, and so on

An alteration amounts to a rerating at a higher pressure and/or temperature. A rerating at a lower temperature can also be an alteration if impact testing now comes into play. Instances of an alteration are the following:

- Replacement components or materials with lower stress or strength properties
- Nozzle replacement or addition where the size is smaller or larger than existing ones and with new reinforcement computations

A calculation package must be completed for an alteration. A hydrostatic pressure test must take place, although the AI might avoid going to 1.5 times the design due to the presence of relief devices and other external components that might be unable to sustain such a pressure.

7.1.1 Tube-To-Tubesheet Joint Repair

Most tube-to-tubesheet joint problems occur on the inside face (shell side) of the tubesheet where the bending stresses are greatest. Tube-to-tubesheet joints can also suffer from crevice corrosion in the gaps between the tube walls and tubesheet holes. These bonds can crack from the normal expansion and contraction experienced by the tubesheet due to pressure loading and/or temperature differential. Table 7-1 lists various tubesheet joint issues that can occur and the types of repairs recommended for each.

Table 7-1
Recommended repairs for tubesheet joint issues

Tubesheet joint issues	Repair type
Leakage due to suspect disturbance of tube joint or minimally expanded tube joint.	Re-roll tube joint
Reduce crevice corrosion potential in the unexpanded tube portion of the tubesheet hole.	Step-roll tube full depth of the tubesheet
Eroded or cracked weld at tube end interface of tubesheet	Weld repair
Tube end crevice corrosion due to interface of dissimilar metals.	Tubesheet coatings
Tubesheet erosion from high flow.	Tubesheet coatings
Overall general corrosion of tubesheet	Tubesheet coatings
Cracked tubesheet ligament from over-rolling stress	Weld repair
Tube plugging of a blank tubesheet hole	Welded plug in tubesheet

7.1.1.1 Rolling Repair

Tubesheet leaks can be repaired by tube rolling unless the joint is over-rolled, which is detected by measuring the wall thinning. For original rolling conditions, the appropriate formula is based on tubesheet hole, tube wall thickness, and tube ID:

$$\% \text{ wall reduction} = \frac{100 \times [\text{final ID} - (\text{initial ID} + \text{clearance})]}{2 \times \text{measured unrolled wall thickness}}$$

Where:

ID = Measured tube inner diameter

OD = Measured tube outer diameter

Clearance = (Measured tubesheet hole diameter - OD)

Wall reduction varies from 3%–12%. Over-rolling can distort the tubesheet and ligaments, produce high residual stresses (increasing the chance of stress corrosion cracking), and work-harden materials in the tube ends, while under-rolling fails to develop sufficient joint strength and joint seal.

From the above equation, the original percentage of wall reduction is computed. The rerolling should cause a wall reduction percentage equal to 1.1–1.2 times the original value. (As an example, if the original wall reduction was 10%, the rerolling should be set at 11%–12%.) The roller is set for the correct ID from adjustments through rolling the first few joints. Once tooling is set, it is a very routine procedure. Factors such as improper rolling torque and sequence can damage a tubesheet. Only qualified, experienced personnel should perform tube rolling.

7.1.2 Tubesheet Repair

A tubesheet can be degraded by erosion or corrosion and usually suffers a material loss. Other circumstances, such as thermal fatigue or tube vibration, lead to the more serious problem of cracking.

7.1.2.1 Epoxy Coating

Special epoxy coatings are applied to wasted tubesheet and tube-to-tubesheet joint areas and have proven to be reliable. Prepare the surface for good epoxy contact by sandblasting or an equivalent method to provide a clean and appropriate profile (Refer to the NACE/SSPC standards. White metal blast is typically the best for this application). The coating is brushed on and allowed to dry, and the tube inlets are chamfered. During the coating process, the tube inlets can be protected with corks. It is important to ensure smooth entry of fluid into the tubes; a gap will invite sediment and corrosion, while protrusion past the tubesheet causes local velocity jets that can erode tubesheet material.

A tubesheet coating typically is 3/16–1/4 inch (4.8–6.5 mm) in thickness. (Thinner layers will last only a short time.) Coatings have good wear resistance, but they will crack over time; epoxy coating generally represents an economical solution for many years of life extension. When a coating is applied, some strength is added to the tube joint, but no credit can be taken in calculation for the structural strength. Care must be taken not to scrub the coating with a wire brush, scraper, or strong chemicals. When inspecting the heat exchanger after a coating application, clean it with water and a soft brush, sponge, or rag, when required.

7.1.2.2 Weld Repair of Tubesheets

Weld repair of a tubesheet may be needed to address ligament damage, and this is a very specialized repair when considering excavating individual tube ligaments, welding, and re-machining tube holes.

Welding a tube plug in a blank tubesheet hole where a tube sample has been removed could be considered a tubesheet repair in order to maintain the tubesheet pressure boundary. Carefully consider the weld preparation of the plug end and tubesheet hole edge to ensure weld quality. Welding a square edge tube plug by fillet weld within the tube hole is more difficult and prone to weld flaws than a plug prepared with an open butt-weld configuration at the tube hole edge.

7.1.3 Tube Plugging

Heat exchanger tubes are typically plugged as a result of tube failure or preventatively plugged based on wall reduction indications from eddy current or IRIS inspections. Tube plugs are available in many different forms and, depending on the application, certain plugs are more suitable than others.

7.1.3.1 Tube Plug Selection Criteria

The following criteria should be considered when selecting tube plugs:

- The plug should be permanent and leak tight for the life of the heat exchanger. The plug may need to be removable for retubing processes.
- The plug installation process should be controllable, and the action of installing the plug should not damage the tube, tube sheet ligaments, tube joints, or epoxy coatings that are applied to the tube sheet and/or tube.
- The plug itself should be constructed of material that is rated for continuous duty in the heat exchanger environment. The plug materials should be resistant to corrosion and aging effects that might cause leakage.
- The ideal heat exchanger plug should not require periodic retightening and inspection to verify that it is leak tight.
- The installed plug should be capable of resisting pressure from either direction.

Tube plug types can be grouped into the following three general categories, hammer-in plugs, mechanical plugs, and explosive/welded plugs. Regardless of the plugging method selected, the overall effectiveness will be related to the degree of tube preparation. The following sections describe the three general categories of tube plugs.

7.1.3.1.1 Hammer-in Plugs

Hammer-in plugs appear in two different forms, a simple conical wedge and a two-piece conical pin and collar as shown in Figure 7-1. Hammer-in plugs can be fabricated from many different materials, for example, wood, plant fiber, plastic, and any metallic alloy. The taper angle of the pin generally ranges from 1.5 degrees to 7 degrees. Hammer-in plugs are sized so that the minor diameter end fits the tube ID and the major diameter end does not. Two-piece plugs are sized following the manufacturer's instructions. Installation is accomplished by using a hammer to drive the pin into the tube end or, in the two-piece style, to drive in the pin into the collar so that the collar swells outward. In higher pressure applications, hammer-in plugs may be welded to the tube end and/or tube sheet as shown in Figure 7-2.

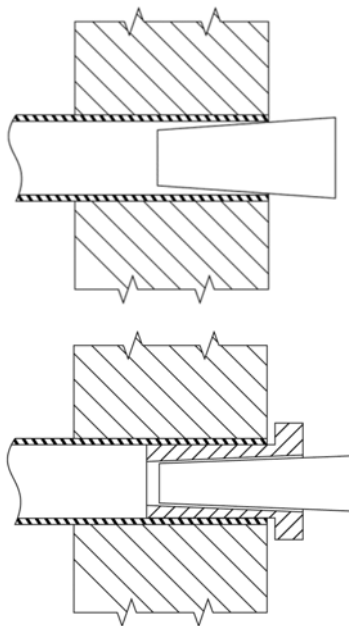


Figure 7-1
Two-piece conical pin and collar hammer-in plug

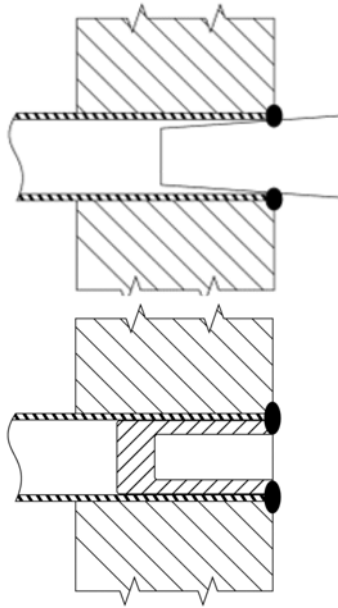


Figure 7-2
Hammer-in plug welded to tube

Pros for using hammer-in plugs are the following:

- There is a low initial cost (unless seal welded).
- They can be manufactured on site as needed.
- They can be quickly installed.
- They require no special tooling or training.

Cons for using hammer-in plugs are the following:

- They install at the tube end, provide a minimal contact point immediately at the tube end; this is also the area of highest erosion and corrosion. The two-piece design has a smooth outer surface on the collar, which must be deformed against the tube wall to make a seal.
- There is little or no control over installation loads. You cannot identify when the plug is installed fully into the tube.
- They should not be used where tube sheets have been epoxy coated.
- They can only be installed in low working pressures unless they are seal welded.
- Nonwelded plugs can eject under pressure, leading to injuries.
- Welding may require pre-heat, post-weld heat treatment, elevated NDE inspection, and could cause subsequent leakage of adjacent tubes or tube joints.
- They are difficult to remove and may require drilling and tapping in place. Seal-welded variations require weld material to be ground away before drilling, tapping, and pulling plugs.

7.1.3.1.2 Mechanical Tube Plugs

Plugs in this category use some mechanical means to expand a component of the plug into contact with tube, creating a seal. There are two types of mechanical type plugs: expandable rubber plugs and expandable metallic plugs.

- **Expandable rubber plugs** – Expandable rubber plugs have one or more elastomer seal elements that are sandwiched between washers, all of which are nested on a common threaded shaft. A nut is tightened to a prescribed torque that compresses the elastomer seals axially, causing them to swell outward into contact with the tube wall. This plug type relies on the friction created between the elastomer seal and the tube wall to remain in position. Some expandable elastomer plugs have integral gripping mechanisms to offset higher pressures. Figure 7-3 illustrates some examples of expandable rubber plugs.



Figure 7-3
Common manual tube repair plugs

Pros for using expandable rubber plugs are the following:

- They are moderately inexpensive, depending on the elastomer material and shaft/bolt materials.
- They install with a torque wrench.
- They are removable.

Cons for using expandable rubber plugs are the following:

- They can only be used in low working pressure unless the gripper style is used.
- Depending on the elastomer that is used, there may be a limited maximum working temperature allowed.
- Elastomer materials are subject to compression set, causing the compressive load used to expand the plugs to relax, loosening the plugs.
- They require periodic inspection, maintenance, and retightening to ensure leak tightness.
- Service life concerns are due to elastomer material deterioration.
- There can be shelf life and storage concerns.

- **Expandable Metallic Plugs** – Expandable metallic plugs in this category use a mechanical means to expand a metallic sealing member outward against the tube wall. The mechanical means may be either tension- or torque-controlled plugs or a roll-in thimble design.

Tension-controlled plugs use a tensile member to control installation loads. Typically, a conical pin is drawn under tension through a sealing ring. As the pin is pulled through the ring, the ring expands outward against the tube. Outward expansion is controlled by the tensile member, eliminating damage to tube or tubesheet joints. At the correct installation load, the tensile member pops like a pop-rivet.

Pros for using tension-controlled plugs are the following:

- They are available in many different alloys.
- High- and low-pressure versions are available.
- They can be installed at any depth within the tube sheet, moving the plug away from the area of highest erosion and corrosion.
- They can be hydraulically or manually installed.
- Only compact tooling is available to work in confined areas.
- They are easily removable.
- No welding or hot work is required.
- They can be used where the tube sheets have been epoxy coated.

Cons for using tension-controlled plugs are the following:

- They require a trained installer.
- Equipment setup is more difficult than other tube-plugging options.

Torque-controlled plugs use torque as the mechanical means to expand the sealing component. Pros for using torque controlled plugs are the following:

- They are easy to install.
- They are available in many different metallic alloys.
- They can be used in higher operating pressures than hammer-in plugs.

Cons for using torque-controlled plugs are the following:

- The locking mechanism sometimes fails; plugs do not engage.
- They are very difficult to remove and are often abandoned in place.
- Some installation load is lost in friction between mating surfaces as torque is applied.

A roll-in thimble design plug is a thimble-shaped insert that is fitted into the tube or tubesheet hole, then mechanically roller-expanded with a tube roller by hand or by using a torque-controlled rolling motor. Pros for using roll-in thimble plugs are the following:

- They are available in many different alloys.
- They are removable.

Cons for using roll-in thimble plugs are the following:

- They require an experience installer.
- The installation is time consuming.
- Over-rolling can cause joint leaks in adjacent tubes.
- The installation is difficult in tight confines.

7.1.3.1.3 Explosive and Welded Plugs

Welded or explosive type plugs typically are an option for high-temperature and pressure heat exchangers. The focus of this guide is low-energy-type heat exchangers where design conditions do not warrant welded or explosive plugs. However, a welded plug option might be considered where a tube has been removed from the tubesheet and the blank hole requires plugging.

The pro for using explosive plugs is high pressure-holding capability.

Cons for using explosive plugs are the following:

- They require a highly trained installer.
- Their use requires a permit to handle/store explosives.
- Damage could be done to the tube wall.
- Incorrectly installed plugs may damage adjacent tube joints.
- They are very difficult to remove.
- They are expensive compared to other heat exchanger plugs.

7.1.3.2 Tube Plugging Criteria

The plugging criteria for heat exchangers vary from component to component and plant to plant and are based on a percentage of tube material wall loss. This tube wall loss plugging criteria has ranged from a low 40% to a high 80% of material degradation. The established percent of wall loss plugging criteria is not generally damage or location specific and is applicable to all flaw types, regardless of flaw locations. A common practice is to evaluate the eddy current analysis results first and then decided on the final plugging criteria. This normally results in a higher numerical wall loss plugging criteria than the value used initially to plug defective tubes. The practice minimizes the number of plugged tubes, thus maintaining the heat exchanger capacity factor by maintaining the number of plugged tubes below the established design-plugging limit.

The established heat exchanger plugging criteria mostly relies on similar plugging criteria using in the NRC Regulatory Guide 1.121, *Bases for Plugging Degraded PWR Steam Generator Tubes*. The following factors are considered in the guide:

- The minimum tube wall thickness needed for tubes with defects to sustain the imposed loading under normal and postulated accident conditions
- An operational allowance for degradation between inspections
- The crack size permitted to meet the leakage limit allowed according to the technical specification

As an example, more prevalent United States steam generator tube plugging limits of 40% wall loss were based on a model of remaining tube integrity for wastage-type degradation. These plugging criteria includes factors for an increase in the flaw size between inspections (10%) and for measurement errors (10%) associated with eddy current examination. The industry views these plugging criteria as overly conservative.

For service water heat exchanger applications, updated plugging criteria consider the allowable wall loss based on heat exchanger operating environment, damage mechanism, growth rate, and NDE accuracy in terms of sizing error. The plugging criteria are calculated using an EPRI-generated Excel spreadsheet called *Heat Exchanger Tube Plugging Criteria Calculator* (Product 1019322). The tube plugging criteria in percentage of wall loss are equated to allowable wall loss minus eddy current sizing error.

Depending on the degradation factor, the allowable tube wall loss can be in the range of 50%–90%. Consequently, if the eddy current sizing error of 10% is used, the resultant plugging criteria can be 40%–80% wall loss.

Different utilities use different plugging allowances, depending on degradation mechanism, location of flaw, and potential impact to safety and unit availability. For example, heat exchangers cooled with raw water may require a variable plugging criteria depending on the type of tube degradation. Specifically, these criteria are summarized as follows:

- 80% for general pitting (both ID and OD isolated pit-like indications)
- 60% for wear/fretting at tube support plate locations
- 40% for free span thinning due to erosion/corrosion
- 0% for evidence of any tube cracking other than superficial

The EPRI *Heat Exchanger Tube Plugging Criteria Calculator* is not applicable to crack-related damage mechanisms. Crack-type tube degradation mechanisms require specific and sophisticated analysis techniques that are beyond this criteria calculator.

When developing an allowable wall loss plugging criteria, consider the heat exchanger's operating environment, the damage mechanism/growth rate, and the NDE uncertainty in terms of sizing error. Acceptable wall loss criteria should consider the list of 10 tube wall degradation factors shown below in percentage of wall loss:

1. Consequence of leakage	20%
2. Safety-related equipment	15%
3. Type of damage mechanism	15%
4. Flaw growth rate	15%
5. Tube material type	10%
6. Available leak detection method	5%
7. Condition of water chemistry	5%
8. Fouling potential	5%
9. Design pressure	5%
10. Design temperature	5%

These factors are then weighted (multiplied) by an individual heat exchanger performance factor and applied to a degradation chart. Once the chart is read and an eddy current sizing error is applied, final recommended tube plugging criteria are achieved. A case study involving actual calculation of plugging criteria for given condition is provided in Appendix B of EPRI guide, *Eddy Current Testing of Service Water Heat Exchangers for Engineers Guideline*, TR-110392.

A record of tube plugging and replacement is an asset to long-term maintenance and repair. A list of relevant data to capture when tube plugging includes the following:

- Date of repair
- Tube location
- Longitudinal position of damage (if known)
- Circumferential position of damage (if known)
- Root cause of failure (reason for plugging)
- Physical condition of tube and its neighbors
- Any NDE test results

7.1.4 Tube Repair

Tubing is a heat exchanger's most important component. A tube provides a pressure boundary that separates tube-side and shell-side fluids, as well as a heat transfer surface as the thermal energy is passed across the tube wall.

7.1.4.1 Epoxy Coating

An epoxy coating can be applied to the inlet area of a tube to replace eroded or corroded material or to provide an inert barrier between the tube material and fluid. The coating is done in several steps to build thickness. It is also feasible to coat an entire tube ID by spraying one or two thin coats of epoxy, but expect no more than a 10-year coating life, and the coated tube will exhibit a decrease in thermal performance.

The types of tube damage suitable for full-length coating are more limited than those for inlet-only damage. A soft tube material such as brass or copper that has undergone erosion damage is likely to have a rough nonuniform ID surface, which is far from an ideal substrate for application of very thin film epoxy ID coating. Tubing such as 304 stainless steel that has suffered MIC or manganese pitting still has a very smooth, uniform ID with only occasional small pit openings that are readily filled and bridged by the epoxy. Note that an epoxy-coated tube will transfer more heat than a plugged tube.

7.1.4.2 Sleeves

To repair a tube or to avoid failures, sleeves can be installed in the tube ID of a heat exchanger. Sleeves can be made of brass, carbon steel, stainless steel, or other metals and are slipped inside a tube and rolled to create a seal with the tube. The common industry term for a sleeve is a *ferrule*. The ferrule diameter must be sized correctly. When in place, the lip of the sleeve covers the damaged tube-to-tubesheet inlet area. Note that the tube diameter is slightly reduced by the sleeve (a nominal 20 BWG tube reduces to 14 BWG, for instance). Some erosion potential exists inside the tube, downstream of the insert, due to disruption in the flow.

Sleeves may be expanded to seal leaks in the middle of a tube. In such a case, the pressure drop and thermal resistance changes must be considered. If the tube is partially or completely severed, a more complex analysis is required because the sleeve becomes a pressure boundary.

Sleeves can be supplied along the full length of a straight tube; a mechanical expansion of the sleeve over the entire length will minimize wall thermal impedance. A full-length sleeve may be an option in some instances when retubing is not feasible. The original tube wall still supplies the strength to the pressure boundary, while the sleeve material repairs the leaks. Figure 7-4 is an example of a tube bundle that has had tubes sleeved.



Figure 7-4
Example of a set of heat exchanger tubes with installed sleeves

7.1.4.3 Tube Stabilization

In situations where a heat exchanger tube has failed and damaged adjacent tubes or where a heat exchanger tube has suffered a fracture and concerns exist that the flow-induced oscillations of the severed ends may damage adjacent tubes, the affected tube(s) should be stabilized prior to plugging. Tube stabilizers are generally available in two configurations: a rod type and a cable type. The type should be chosen to suit the situation. Regardless of the type selected, the stabilizer should be anchored at one end to prevent movement of the stabilizer within the tube during thermal cycling of the heat exchanger. Anchoring the stabilizer at both ends is not advised due to the stresses created in the tube when the stabilizer is thermally cycled. Figure 7-5 shows an example of a tube stabilizer installed in a tube.

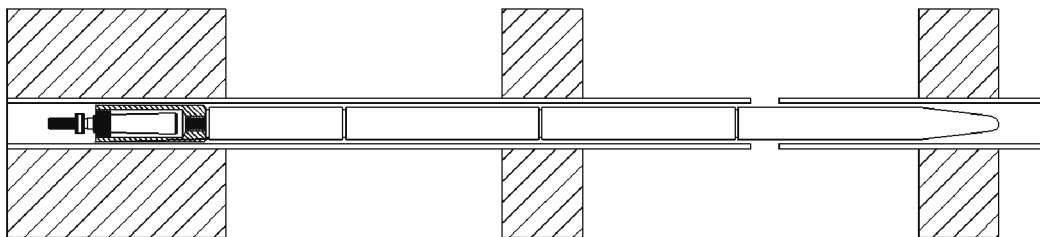


Figure 7-5
Tube stabilizer installed in a tube

7.1.4.4 Tube Replacement

This section contains some general comments about retubing. However, recommendations by the manufacturer and retubing contractors should be considered when replacing tubes.

7.1.4.4.1 General Heat Exchanger Retubing Details

Below is an example of a brief retubing sequence for a shell-and-tube heat exchanger:

11. Sever one end of the tube behind the tubesheet with an ID tube cutter.
12. Release the tube joint on the other end by a hydraulic collet puller, or drill out the tube joint.
13. Spear the tube end, and pull the tube through the heat exchanger baffle supports.

Note: Tubes can be pushed out, but tube buckling due to high drag force in baffle holes can result in more difficult corrective measures needed to remove the tube.

14. Optional—Insert the pulled tube in a tube flattener machine, through a tube chopper, and into barrels or other receptacles to efficiently handle tube scrap.
15. Pull all tube stubs at the other tubesheet.
16. Mechanically brush the tubesheet holes thoroughly to remove corrosion and all remnants of the tubes in the tubesheet holes and grooves.
17. Ream all baffle support tube holes to remove any accumulated shell-side deposits and corrosion that could otherwise lead to high drag force and potential tube damage during tube reinstallation.
18. Sample measure tubesheet hole IDs for determining the range of hole sizes for use in determining roller expansion measurements and control.
19. Clean the OD of the new tubes, and push the tubes through the bundle supports, monitoring the alignment from tubesheet to tubesheet.
20. Roller or hydraulically expand the tubes in the tubesheets.

Note: In the case of relatively thin tubesheets, set the expander tool depth to limit the depth of the expansion seal to within 1/8 inch (3.2 mm) of the tubesheet thickness. Expanding the portion of the tube beyond the tubesheet backface adds a stress riser in the tube that could be a source of tensile or bending failure in later plant operation.

21. Pressure test the shell to validate the tubesheet pressure boundary.

7.1.4.4.2 Planning for Retubing

In fixed tubesheet applications, each new tube should measure about 1/8 inch (3.2 mm) longer than the length specified on the vendor drawing of the inlet channel tubesheet face to the outlet tubesheet face. The extra length accounts for field variances from heat exchanger fabrication. Any excess tube length can be removed by a tube trimming tool after tube roller expansion.

In preparing for a heat exchanger retubing where the tube bundle is not removable as in the case of fixed tubesheets, check the tube bundle for straightness. Tube bundles have been found with a distinguishable twist, which misaligns baffle tube lanes, resulting in higher drag loads in the baffle holes when extracting and reinstalling tubes.

Thermal expansion over relatively long tubes tends to buckle the bundle near mid-length of the vessel. Repeated occurrences of this operating practice further magnify the buckling.

A limited degree of tube straightness can be verified by sighting through tubes from one end of the heat exchanger with a strong light in the waterbox of the opposite tubesheet. Note areas across the tube bundle where light cannot be sighted. Large areas of dark tubes may indicate a twist in bundle alignment. The full degree of buckling is difficult to assess unless windows are cut in the shell for direct visual inspection. Discussion with the retubing contractor on addressing a misalignment issue may be helpful in the planning phase before retubing execution.

7.1.4.4.3 Other Specific Retubing Details

One sample method for retubing fixed tubesheet heat exchangers involves pulling and replacing tubes in a four-phase arrangement. Each phase entails removing one-fourth of the heat exchanger tubes, cleaning the tube holes, and then replacing the tubes. The tubes are removed and replaced in a pattern of every other tube in every other row that allows a complete surrounding of the removed tubes with old tubes, limiting the chance of tube lane crossing when inserting the new tubes.

With fixed tubesheet designs where the bundle has a definite twist, an alternative retubing process is used that involves multiple shell access hole cuts along the axis of the bundle between the tie rods. The bundle is completely detubed, starting in the area in front of the access shell holes and working inward. With physical access to the shell, straightening of the tube bundle or other alignment repairs can be completed before reinstalling the tubes. Shell access provides an excellent opportunity to fully inspect the bundle cage (tie rods, baffles, spacers, and so on) and to thoroughly clean the shell of debris from tube cutting and pulling. Tube insertion alignment is maintained by physical reach through the shell holes. New tubes are filled in, starting at the opposite side of the shell window holes.

For severe degradation problems that are not easily corrected, heat exchanger materials are changed. Retubing with a metal more resistant to degradation is good practice. Stress corrosion cracking is minimized by Inconel (a nickel-based alloy) and AL-6XN (stainless steel). Titanium is a highly corrosion-resistant material for heat exchangers and also has higher strength properties than other materials that may be used.

If the existing tubesheet is to be reused with new tube material, care must be taken in tube material selection to ensure galvanic compatibility between the metals. New tube materials, especially titanium, can result in the need for additional vibration support within the tube bundle. A full evaluation of any tube material change should be made. General guidelines for selection of common heat exchanger materials are given in Table 7-2.

Table 7-2
Guidelines for selecting heat exchanger materials

Type of failure	Component materials				
	Brass	Copper nickel (CuNi)	Types 304/316 stainless	AL6XN high-alloy stainless	Titanium
Erosion/corrosion	Note	Good	Better	Best	Best
Erosion	Note	Good	Better	Best	Best
Stress corrosion cracking	Susceptible	Susceptible	Susceptible	Better	Resistant
Pitting	Susceptible	Susceptible	Good	Best	Best

Note: Although generally acceptable, brass may be considered marginal for resistance to these failure mechanisms in raw water or once-through cooling water systems unless the heat exchanger is in standby service.

7.1.5 Shell Repair

With fixed tubesheet heat exchangers, shell replacement is not practical although repairs can be performed. In floating head units, the shell is available for repair or even replacement because the entire bundle is removable. Typical shell repairs are weld buildups of wasted areas, shell repairs, and expansion joints.

7.1.6 Nozzle Repair

Under most conditions, it is more cost effective to replace a wasted or distorted nozzle than to use welding to build up the component. The replacement nozzle must conform to the design pressure and temperature ratings of the existing nozzle; otherwise, a reinforcement pad is added to the outside of the shell. When inlet tube bundle erosion damage is encountered, a replacement nozzle with an integral impingement plate can be substituted. The old nozzle is cut out and the new one welded in. Engineering and calculations need to be completed for any changes made to the original nozzle design.

7.1.7 Heads, Channels, and Gasket Joints

When removing the heads, mark each of them in such a way that the head can be reinstalled in the exact position as before. A marking pencil is a good way to do this. Also, use proper lifting components (lugs) and techniques to avoid damage to heat exchanger components and surrounding equipment. The manufacturer can be contacted for lifting instructions if there is any concern.

Follow the vendor instructions while unbolting a head and other heat exchanger gasket joints. Failure to do so can permanently distort the joint when gasket forces are released and concentrated. A common mistake is to completely loosen and remove each bolt in one pass.

To reinstall the head, take care not to move the gasket when aligning the head. Follow the manufacturer's procedures for torque, torque pattern, and number of torque passes when seating the gasket joint. Samples of bolting patterns for different numbers of bolts and joint patterns are available in Figure 7-6.

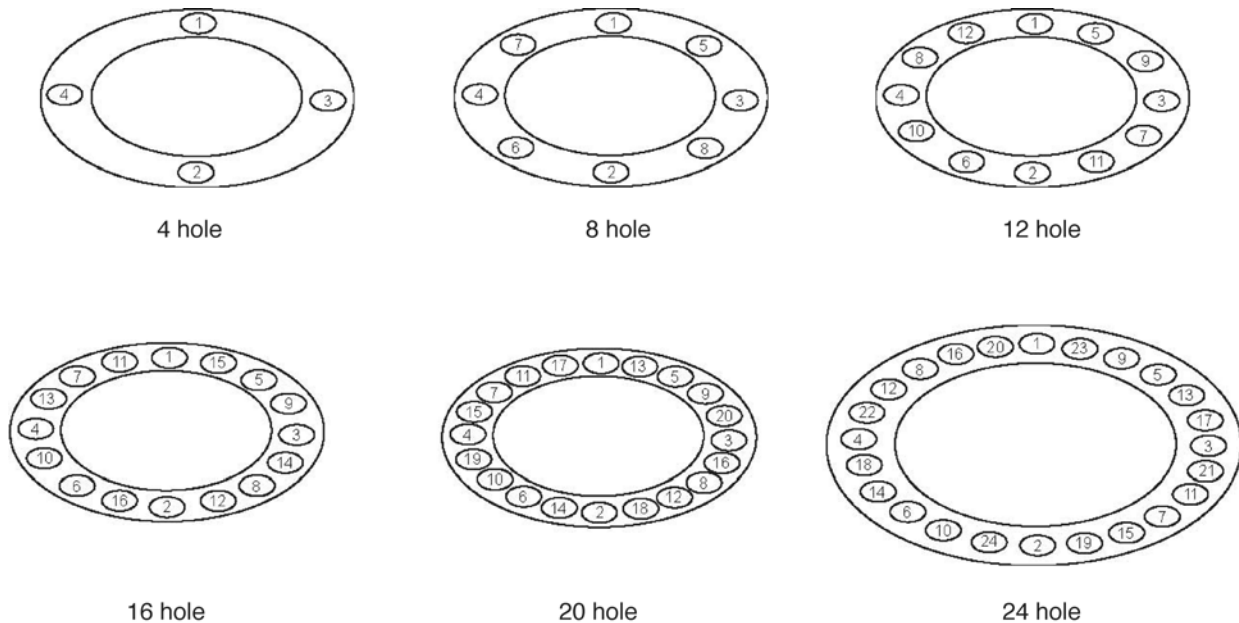


Figure 7-6
Sample bolting patterns for a gasket joint

The head or flange should seat the gasket, not crush it. A large amount of gasket protruding from the edge of a flange joint indicates over-tightening and gasket extrusion. Lubricant may need to be applied to the bolts prior to tightening.

For complete certainty of bolt preloading, the bolt elongation is determined. Measuring the required preload by torque can be distorted by deposits/corrosion within fastener threads, thread damage, and lack of proper thread lubricant. A bolting procedure might call for a recheck of torque at a later date to compensate for gasket relaxation or expansion. Distorted bolts, covers, and flanges are a sign of improper fastening.

Gasket mating surfaces of waterboxes and end covers may be a source of potential joint leakage due to corrosion undermining of the gasket seats. This condition is more applicable to service water heat exchangers where waterboxes and end covers are bare carbon steel.

Weld repair and subsequent machining to true the gasket seat surfaces is one solution. However, if the repair is not protectively coated, corrosion attack will continue. Applying a protective coating across the gasket seats presents an issue in that typical epoxy coatings will not withstand the bearing stress of bolted flanges if the coating is applied at the full recommended specification thickness. Typically, the coatings manufacturer will limit the coating thickness to 4–5 mils (0.10–0.13 mm) in gasket seat areas to minimize coating failure. The relatively thin coating film will become an area for inspection due to later potential damage from routine access to the waterbox for inspection purposes. Figure 7-7 illustrates how this thin coat can become damaged after routine and repeated access.



Figure 7-7
Coating failure due to routine and repeated access

A solution to this problem in lieu of a welding repair is an application of coatings termed “metal replacement epoxy,” which are materials specifically designed with physical properties that exceed the bearing stress requirements of typical heat exchanger bolted joints. These materials have been used to rebuild damaged gasket seating surfaces and provide corrosion protection. The metal replacement epoxies can be formed to a plane profile or machined, depending on the epoxy’s material properties. Figures 7-8 and 7-9 illustrate a flange before repair with a metal replacement epoxy, and the flange after the epoxy was applied to rebuild the flange gasket seating surface.



Figure 7-8
Flange condition before repair with a metal replacement epoxy

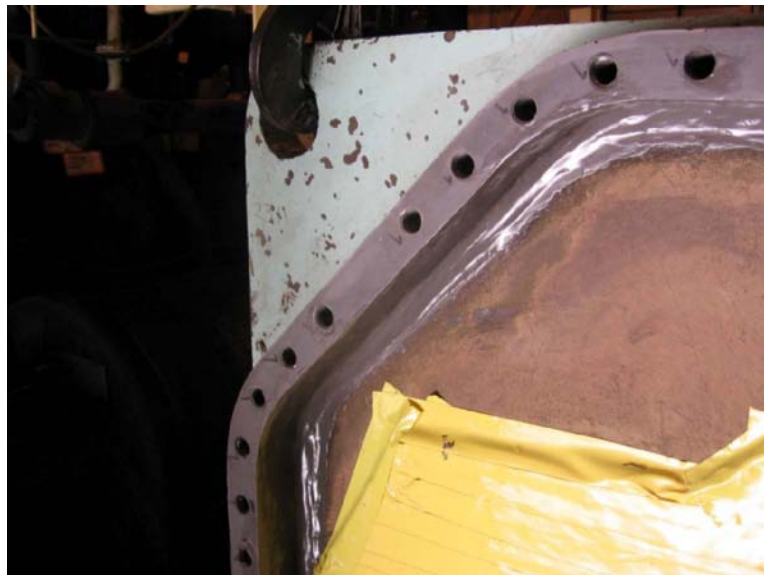


Figure 7-9
Flange condition after repair with a metal replacement epoxy

7.1.8 Gasket Replacement

Gasket construction is based on a design that considers pressure, temperature, and thickness of mating surfaces. Consult the manufacturer to obtain an exact replacement that matches the material, thickness, and strength. Gaskets should always be replaced after unbolting a joint unless there are special circumstances for the joint.

Clean the mating gasket surfaces before replacement. A scraper or wire brush with a cleaning agent aids in removing gasket remnants from flange faces. Always take the time to examine the old gasket for deterioration. If there is extensive uneven crushing of the gasket, an alternative gasket/flange design may need to be considered. Check the new gasket for defects.

If the gasket is to be reused (generally not recommended), clean it with water using a soft brush, sponge, or rag. In addition, verify the flatness of the gasket seating surfaces. If the flatness is not within 1/32 inch (0.8 mm), sealing problems might be encountered, depending on the specific gasket. If the surfaces are significantly distorted, repair or replace the component.

Similar procedures apply when dealing with packing seals. TEMA P and W designs contain packing that must be properly handled and reinstalled according to the manufacturers' instructions.

7.2 Plate Heat Exchangers

The following sections provide guidance for performing corrective maintenance activities for plate heat exchangers. The guidance in Section 7.1 regarding ASME stamps is also applicable to this type of heat exchanger and should be considered.

7.2.1 Introduction to Plate Heat Exchanger Repair

Coat the upper carrying bar and lower guiding bar with lubricant to enable the plates to slide smoothly. Lubricate the tightening nuts and tightening bolts periodically so that they can be loosened easily at disassembly. As noted in Section 4.3, check the tightening nuts regularly to ensure that they remain tightened to the manufacturer's recommended torque(s). Temperature and pressure changes in the system may cause the plate pack length to shrink. They should always be retightened to specified dimensions.

7.2.2 Dismantling and Reassembly

Before opening the heat exchanger, be sure that both sides are gradually lowered to atmospheric pressure. Allow the temperature to fall to ambient to avoid loosening the gaskets. Loosen the tightening bolts, and pull the moving frame back toward the column, exposing the plate pack. Remove the plates one by one, if required. Number the plates before taking them out (if this has not already been done). To remove a plate from the frame, lift it and tilt it on an angle until it can be removed. If desired, clean the plates or inspect them one by one while they are separated in the frame and do not need to be removed.

Before reassembly, wipe all plates and gaskets free of dirt. Solid particles that adhere to the gaskets can cause damage and can also result in leakage when the unit is put back in operation. After each plate is inspected and cleaned, close and tighten the unit.



Key Human Performance Point

CAUTION! Plates may have sharp edges. Wear gloves during the disassembly and assembly of plate heat exchangers.

7.2.2.1 Tightening Plate Packs

The following basic procedure should be considered when tightening the plate pack:

1. Push the moveable follower until contact is made with the rear of the plate pack.
2. Install the tightening bolts and nuts.
3. Starting with the center bolts, tighten them using hand tools. It is important to keep the follower parallel to the fixed head during the entire tightening operation.

Larger units will require power tools (such as pneumatic wrenches) to tighten the bolts further.

4. When the required tightening measurement has been reached at the center of the pack, continue tightening the bolts out from the center. Continue until the frame is parallel and tightened to no more than the recommended tightening measurement.



Key Human Performance Point

WARNING! The recommended tightening measurement is a minimum value that should not be exceeded. Permanent plate deformation can occur if the pack is over-tightened. A unit might be shipped from the factory with a plate-pack measurement greater than the value shown on the manufacturer's drawing. This is due to manufacturing tolerances and is normal.

7.2.3 Key Issues Related to Plate Heat Exchangers

Foreign materials – Care should be taken before connecting any piping to the plate heat exchanger to ensure that all foreign objects have been flushed out of the system. Ensure that fluids are clean of debris because debris will plug a plate heat exchanger.

Piping connections – Some plate heat exchangers may have connections on the pressure plate. In such cases, it is important to check against the drawings or the nameplate to ensure that the plate pack has been tightened to the right measurement before the piping is connected. When piping is connected to the pressure plate, a short 90° spool piece should be installed between the plate heat exchanger and the piping. These should be directed upward or to the side, as shown in Figure 7-10.

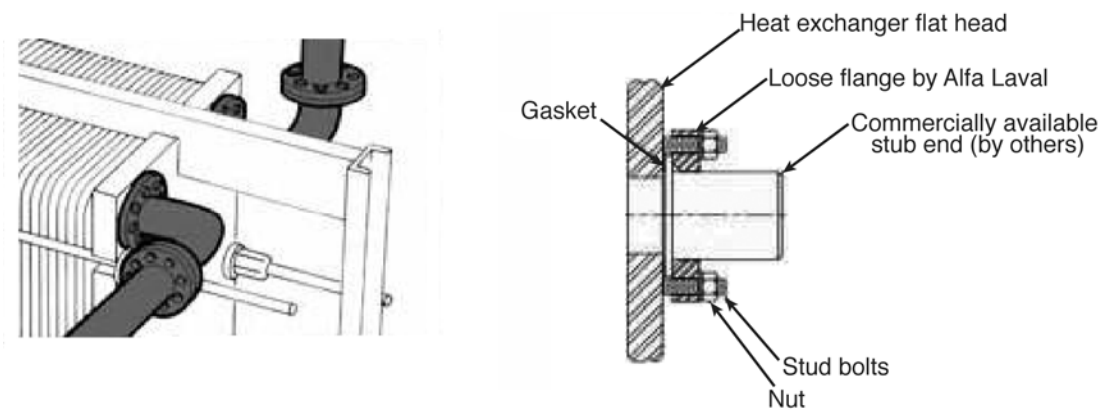


Figure 7-10
Proper installation of spool pieces

7.2.4 Special Tools Required and Accessories

The special tools listed below should have been supplied during the installation of the plate heat exchanger. The appropriate tools should be available, have been inspected, be used properly, be calibrated, and be used by qualified/certified personnel. These following tools and consumables should be made available by the maintenance department during the repair of the plate heat exchanger:

- Hydraulic equipment for disassembly
- Large wrenches
- Drip trays for collection of drained fluids
- Provisions for a spray screens
- Availability of air and water for cleaning/maintenance activities
- High-pressure sprayer (4000 psi [276 bar]), usually for on-site cleaning

7.2.5 Replacing Gaskets

The gaskets on the plate heat exchanger can be attached by mechanical means or by glue. Mechanical methods of attachment allow easy on-site replacement of the gasket by the maintenance crew. However, debris can be caught behind the gasket and cause leaks upon reassembly. Mechanical methods of gasket attachment are best used when both fluids are clean and when the unit will not be opened for many years. For most power plant applications, it should not be necessary to replace gaskets very often, and certainly not each time the unit is cleaned or opened for inspection. Gasket replacement can be based on service life, compression set, loss of physical properties of the gasket, and allowable leakage, but it should be based primarily on the manufacturer's recommendations.

Service water plate heat exchangers will typically need cleaning, and gaskets normally last a long time; therefore, a glued system that does not break down should be used. If the glue breaks down, the gaskets will fall off the plates at random spots, and debris may get underneath. Field repairs of glued gaskets are not recommended. The plates should be replaced, and the failed gasket plate should be returned to the manufacturer for regasketing.

Regasketing can be performed on either the glue-free design or the glued-gasket configuration. The glue-free design uses a clip-on type of gasket, one example of which is illustrated in its unattached configuration in Figure 7-11.

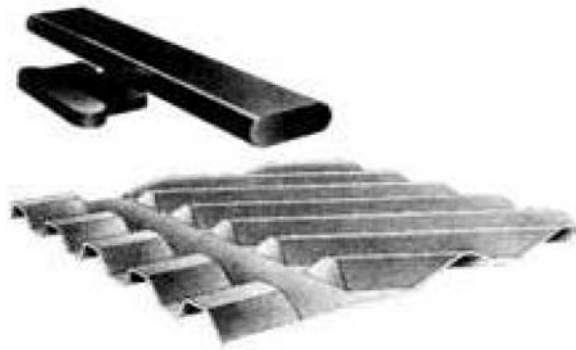


Figure 7-11
Clip-on gasket in a glue-free system

The clip-on gasket is attached to the plate by two gasket prongs, which slip under the edge of the plate to hold the gasket securely in alignment in the gasket groove. The prongs are shown on the gasket positioned above the plate in Figure 7-11. The prongs on the gasket are situated at regular intervals around the periphery of the plate. When the plate heat exchanger is then assembled and tightened, the gasket provides a tight seal around the plate, as shown in Figure 7-12.



Figure 7-12
Properly installed clip-on gasket

Regasketing of mechanically attached or glue-less gaskets can be performed in the field using the recommended preparatory and installation guidance provided by each plate heat exchanger manufacturer.

7.2.6 Replacing Plates

Replacement plates must be clean, dry, and free of oil or grease. Oil deposits on the gaskets or the gasket seating area make it likely that the plates will slip out of place when the unit is tightened. Gasket contamination from dirt or grit can cause leakage. Additionally, the following guidance should be considered:

- Ensure that all seating areas are flat, clean, and undamaged.
- Always use new gaskets.

Fit the plates according to the manufacturer's plate sequence sheet. All gaskets must face the fixed/head frame plate. Then, alternate between left-handed and right-handed plates. If the plate edges form a regular honeycomb pattern, the left-hand/right-hand sequence is correct, as noted on the left side of Figure 7-13.

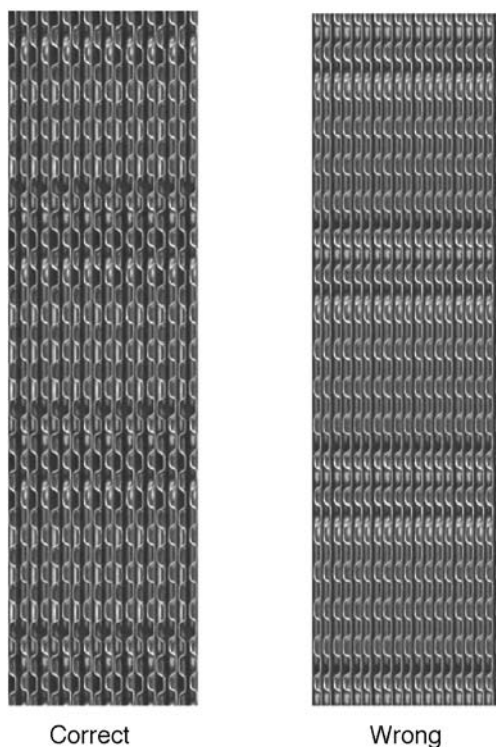


Figure 7-13
Proper sequencing of replacement plates

7.3 Air-to-Water Heat Exchanger

One advantage of an air-to-water heat exchanger is that the air side is open, so a leak exposed by a pressure test on the tube side (either hydrostatic or air/soap bubble) can be identified and possibly repaired. The guidance in Section 7.1 regarding ASME stamps is applicable to these types of heat exchangers also and should be considered.

**Key O&M Cost Point**

For air-to-water heat exchangers, repair may not be economically or technically feasible, and replacement of the entire component may be the best option based on size, design, and price.

For air-to-water heat exchangers, repair may not be economically or technically feasible, and replacement of the entire component may be the best option based on the following reasons:

- These are typically smaller in size.
- They are typically less expensive.
- Serpentine designs cannot be readily repaired.

In the cases where repair is economically feasible, however, the guidance provided in Section 7.1 should be considered where applicable.

The only repair unique to fin-tube heat exchangers would be the repair of damaged fins. Fin combs are available, but typically are suitable only for thin or soft fins. “Flat-nosed” or “duckbill” pliers can be used to straighten stronger fins.

7.4 Determining Replacement Items

Consider establishing with potential suppliers the scope of spare and replacement parts necessary to execute anticipated maintenance, as well as the frequency with which those items should be made available.

7.4.1 Shell-and-Tube Heat Exchangers

Minor spare parts, such as gaskets, nuts, bolts, and tube plugs, to support maintenance are all that are typically needed to repair shell-and-tube heat exchangers. Some plants have found it beneficial to have spare tubes available as well.

7.4.2 Plate Heat Exchangers

The actual number of spare parts should be based on each owner's experience, the perceived criticality of the item, and the system application(s). On a two-year operational cycle, typical spare/replacement items for a plate heat exchanger include the following items:

- **Spare heat transfer plate pack** – If the plate heat exchanger is to be reconditioned frequently, then a spare plate pack (which typically includes the glue-in gaskets) is recommended. The spare plate pack can replace the dirty plates that will be removed from the plate heat exchanger and sent for reconditioning. If there are a number of units of the same model, then the spare plate pack should have the maximum number of plates.
- **Spare heat transfer plates/end plates** – It is normally recommended to store 10% of the heat transfer plates in a plate pack as spare plates and a couple of end plates. As noted, the heat transfer plate will typically include the glue-in gasket.
- **Mechanically attached gaskets/liners** – If the gaskets will be used within five years from date of manufacture, then it is recommended to have 10% of the complete gasket set readily available. If not, then 5% of the total number of flow gaskets is typically sufficient. It is also prudent to maintain one end gasket as a critical spare.
- **Bolts/nuts/washers** – If the unit is opened frequently, it is recommended to have a few spare bolts/nuts/washers on hand.

Take care to ensure that the manufacturer's recommendations for shelf life are considered for replacement gaskets. *Packaging, Shipping, Storage and Handling Guidelines for Nuclear Power Plants*, TR-107101, provides additional guidance and should be considered for long-term storage of the items listed above.

7.4.3 Air-to-Water Heat Exchangers

Because it is often most economical to replace the entire component (for smaller-sized components), it may be beneficial to have a spare heat exchanger available in lieu of stocking spare parts. The heat exchangers can be prepared for long-term storage by pressurizing them with dry air or nitrogen and proper crating to preserve and protect them. When repairs are warranted, minor spare parts, such as gaskets, nuts, bolts, and tube plugs, to support maintenance are all that is typically needed. In the case of air-cooled heat exchangers, fans and motors may need replacing.

8

TROUBLESHOOTING

8.1 Shell-and-Tube Heat Exchangers

Table 8-1 provides troubleshooting guidance for shell-and-tube heat exchangers. Troubleshooting actions are listed in order from least to most intrusive in order to minimize the scope of corrective action, minimize the chances of damaging the component, and reduce foreign material intrusion.

Table 8-1
Troubleshooting guidance for shell-and-tube heat exchangers

Symptom	Possible cause	Troubleshooting actions
Increase in differential pressure	Blockage within the tubes Blockage of flow within the shell Tube fouling Increase in flow	Evaluate the temperature trends. Evaluate differential pressure trends. Check the flow for abnormalities. Check the valve lineup. Verify an alternative pressure indication. Check the pump outlet flow and pressure. Open the heat exchanger and inspect.
Decrease in differential pressure	Internal bypass of flow Gasket failure Loose bolts on the partition plate Crack of weld Decrease in system flow	Evaluate the temperature trends. Evaluate differential pressure trends. Perform thermography of the channel outlet flow pattern. Check the flow for abnormalities. Check the valve lineup. Verify an alternative pressure indication. Check the pump outlet flow and pressure. Open the heat exchanger and inspect.

Table 8-1 (continued)
Troubleshooting guidance for shell-and-tube heat exchangers

Symptom	Possible cause	Troubleshooting actions
Change in water chemistry	Tube leak Tube-to-tubesheet leak Gasket failure Release of deposits	Check for changes in the chemistry of the process fluid. Check for changes in the chemistry of the shell-side fluid. Take additional fluid samples. Evaluate other potential leakage paths. Check for changes in the system operating conditions. Adjust the chemistry of the fluids. If a redundant heat exchanger is available, perform a leak check test on the suspect heat exchanger. Open the heat exchanger, and inspect for leaks or gasket failures.
Increase in outlet temperature of cooled fluid (differential temperature between inlet and outlet)	Internal bypass of flow Corresponding change in inlet temperature Reduction in cooling water flow Increase in the process fluid flow Tube-side fouling Shell-side fouling Shell-side air pocket Exceeded the limit for tube plugging Improper reassembly of multi-pass heat exchangers Tube blockage caused by foreign materials introduced during maintenance	Flush the heat exchanger tubes. Back-flush the heat exchanger shell and/or tubes. Check the cooling water temperature and flow. Evaluate the temperature trends. Evaluate differential pressure trends. Check the flow for abnormalities. Check the valve lineup. Verify an alternative temperature indication. Check the pump outlet flow and pressure. Verify the most current maintenance records. Open the heat exchanger, and inspect for fouling and blockage.

Table 8-1 (continued)
Troubleshooting guidance for shell-and-tube heat exchangers

Symptom	Possible cause	Troubleshooting actions
Increased make-up rate in a closed-loop system	Tube leakage Gasket leak Leak on the closed-loop side from other components External leak	Evaluate other potential leakage paths. Check the water chemistry. Check for changes in the system operating conditions. If a redundant heat exchanger is available, swap heat exchangers, and monitor the make-up rate. If a redundant heat exchanger is available, perform a leak check test on the suspect heat exchanger. Open the heat exchanger, and inspect for leaks.
External leakage of heat exchanger	Gasket failure Improper reassembly after maintenance Shell cracks Through-wall leak due to corrosion	Visually inspect to assess leak location and severity
Vibration	High shell-side flow	Check the shell-side flow rate.
Noise	Internal damage of partition plate Broken shell-side impingement plate or baffle Foreign material in the heat exchanger	Verify the location of the abnormal noise. Adjust the flow rates, and assess changes in the noise. Open the heat exchanger, and inspect for internal damage or foreign material.

8.2 Plate Heat Exchangers

Table 8-2 provides troubleshooting guidance for plate heat exchangers. Troubleshooting actions are listed in order from least to most intrusive in order to minimize the scope of corrective action, minimize the chances of damaging the component, and reduce foreign material intrusion.

Table 8-2
Troubleshooting guidance for plate heat exchangers

Symptom	Possible cause	Troubleshooting actions
Increase in differential pressure	Blockage within the plates on either the process or service side Plate fouling on either the process or service side Increase in flow	Evaluate the temperature trends. Evaluate differential pressure trends. Check the flow for abnormalities. Check the valve lineup. Verify an alternative pressure indication. Check the pump outlet flow and pressure. Open the heat exchanger and inspect.
Decrease in differential pressure	Internal bypass of flow Gasket failure Crack or holes in plates Decrease in system flow	Evaluate the temperature trends. Evaluate differential pressure trends. Perform thermography of the channel outlet flow pattern. Check the flow for abnormalities. Check the valve lineup. Verify an alternative pressure indication. Check the pump outlet flow and pressure. Open the heat exchanger and inspect.
Change in water chemistry	Cracks or holes in one or more plates Gasket failure Change in the chemistry of the fluid Release of deposits	Check for changes in the chemistry of the process fluid. Check for changes in the chemistry of the service fluid. Take additional fluid samples. Evaluate other potential leakage paths. Check for changes in the system operating conditions. Adjust the chemistry of the fluids. If a redundant heat exchanger is available, perform a leak check test on the suspect heat exchanger. Open the heat exchanger, and inspect for leaks or gasket failures.

Table 8-2 (continued)
Troubleshooting guidance for plate heat exchangers

Symptom	Possible cause	Troubleshooting actions
Increase in outlet temperature of cooled fluid (differential temperature between inlet and outlet)	Internal bypass of flow Corresponding change in the inlet temperature Reduction in the cooling water flow Increase in the process fluid flow Plate fouling on either the process or service side. Plate blockage caused by foreign materials introduced during maintenance	Flush the heat exchanger tubes. Back-flush the heat exchanger process and/or service side. Check the cooling water temperature and flow. Evaluate the temperature trends. Evaluate the differential pressure trends. Check the flow for abnormalities. Check the valve lineup. Verify an alternative temperature indication. Check the pump outlet flow and pressure. Verify the most current maintenance records. Open the heat exchanger, and inspect for fouling and blockage.
Increased make-up rate in a closed-loop system	Plate leakage Gasket leak Leak on the closed-loop side from other components External leak	Evaluate other potential leakage paths. Check the water chemistry. Check for changes in the system operating conditions. If a redundant heat exchanger is available, swap heat exchangers, and monitor the make-up rate. If a redundant heat exchanger is available, perform a leak check test on the suspect heat exchanger. Open the heat exchanger, and inspect for leaks.
External leakage of heat exchanger	Gasket failure Improper reassembly after maintenance Plate cracks or holes	Visually inspect to assess the leak location and severity.
Vibration	High process or service flow	Check the flow rate.

8.3 Air-to-Water Heat Exchangers

Troubleshooting air-to-water heat exchangers is somewhat similar to shell-and-tube heat exchangers but the user must recognize that there is no cross contamination occurring in air-to-water heat exchangers. In the majority of cases, the “shell side” fluid is air, and the tube side is liquid. Table 8-3 provides troubleshooting guidance for air-to-water heat exchangers. Troubleshooting actions are listed in order of less intrusive to most intrusive so as to minimize the scope of corrective action and minimize the chances of damaging the component or to reduce foreign material intrusion.

Table 8-3
Troubleshooting guidance for air-to-water heat exchangers

Symptom	Possible cause	Troubleshooting actions
Increase in differential pressure	Blockage within the tubes Tube fouling Increase in flow	Evaluate the temperature trends. Evaluate differential pressure trends. Check the flow for abnormalities. Check the valve lineup. Verify an alternative pressure indication. Check the pump outlet flow and pressure. Open the heat exchanger and inspect (if an RCP type). Video probe the tubes (if an MR type).
Decrease in differential pressure	Internal bypass flow Gasket failure/leakage Tube leak	Inspect for signs of a leak. Evaluate the temperature trends. Evaluate differential pressure trends. Perform thermography of the channel outlet flow pattern. Check the flow for abnormalities. Check the valve lineup. Verify an alternative pressure indication. Check the pump outlet flow and pressure. Open the heat exchanger and inspect.

Table 8-3 (continued)
Troubleshooting guidance for air-to-water heat exchangers

Symptom	Possible cause	Troubleshooting actions
Increase in the outlet air temperature (if the air is being cooled)	Internal bypass of cooling flow Corresponding change in inlet temperature Reduction in cooling water flow Increase in the air flow Tube-side fouling Air-side fouling Exceeded limit for tube plugging Improper reassembly of multi-pass heat exchangers Tube blockage caused by foreign materials introduced during maintenance	Flush or back-flush the heat exchanger tubes. Check the cooling water temperature and flow. Check the air temperature and flow. Evaluate the temperature trends. Evaluate differential pressure trends. Check the flow for abnormalities. Check the valve lineup. Verify an alternative temperature indication. Check the pump outlet flow and pressure. Check the most current maintenance records. Open the heat exchanger, and inspect for fouling and blockage.
Increased make-up rate in a closed-loop system	Tube leakage Gasket leak Leaks from other components External leak	Evaluate other potential leakage paths. Check the water chemistry. Check for changes in the system operating conditions. If a redundant heat exchanger is available, swap heat exchangers, and monitor the make-up rate. If a redundant heat exchanger is available, perform a leak check test on the suspect heat exchanger. Open the heat exchanger, and inspect for leaks.
External leakage of the heat exchanger	Gasket failure Improper reassembly after maintenance Through-wall leak due to corrosion	Visually inspect to assess the leak location and severity. Perform a pressure test (pressurize the tube side). Perform a soap bubble test.

Table 8-3 (continued)
Troubleshooting guidance for air-to-water heat exchangers

Symptom	Possible cause	Troubleshooting actions
Noise	Internal damage of partition plate Foreign material in the heat exchanger	Verify the location of the abnormal noise. Adjust the flow rates, and assess changes in the noise. Open the heat exchanger, and inspect for internal damage or foreign material.

9

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A

KEY POINTS

A.1 Key O&M Cost Points



Key O&M Cost Point

Emphasizes information that will result in overall reduced costs and/or increase in revenue through additional or restored energy production.

Page Number	Key Point
6-2	Effective preventive maintenance strategies to mitigate the effects of erosion-corrosion in the heat exchanger can prolong the life of the heat exchanger and its components in the system.
6-5	A borescope is a valuable tool to use during visual inspections to access areas of the heat exchanger that cannot normally be seen by the inspector.
7-25	For air-to-water heat exchangers, repair may not be economically or technically feasible, and replacement of the entire component may be the best option based on size, design, and price.

A.2 Key Technical Points



Key Technical Point

Targets information that will lead to improved equipment reliability.

Page Number	Key Point
3-3	Sedimentation is a seasonal occurrence at many plants if cooling water flow is throttled or bypassed when water temperatures are low, which results in low tube velocities and the subsequent settling of suspended materials.
3-6	The flow passages in plate heat exchangers are normally smaller than the tube ID of shell-and-tube heat exchangers and, thus, are more susceptible to fouling without adequate filtration present.
4-3	Crevice corrosion is one of the most common degradation mechanisms for stainless steels, particularly in open loop systems.

Page Number	Key Point
4-3	Because seawater contains substantial chlorides (approximately 19,000 ppm), seawater-cooled plants are more prone to experience pitting in austenitic stainless steel tube materials than freshwater-cooled plants.
4-5	Exfoliation is a special form of intergranular corrosion attack that is characterized by elongated grain attack on a plane parallel to the rolled or extruded surface. This results in a characteristic delamination or peeling of the metal strata. Susceptible alloys other than aluminum and magnesium are the 70/30 and the 80/20 copper-nickel alloys. The 90/10 copper-nickel alloy is immune.
4-5	Stress corrosion failures of Monel 400 tubing have occurred in a few applications, primarily at U-bend locations. The susceptibility to stress corrosion can be eliminated by properly heat treating U-bends to sufficiently relieve the residual stress produced by tube bending.
4-8	Tube inlet erosion is particularly intense within the first several inches (25–100 mm) of the tube. A borescope inspection of the first 6 inches (15 cm) of a random number of inlet end tubes should be made if tube inlet erosion is suspected or likely. This allows for early detection of erosion symptoms such as excessive metal polishing or wear. If erosion is detected, it is recommended to inspect farther down the tube (10 inches [250 mm]) to the end of the damage.
4-9	Every time a tube is plugged, the velocity through the remaining tubes is likely to increase in both the plugged heat exchanger and other heat exchangers in the system. As more tubes need to be plugged, check to ensure that velocities do not go above design conditions for the tube material.
6-9	The most commonly used NDE technique for determining the condition of installed tubes is eddy current testing (ECT). It is fast, repeatable, good for baseline screening, and accurate in sizing known defects. However, ECT is operator dependent. Quantification of certain types of defects is sometimes difficult, and other NDE methods may be needed in conjunction with ECT.
6-10	After the final NDE report has been received, you are strongly urged to record the latest ECT information in a database. This would help you monitor heat exchanger conditions and estimate remaining operating life. Depending on economic and operational factors, it might be necessary to re-evaluate the established plugging criteria because they ultimately affect the remaining heat exchanger operating life.
6-17	Whenever acids are used, they must be properly inhibited to eliminate or minimize the removal of base metal.

A.3 Key Human Performance Points



Key Human Performance Point

Denotes information that requires personnel action or consideration in order to prevent personal injury, equipment damage, and/or improve the efficiency and effectiveness of the task.

Page Number	Key Point
6-10	A basic objective is to optimize the tube sampling plan by using a combination of targeted and random sampling to minimize the risk of potential tube failures. A general approach is to test the peripheral tubes, the tubes surrounding plugged tubes, and then a random selection of tubes.
7-21	CAUTION! Plates may have sharp edges. Wear gloves during the disassembly and assembly of plate heat exchangers.
7-21	WARNING! The recommended tightening measurement is a minimum value that should not be exceeded. Permanent plate deformation can occur if the pack is over-tightened. A unit might be shipped from the factory with a plate-pack measurement greater than the value shown on the manufacturer's drawing. This is due to manufacturing tolerances and is normal.

B

VISUAL INSPECTION GUIDANCE AND DATA SHEET EXAMPLE

This appendix provides visual inspection guidance and an example of an inspection data sheet that can be used when performing a visual inspection on a shell-and-tube heat exchanger. The example is provided for illustrative purposes only and should be modified to meet your needs. Implementation of this guidance, however, may ensure that a common approach is taken to the inspection of heat exchangers. The guidance contained in this appendix is based on EPRI Report 1003320, *Supplemental Guidance for Testing and Monitoring Service Water Heat Exchangers*.

B.1 Introduction

A thorough visual inspection, which can include the complete range of NDE inspection techniques, is the most powerful tool in a heat exchanger maintenance program. For GL 89-13 heat exchangers that are not performance tested, the results of visual inspections form the basis of proof that provides assurance that the heat exchanger will be capable of performing its safety function during the interval between inspections.

The scope of a visual inspection is not limited to the physical act of observing the condition of a component and its parts. The inspection is based upon the specific knowledge of the inspector concerning key aspects of the heat exchanger being inspected. This includes a thorough familiarity with the last inspection results and specific component material details, such as familiarity with the tube map and tubes plugged and the presence of coatings or sacrificial anodes. Additionally, from the system manager, the inspector should determine any performance changes, including abnormal service water flow or temperature trends (if available), known interruptions in chemical treatments, and changes to the design thermal margin. In order to formulate acceptance criteria, the inspector must know what to expect before the inspection.

Color photographs (preferably digital), especially of as-found conditions, and the results of optional surface contaminant sampling taken in conjunction with the draining and opening of the heat exchanger provide invaluable information toward completion of the inspection. The complete range of NDE inspection techniques including eddy current testing (ET), ultrasonic testing (UT) (for determining head or channel material thickness in areas of significant corrosion or under tubercles), and the use of a video-capable borescope should be routinely used for these inspections.

The use of a borescope is important to determine down-tube conditions, such as the presence of microfouling, including sedimentation deposits or scale, especially on those heat exchangers with known low design thermal margins. Interpreting what borescopy reveals requires practice because the probes substantially magnify the surface. Interpreting results is problematic without such practice.

B.2 Limitations

As with the temperature difference and pressure loss methods, the visual inspection method is not considered a test method. Therefore, the visual inspection method alone cannot be used to quantitatively determine the thermal performance of a heat exchanger. The visual inspection method can be used to encourage maintenance (mechanical or chemical cleaning) based on routine inspections for fouling or accumulation of foreign material.

Visual inspections, as a key part of a heat exchanger program, are intended to verify and validate, in a way that cannot be duplicated by a thermal performance test, that the condition of the heat exchanger has not degraded between inspections to the point that it cannot perform its intended safety function.

This verification and validation, by its very nature, is a qualitative and subjective application of engineering judgment on the part of the inspector. As a result, the quality of the inspection relies heavily on the technical skill and knowledge of the inspector. In addition to the basic education and training expected, an inspector should have specific knowledge of the following:

- Basic component construction and flow paths of the heat exchanger
- Basic heat transfer concepts, as applied to heat exchangers, that are used to determine or can affect overall thermal capability
- The programmatic steps that are taken at the station to mitigate or control the possible degradation mechanisms that can affect the material condition or thermal capability of the heat exchanger
- Various corrosion mechanisms (that is, general, localized, crevice, galvanic, stress corrosion cracking [SCC], and microbiologically influenced corrosion [MIC]) and the identification of type, cause, active versus inactive, extent, and possible impact on heat transfer of any corrosion present
- The eddy current testing (ET) process, including equipment used, equipment setup and adjustments, fault indications, capabilities and limitations, and visual validation possibilities

B.3 Programmatic Basis

The key features of the programmatic steps taken to support the heat exchanger maintenance program and the validity of visual inspections are the controls put in place to mitigate the two major fouling mechanisms that can degrade service water system material condition and thermal capability:

- **Macrofouling:** Minimal macrofouling in heat exchangers is desired. This is achievable through the following:
 - Rigorous chemical treatment of service water and structures to prevent the very existence of macro-organisms
 - Frequent inspection and cleaning or dredging of key intake structures and bays
 - Inspection and maintenance of in-line strainers, if available
 - Maintenance of continuous design flow through all service water components, or, if designed for intermittent service, frequent and routine operation or flushing at design flow or greater
- **Microfouling:** An equally rigorous standard, although not as easily measured, is the maintenance of down-tube microfouling (by any combination of microorganisms, scale, or other deposition) at below design values. This relies on the following:
 - The rigorous application of chemical treatments, including biocide application, scale inhibitors, and silt dispersant, where needed
 - Heat exchangers operating at optimum flow velocities that minimize microfilm growth and the sedimentation of suspended solids
 - Normal (non-accident) operating temperatures that are not conducive to scale formation and do not encourage microbiological growth
 - Copper-bearing tube materials that are nominally toxic to the microorganism component of microfouling

Additionally, whenever available, certain quantifiable tools can be used to substantiate the judgment of the inspector and provide positive feedback for changes in the heat exchanger maintenance program.

Design margins, as quantified in terms of tube plugging limits or mass flow rate reduction limits can be used to assist in the formulation of the results of the inspection and provide the basis for an appreciation or quantification of fouling or the fouling rate. Monitoring and trending of key indicators, such as differential pressures and component temperatures, if available, also provide and support the effort of monitoring for unexpected fouling.

Results of inspections provide an indication if programmatic activities (such as heat exchanger and intake bay inspection and cleaning frequency and chemical treatments) need changes or are providing adequate controls to ensure heat exchanger performance.

B.4 Prerequisites and Preparations for Inspection – Establishing Visual Inspection Acceptance Criteria

The knowledge and skills of the inspectors are equally important to the robustness of the programmatic actions that have been established to ensure satisfactory heat exchanger conditions. As a result, the preparatory phase of the inspection provides the opportunity for inspectors to familiarize themselves with the following key heat exchanger attributes:

- **Last inspection results.** Performance changes should also be determined from the system manager, including abnormal service water flow and temperature trends (if available), known interruptions in chemical treatments, and changes to the design thermal margin.
- **Tube plugging limit.** (**Note:** This is normally based on the design or basis heat load and heat exchanger data sheet information and is formally documented; however, this information might not be available for some small or component- or skid-mounted coolers.)
- **Specific component material details,** such as the number of tubes plugged and their location, and the presence of coatings or overlays and sacrificial anodes.

Based on the previous information, a pre-conceived, pre-planned, pre-engineered set of expectations and visual inspection acceptance criteria (VIAC), based, in part, upon the judgment of the inspector, should be recorded prior to the inspection. The information that follows is intended to provide the inspector with examples of concise quantitative and qualitative terms for use in describing VIAC and in documenting inspection acceptability or failure.

B.4.1 Macrofouling

This fouling is most often represented by direct tube sheet fouling or matting, but it also could be caused by significant sedimentation in heads that cover portions of the tube sheet.

This type of fouling is the easiest to establish quantitatively based acceptance criteria for, based upon the design thermal margin. This plugging limit should be established on a formal engineering calculation or evaluation. (**Note:** 100% flow blockage is required to remove a tube from service. In terms of heat transfer, very little flow in a tube keeps that tube [that is, its surface area] in play. The estimation of partial- versus full-tube fouling is based on the qualitative judgment of the inspector in the field).

The following acceptance criteria statement would be typical.

A total of ___ tubes per pass can be fully (100%) plugged/blocked in the ___-pass heat exchanger, either with temporary/permanent plugs or by foulants.

For a cubicle heat exchanger: A total of ___ circuits can have plugged/ blocked tubes either with temporary/permanent plugs or by foulants.

In either case, the documentation of as-found condition should be written unambiguously to demonstrate acceptability or failure when measured against these criteria (for example, ___ tubes [as found] were permanently plugged. ___ tubes were fully fouled/blocked by debris, shells, silt [total plugged = ___] and ___ were partially fouled).

Failure of these criteria would require an engineering evaluation of past operability. In addition, even acceptable conditions, reflective of significant increases in fouling from previous inspections can require evaluation, including assessment of the effectiveness of programmatic activities.

B.4.2 Microfouling

This is the most difficult inspection area to evaluate directly during an inspection because of the down-tube location, dimensions of the foulants, and very limited ability to even qualitatively assess the impact on capability. The efficacy of the programmatic activities, as previously described, provides an indirect measure of microfouling.

The following acceptance criteria statement would be typical: Based upon historical inspection results and a review of system operations and chemical treatment reliability or changes during the operating period, no evidence of ID tube scaling or slime formation on tube or head surfaces is expected. Evidence to the contrary during the inspection should result in engineering evaluation, borescopy, cleaning prior to restoration to service, and a review of associated program activities.

B.4.3 Corrosion

The pressure boundary components normally subject to corrosion are the barrel (channel), the end cover (head), and flanges. The acceptance criteria would be qualitatively based upon previous inspection results (for example, an unusual number or depth of corrosion nodules), and would be component specific (corrosion-related holidays in coated components or missing anodes). If the visual inspection or measurement of corroded areas cannot confirm that pressure boundary wall thickness conforms to code requirements, follow-up NDE (UT) would be required to provide the confirmation.

The following acceptance criteria statement would be typical, but would need to be tailored to the specific heat exchanger application.

No deep pitting (> __ inch) is expected underneath the nodules. Light general corrosion on other head surfaces is expected. (Also comment on the expected condition of anodes or coatings, if present). Corrosion exceeding this should result in:

- Evaluation
- UT to determine remaining wall thickness
- Repair of locations that are below the minimum required thickness ($T_{\min}$) and those areas that might drop below $T_{\min}$ prior to the next inspection
- Restoration of coatings, if applicable

B.4.4 Bypass Flow

Partition plate corrosion or warping and gasket deterioration are the most common degradation mechanisms that most significantly impact through-tube flow and heat transfer capability. The acceptance criteria would be a qualitative assessment of partition plate, gasket, and sealing surface in the as-found condition. Check and relief valves that are integral to the divider plate used to limit the pressure drop across the heat exchanger should also be checked periodically for proper functionality.

The following acceptance criteria statement would be typical: Based upon historical inspection results, partition plate degradation has/has not been experienced in this heat exchanger. A review of system flows and differential pressures indicates no abnormalities. Evidence of excessive corrosion, partition plate warping, or gasket distortion should result in engineering evaluation, repairs, and possible follow-up engineering evaluation for operability determination. The as-found inspection documentation should include an estimate of bypass-flow area (for the purposes of engineering bypass-flow calculation). Inspection results for signs of washout or areas where bypass flow was prevented (for example, by gasket or corrosion product accumulation) should be included.

Example of an HX/Component Inspection Data Sheet

Page 1 of 4

HX/Component Name _____ Component Information _____

Date of Inspection _____ Work Order # _____

Date of Last Inspection _____

Inspector(s) –Names/Signatures _____ / _____

Check all applicable statements and add comment where necessary. Additional paper can be used if the space provided is not large enough for comments.

1. Define operational problems experienced since last inspection:

_____ None noted

_____ Abnormal pressure drop (explain) _____

_____ Insufficient cooling (explain) _____

_____ Other (explain) _____

2. Specify visual inspection acceptance criteria (VIAC) – Complete prior to inspection***Specific VIAC that are recommended for each HX***

A. Macrofouling: A total of ____ tubes per pass in this ____ -pass HX can be fully (100%) plugged/blocked or a total of ____ circuits in this cubicle HX can have plugged/blocked tubes either with temporary/permanent plugs or by foulants.

B. Microfouling: Based upon historical inspection results, a review of system operations, and chemical treatment reliability/changes during this operating period, no evidence of ID tube scaling or slime formation on tube or head surfaces is expected.

C. Corrosion: No deep pitting (> ____ inch) is expected underneath the nodules. Light general corrosion on other surfaces is expected. (Comment on expected condition of anodes or coatings, if present). Corrosion exceeding this should result in: Evaluation, UT to determine remaining wall thickness, Repair of locations that are below the minimum required thickness (T_{min}) and those areas that might drop below T_{min} prior to the next inspection and restoration of coatings, if applicable.

D. Bypass Flow: Based upon historical inspection results, divider/partition plate degradation or gasket extrusion has not been experienced in this HX. A review of system flows and D/Ps indicates no abnormalities. Excessive corrosion of the divider/partition plate in the seating area, plate warping, or excessive gasket distortion/extrusion would require repair and engineering evaluation to estimate bypass flow.

E. Other Criteria (if applicable):**As-found conditions** when first inspecting the HX:

Approximate time since isolation/draining _____ (hrs)

Example of an HX/Component Inspection Data Sheet

Page 2 of 4

A. Macrofouling:

Describe macrofoulants/sediments/deposits:

Macrofoulants on tubes/tube sheets _____

Sediments: _____

Deposits: _____

Describe tube blockage conditions:

For cubicle HXs:

Number of circuits with plugged tubes _____

Number of circuits with tubes fully (100% flow restriction) fouled _____

Number of circuits with tubes plugged/blocked _____

Number of circuits with tubes partially blocked _____

For all other HXs:

Number of tubes per pass plugged _____

Number of tubes per pass fully (100% flow restriction) fouled _____

Tubes partially fouled/blocked _____

Total tubes fully plugged/blocked _____

Change in fouling condition since the last inspection (Y/N)? _____

B. Microfouling:

Describe any slime or other coating (that is, scale) on tubes/tubesheet:

Borescopy required (Y/N)? _____

Tube cleaning required (Y/N)? _____

C. Corrosion:

Describe corrosion, tuberculation nodules, scaling, pitting, condition of zinc anodes and coatings (when applicable):

(If the VIAC contains quantitative thresholds, provide the corresponding actual measurements)

NDE services required (Y/N)? _____

Zinc anodes replaced (Y/N)? _____ Condition, weight, and so on _____

Coatings applied/repared (Y/N)? _____

Deposits removed (Y/N)? _____

Example of an HX/Component Inspection Data Sheet

Page 3 of 4

D. Bypass Flow:

Describe partition plate and gasket condition (that is, signs of washout and/or positive statements that bypass flow was prevented):

Estimated bypass flow area (if required) _____

Any repairs (Y/N)? _____

E. Other:

Describe the condition of attributes (if any) required by the VIAC:

Actions/Plans:

Action initiated to repair as-found conditions but which do not exceed the VIAC: _____

Engineering evaluation when VIAC (based upon the as-found conditions) is exceeded: _____

Engineering evaluation performed to evaluate past operability based on the as-found conditions exceeding the VIAC in Section Two prior to returning the HX to service: _____

Engineering evaluation performed to evaluate acceptance or modification of heat exchanger as a result of as-found conditions exceeding the VIAC in Item 2 prior to returning the HX to service:

3. Collect and catalog samples (OPTIONAL): Samples should be marked with inspector(s) name, date taken, and heat exchanger component information

3.1 Sample of tube deposits sent for analysis _____ (Y/N)

3.2 Attach results of sample analysis when received _____

4. Take color photographs that show the general conditions and specific problems (organisms, shells, debris) inside the heat exchanger. Label the photographs the with inspector's name; the date the photograph was taken; the heat exchanger, description and location of the photographic subject. Photos taken _____ (Y/N)

5. Describe the effectiveness of fouling control programs

5.1 Effectiveness of microfouling control program

_____ Effective: Fouling decreased or remained at non-problem levels since last inspection.

_____ Not effective: Fouling has increased or remained at problem level since last inspection.

Example of an HX/Component Inspection Data Sheet
Page 4 of 4

5.2 Effectiveness of macrofouling control program

_____ Effective: Fouling decreased or remained at non-problem levels since last inspection.

_____ Not effective: Fouling has increased or remained at problem level since last inspection.

6. Explain how observations in Item 2 relate to operational problems in Item 1?

7. Summarize inspection results and recommendations:

- A.** As-found inspection: This is a typed or handwritten narrative summary of the as-found inspection, signed by the inspector and appended to these data sheets.

- (1) Make positive statements to determine whether the condition of the HX met the VIAC.
- (2) Document the programmatic feedback (for example, consideration for corrosion control, continue/change present fouling control, or recommendation for changing the inspection periodicity).
- (3) Document and describe the corrective actions or repairs generated.

- B.** As-left condition:

Name/Signature/Date

Reviewed: _____ **Name/Signature/Date**

B.5 Precautions

Biological activity found in heat exchangers serviced by raw water systems must be handled with care. Hands and any exposed skin that come in contact with such material should be thoroughly washed, especially prior to eating. Legionella and Staphylococcus bacteria are possible in the raw water environment, especially in systems that do not routinely receive biocide treatment or where biocide treatment has been interrupted for significant periods.

Removal of deposits for analysis requires great care, especially if microbiologically influenced corrosion (MIC) is suspected.

B.6 Inspection Procedure

The following description provides generic guidance for conducting inspections. The example form included previously is based on the standard EPRI HX Inspection Template. Some stations are able to minimize inspection subjectivity and differences between inspectors by the use of tools such as a graded or numbered inspection scheme.

This report encourages successful inspection and documentation techniques that supplement or improve upon the generic guidelines. The intent of the guidelines should be maintained, especially where specific data are being taken concerning the extent of macrofouling (that is, flow blockage) and evidence of microfouling.

Guidelines for performing heat exchanger as-found inspections include the following:

- Document inspections on a form similar to the one included above. Following any cleaning or maintenance, document the as-left condition also.
- Note and minimize the time between the cessation of service water flow or draining and the as-found inspection.
- Take color photographs (digital, if possible) during inspections because they provide one of the most objective forms of documentation. Take photos of significant corrosion, deposition, or macrofouling of tubes.
- Photographic and/or video of tube conditions (that is, ID) and quantified measurement of tube damage, if that capability is available, provide the best visual evidence in support of the heat transfer evaluation during an exchanger inspection. If consistently used, this information can also provide sufficient data to trend the visual inspection.
- Measure sediment and deposit thickness to within 1/8 inch (3.2 mm), and record the results for comparison with previous and follow-on inspections. Describe layers that are less than 1/8 inch (3.2 mm) as *films*. Distinguish sediments (silt, sand, clay, etc., that are easily removed) from deposits (for example, hard, adherent buildups such as scale).
- In channel or head areas where significant erosion or corrosion is apparent, verify that wall thicknesses are within Code-allowable values or verify them acceptable by an appropriate engineering evaluation.

- Record the characterization of the sediments and deposits, including the following points of interest:
 - Distribution of amounts versus locations. Deposits and sediments can vary significantly from location to location depending on operating conditions (that is, velocity and temperature).
 - Thickness and hardness.
 - The relative moisture content of the surface.
- Describe the texture of material found within the component. Typical texture descriptors include: smooth, slick, slimy, gritty.
- Use descriptive colors, such as bluish-black, greenish-black, reddish-brown, rather than the simpler red, black, and green.
- Note any tuberculation nodules that are present, their distribution in the piping and heat exchanger, and any colors associated with them. Relative hardness of the nodules and the occurrence of cavities within the nodules are important.
- Record any apparent layering of a deposit (color changes in the nodule).
- Record any notable smell present (sulfate-reducing bacteria can produce a rotten egg smell). Open a nodule and smell it, rather than looking for a general smell in the HX.
- Record the loose, adherent, or sludge (silt-like) nature of sediment.
- Assess and record how well deposits that are found adhere to the surface of the component. This specifically includes how the deposits adhere to heat transfer surfaces.
- Check the coatings of heat exchangers and pipes while heat exchangers are open for inspection. Signs of coating degradation include chips, iron deposits on the surface (indicative of holidays in the coating surface), scrapes, and any other sign of surface abrasion.
- Identify damage mechanisms found using available references. This includes damage caused by:
 - General corrosion, including tuberculation (channels, heads, and piping).
 - Crevice corrosion (at tube and tubesheet areas or partition plate-to-tube sheet or head).
 - MIC (in heads, channel, and piping. This is similar to tuberculation, except that the outer crust is soft for MIC and brittle for tuberculation.) **Note:** Older MIC nodules can become hard. Bright orange blotches over an otherwise black or greenish nodule would indicate a *Gallionella* colony.
 - Flow erosion.
 - Cracking.
- Note any foreign material found stuck in the tubes.
- Sample any material of unknown origin found in inspected components, and send it to a vendor for identification, analysis, and source determination.
- Visually inspect zinc anodes, and if wastage is apparent, remove and weigh them to determine their suitability for continued use.

The following heat exchanger as-left conditions should exist after cleaning (if cleaning is required):

- No silt or debris is present in the end bells.
- No material is blocking the heat exchanger tubes.
- The inlet and outlet lines are not occluded by corrosion products.
- The end bells are free of major pits and damage.
- If present, coatings should be free of chips and holidays. Coatings should not bridge floating and fixed components.

Additional documentation should include the following:

- Date of inspection and heat exchanger identification (HX ID).
- Pre-established VIAC.
- Description of the as-found conditions.
- A written assessment by the inspector of the as-found conditions and whether they met or failed to meet the pre-inspection VIAC. A description of the actions taken as a result of the inspection should be included.
- Verification that the as-left conditions are satisfied.

C

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ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Electric Power Research Institute (EPRI)

核電廠維護應用中心：熱交換器維護指南

1018089

2009 年 6 月總結報告

EPRI 專案經理
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產品描述

本指南為電廠人員提供有關熱交換器運作、維護和性能方面的資訊。本指南的內容將協助電廠人員改善熱交換器的可靠性、性能以及維護作業。

結果和發現

本技術報告概述了系統設計參數，使核電廠維護和工程人員熟知各種不同類型的熱交換器所包含的部件及其功能。本報告的重點在於針對熱交換器預防性維護的進行提供指南。針對本報告中包含的各種類型熱交換器，均提供故障排除指南。

挑戰和目的

本文的目的在於為美國電力科學研究院 (EPRI) 成員提供適當的熱交換器維護指南。文件修訂版包括內容如下：

- 針對缺乏經驗和擁有不同經驗的讀者提供指南
- 熱交換器設計和製造
- 管殼式熱交換器維護指南
- 板式熱交換器維護指南
- 空氣/水熱交換器維護指南
- 狀態監測
- 預防性維護
- 檢修性維護
- 故障排除

應用、數值和使用

本報告將管殼式熱交換器和板式熱交換器維護指南擴編為一份綜合報告。另外，還增加了關於空氣/水熱交換器維護指南。本報告的範圍包括按照低能耗、單相和水冷分類的熱交換器；不包括相變型（即凝汽器、給水加熱器）、高能耗型（即汽水分離再熱器、蒸汽發生器、給水加熱器），以及空氣冷凝器（即輔助冷凝器、強迫通風熱交換器）。

EPRI 遠景

熱交換器運作和維護成本會隨著設備的老化而增加。熱交換器性能會影響機組的可靠性和能耗。本指南全面概述了持續可靠的運作所需要的設備實務。

方法

本技術報告旨在解決一般針對熱交換器進行之預防性和檢修性維護作業的各種工程、維護和運作問題，以及進行故障排除的方法。為確保本文中的指南能夠反映業界的最新技術，我們向各大熱交換器供應商徵詢意見。另外也成立技術顧問小組，由來自 EPRI 核電廠維護應用中心 (NMAC)

機構成員的維護和工程人員組成。請他們為本報告範圍內包括的各種熱交換器的現有維護問題提供意見，確認經過實際檢驗的方法和技術，並將其編入本報告。

關鍵字

熱交換器維護性能可靠性故障排除

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核电厂维护应用中心：热交换器维护指南

1018089

总结报告 2009 年 6 月

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产品描述

本指南为电厂人员提供有关热交换器运行、维护和性能方面的信息。本指南的内容将帮助电厂人员提高热交换器的可靠性、性能以及改善维护实践。

结果和发现

本技术报告概述了系统设计参数，使核电厂维护和工程人员熟知各种不同类型的热交换器所包含的部件及其功能。本报告的重点在于为进行热交换器预防性维护提供指南。针对本报告中包含的各种类型的热交换器提供故障排除指南。

挑战和目的

本文的目的在于为美国电力科学研究院 (EPRI) 成员提供适当的热交换器维护指南。文件修订版包括如下内容：

- 针对缺乏经验和拥有不同经验的读者提供指南
- 热交换器设计和制造
- 管壳式热交换器维护指南
- 板式热交换器维护指南
- 空气/水热交换器维护指南
- 状态监测
- 预防性维护
- 检修性维护
- 故障排除

应用、数值和使用

本报告将管壳式热交换器和板式热交换器维护指南扩编为一份综合报告。另外，还增加了关于空气/水式热交换器维护指南。本报告的范围包括按照低能耗、单相和水冷分类的热交换器；不包括相变型（即凝汽器、给水加热器）、高能耗型（即汽水分离再热器、蒸汽发生器、给水加热器），以及空气冷凝器（即辅助冷凝器、强迫通风热交换器）。

EPRI 远景

热交换器运行和维护成本随着设备的老化而增加。热交换器性能会影响机组的可靠性和能耗。本指南全面概述了持续可靠的运行所需要的设备实践。

方法

本技术报告旨在解决一般针对热交换器进行的预防性和检修性维护活动的各种工程、维护和运行问题，以及进行故障排除的方法。为确保本文中的指南能够反映业界的最新技术，我们向热交换器主要供应商寻求帮助。我们也成立了技术顾问小组，由来自 EPRI 核电厂维护应用中心 (NMAC)

机构成员的维护和工程人员组成。请他们为本报告范围内包括的各种热交换器的现有维护问题提供意见，确定经过实际检验的方法和技术，并将其编入本报告。

关键词

热交换器维护性能可靠性故障排除

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Centre d'applications de maintenance nucléaire : Guide de maintenance des échangeurs de chaleur

1018089

Rapport final, juin 2009

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DESCRIPTION DU PRODUIT

Ce guide fournit au personnel de centrale les informations sur l'exploitation, la maintenance et la performance des échangeurs de chaleur. Le contenu du guide permettra au personnel de centrale d'améliorer la fiabilité, la performance et les pratiques de maintenance des échangeurs de chaleur.

Résultats et conclusions

Ce rapport technique offre un aperçu des paramètres de conception du système et permet au personnel technique et de maintenance de se familiariser avec ces éléments et leurs fonctions qui se retrouvent dans divers types d'échangeurs de chaleur dans une centrale nucléaire. Le rapport offre principalement des directives quant à l'exécution d'une maintenance préventive sur les échangeurs de chaleur. Des conseils de dépannage sont fournis pour chaque type d'échangeur de chaleur mentionné aux présentes.

Défis et objectifs

Ce document a pour objet de fournir aux membres de l'Electric Power Research Institute (EPRI) des conseils sur la maintenance appropriée des échangeurs de chaleur. Les révisions au document comprennent ce qui suit :

- Conseils ciblés pour des destinataires possédant une expérience moindre ou différente.
- Conception et fabrication des échangeurs de chaleur.
- Directives de maintenance pour échangeurs de chaleur à calandre.
- Directives de maintenance pour échangeurs de chaleur à plaques.
- Directives de maintenance pour échangeurs de chaleur air-eau.
- Contrôle d'état.
- Maintenance préventive.
- Maintenance corrective.
- Dépannage.

Applications, valeur et utilisation

Ce rapport développe le guide de maintenance des échangeurs de chaleur à calandre et à plaques dans un rapport unique complet. Il ajoute aussi des directives de maintenance pour échangeurs de chaleur air-eau. Ce rapport touche aux échangeurs de chaleur qui peuvent être classés comme étant à faible énergie, à phase simple et à refroidissement à l'eau. Il exclut le type à changement de phase (soit les condenseurs, les réchauffeurs d'eau d'alimentation), à haute énergie (soit les réchauffeurs de séparateur d'humidité, générateurs de vapeur, réchauffeurs d'eau d'alimentation) et les condenseurs à air (soit les condenseurs auxiliaires, les échangeurs de chaleur à ventilation forcée).

Point de vue de l'EPRI

Les coûts d'exploitation et de maintenance des échangeurs de chaleur augmentent en fonction du vieillissement du matériel. La performance des échangeurs de chaleur peut influencer sur la fiabilité de l'appareil et les coûts énergétiques. Ce guide offre un aperçu complet des pratiques reliées au matériel et nécessaires pour une exploitation fiable permanente.

Approche

Ce rapport technique a pour but de traiter diverses questions relatives aux applications techniques, à la maintenance et à l'exploitation des activités de maintenance préventive et corrective qui sont généralement effectuées sur les échangeurs de chaleur et la manière d'effectuer leur dépannage. Les principaux fournisseurs d'échangeurs de chaleur ont été sollicités afin d'assurer que le guide reflète bien les technologies les plus récentes qui sont disponibles dans l'industrie. Un groupe consultatif technique a été mis sur pied et se composait de personnel de maintenance et technique provenant des membres de services publics du Centre d'applications de maintenance nucléaire (CAMN) d'EPRI. Il leur a été demandé des informations sur les problèmes actuels de maintenance en ce qui a trait aux divers types d'échangeurs de chaleur mentionnés aux présentes. Des pratiques et techniques confirmées par l'expérience ont été identifiées pendant cet effort et sont présentées dans ce rapport.

Mots-clés

Échangeur de chaleur

Maintenance

Performance

Fiabilité

Dépannage

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原子力保全アプリケーションセンター ：熱交換器保全ガイド

1018089

2009年6月最終レポート

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製品説明

このガイドは、発電所の技術者に対し、熱交換器の運転、保全、パフォーマンスに関する情報を提供します。このガイドの内容は、発電所の技術者による熱交換器の信頼性、性能、保全プラクティスの改善を支援します。

結果と知見

この技術レポートは、系統設計パラメータの概要を提供すると共に、原子力発電所の保全およびエンジニアリングの技術者が各種の熱交換器に含まれる構成要素とその機能に習熟することを狙いとしています。レポートの焦点は、熱交換器に予防保全を実施するためのガイドを提供することにあります。

ここに記載されている各種の熱交換器に対するトラブルシューティングガイドも提供されています。

課題および目的

この文書の目的は、Electric Power Research Institute (EPRI) のメンバーに適切な熱交換器保全のガイドを提供することです。本文書の改訂内容には以下が含まれます。

- 経験の少ない読者、および異なる経験をもった読者向けのガイド
- 熱交換器の設計および製造
- シェル-チューブ型熱交換器の保全ガイド
- プレート型熱交換器の保全ガイド
- 空気-水熱交換器の保全ガイド
- 状態監視
- 予防保全
- 事後保全
- トラブルシューティング

適用、価値、および使用

このレポートでは、保全ガイドを、シェル-チューブ型熱交換器とプレート型熱交換器の両方を含めて拡張し、一つの包括的なレポートとしています。また、空気-水熱交換器保全ガイドも加えてあります。このレポートの範囲は、低エネルギー、単一相、および水冷式に分類される熱交換器を含みます。相変化型（すなわち、復水器、給水ヒーター）、高エネルギー型（すなわち、湿分分離型再加熱器、蒸気発生器、給水ヒーター）および空気凝縮器（すなわち補助凝縮器、強制通風型熱交換器）は含まれません。

EPRIの展望

熱交換器の運転および保全コストは、機器が高経年化すると共に増加します。熱交換器のパフォーマンスは、発電所の信頼性とエネルギーコストに影響します。このガイドでは、継続的に信頼性の高い運転を行うために必要な機器プラクティスの、包括的な全体像を提供します。

アプローチ

この技術レポートの意図は、熱交換器に特徴的に実施される予防保全および事後保全活動に関するさまざまなエンジニアリング、保全および運転上の問題への対応をすることおよびそのトラブルシューティング方法に取り組むことです。このガイドに産業界の最新の技術が反映されていることを確認するため、主な熱交換器サプライヤーに支援が要請されました。EPRI 原子力保全アプリケーションセンター（NMAC）の電力メンバーの保全およびエンジニアリングの技術者より構成される技術アドバイザリーグループが結成されました。対象範囲内の各種熱交換器における現在の保全問題について、情報の提供を要請しました。この取り組みにより、経験に裏付けられたプラクティスと技術が特定され、このレポートにまとめられました。

キーワード

熱交換器

保全

性能

信頼性

トラブルシューティング

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Centro de Aplicaciones de Mantenimiento Nuclear: Guía de Mantenimiento para Intercambiadores de Calor

1018089

Informe final, junio de 2009

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DESCRIPCIÓN DEL PRODUCTO

En esta guía se suministra información al personal de la planta sobre la operación, mantenimiento y rendimiento de los intercambiadores de calor. El contenido de la guía ayudará a dicho personal a mejorar la fiabilidad y el rendimiento de los intercambiadores de calor, así como las prácticas de mantenimiento.

Resultados y descubrimientos

Este informe técnico ofrece una descripción general de los parámetros de diseño del sistema y permite que la plantilla de mantenimiento e ingeniería de una planta de energía nuclear conozca los componentes de diversos tipos de intercambiadores de calor y sus funciones. El informe se centra en ofrecer directrices para las labores de mantenimiento preventivo de los intercambiadores de calor, e incluye directrices de resolución de problemas para cada tipo de intercambiador de calor aquí incluido.

Retos y objetivos

El objetivo de este documento consiste en ofrecer directrices a los miembros del Instituto de Investigación de Energía Eléctrica (EPRI) para el mantenimiento adecuado de los intercambiadores de calor. Las modificaciones del documento incluyen:

- Directrices destinadas a lectores con menor experiencia y con experiencias diferentes
- Diseño y fabricación de intercambiadores de calor
- Directrices de mantenimiento para intercambiadores de calor haces de tubos
- Directrices de mantenimiento para intercambiadores de calor de placa
- Directrices de mantenimiento para intercambiadores de calor de aire-agua
- Monitorización de la condición
- Mantenimiento preventivo
- Mantenimiento correctivo
- Resolución de problemas

Aplicaciones, valor y uso

Este informe es una ampliación de las directrices de mantenimiento para los intercambiadores de calor de haces de tubos y de placas, en un mismo documento completo que también incluye directrices de mantenimiento para intercambiadores de calor de aire-agua. La temática del informe comprende los intercambiadores de calor que pueden clasificarse como de baja energía, monofásicos y enfriados por agua. No incluye los intercambiadores de cambio de fase (es decir, condensadores, calentadores de agua de alimentación), de alta energía (es decir, recalentadores separadores de humedad, generadores de vapor, calentadores de agua de alimentación) y condensadores de aire (es decir, condensadores auxiliares, intercambiadores de calor de tiro forzado).

La perspectiva de EPRI

El coste de la operación y el mantenimiento de los intercambiadores de calor aumentan a medida que el equipo envejece. El rendimiento del intercambiador de calor puede afectar la fiabilidad de la unidad y los costes energéticos. En esta guía se ofrece una descripción detallada de las prácticas relacionadas a equipos que deben emplearse para obtener una continua y fiable operación.

Enfoque

Este informe técnico tiene el fin de abordar distintos problemas de ingeniería, mantenimiento y operaciones relativos a las actividades de mantenimiento preventivo y correctivo que comúnmente se realizan en intercambiadores de calor, y la forma de resolver tales problemas. Se pidió ayuda a importantes proveedores de intercambiadores de calor para asegurar que las directrices de este documento reflejaran las tecnologías más recientes disponibles en la industria. Se formó un grupo de asesoría técnica integrado por responsables de mantenimiento e ingeniería de entre los miembros de empresas de servicios públicos del Centro de Aplicaciones de Mantenimiento Nuclear (NMAC). Se pidieron aportaciones acerca de los problemas actuales de mantenimiento para los distintos tipos de intercambiadores de calor incluidos en la temática del informe. Durante este proceso, se identificaron prácticas y técnicas comprobadas a través de la experiencia y se incluyeron en este informe.

Palabras clave

Intercambiador de calor

Mantenimiento

Rendimiento

Fiabilidad

Identificación y resolución de problemas

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원자력 보수 응용 센터 열 교환기 유지관리 안내서

1018089

최종 보고서, 2009년 6월

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- 원통다관형 열 교환기의 유지관리 지침
- 판형 열 교환기의 유지관리 지침
- 공기 대 물 열 교환기의 유지관리 지침
- 상태 모니터링
- 예방적 유지관리
- 시정적 유지관리
- 문제해결

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주요 용어

열 교환기

유지관리

성능

신뢰성

문제 해결

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Printed on recycled paper in the United States of America

1018089

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