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Guidance for an Effective Heat Exchanger Program

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REPORT SUMMARY

Heat exchangers are used extensively in the nuclear power generation industry. Their proper operation is essential for reliable and safe nuclear plant operation. Increased emphasis on heat exchanger reliability at nuclear power plants has resulted in the development of engineering programs or equivalent actions to maintain the required thermal performance and structural integrity.

Background

Challenges to the thermal performance capability of safety-related open cooling water system heat exchangers resulted in the Nuclear Regulatory Commission's issuing Generic Letter 89-13, "Service Water System Problems Affecting Safety Related Equipment." This letter required licensees to commit to various on-going actions to ensure that thermal performance requirements were met for heat exchangers supporting the ultimate heat sink function. These on-going regulatory commitment actions provide the general basis for what is commonly referred to as the Generic Letter 89-13 program.

Efforts to improve heat exchanger pressure boundary reliability (for example, avoiding tube leaks) are commonly implemented by the station's preventive maintenance (PM) program with engineering oversight provided by the balance-of-plant heat exchanger program.

Objectives

- To provide guidance for engineering program–type actions related to heat exchangers
- To provide cross references to various heat exchanger–related documents, reports, and resources
- To provide technical detail for heat exchanger issues that are not thoroughly addressed in other documents

Approach

Development of this program guide included a series of benchmarking/assessment information gathering visits to nuclear plants. The visits included heat exchanger engineers from the site and those from other utilities. The benchmarks provided information related to variations in heat exchanger program implementation and health reporting, monitoring/inspection/testing methods, awareness of references and industry events, and gaps in technical guidance.

Results

This guide will be helpful to nuclear utility engineers involved with service water system heat exchanger actions related to GL 89-13, as well as those involved with tube integrity and other PM inspection actions for heat exchangers in any system.

Keywords

BOP Heat Exchanger Program
Eddy current testing
GL 89-13
Heat exchanger

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1 INTRODUCTION AND OVERVIEW

1.1 Introduction and Background

Heat exchangers are used extensively in the nuclear power generation industry. Their proper operation is essential for reliable and safe nuclear plant operation. Increased awareness of heat exchanger importance at nuclear power plants has led to development of programmatic actions to ensure both adequate thermal performance and structural integrity.

Challenges to the thermal performance capability of safety-related open cooling water system heat exchangers resulted in the Nuclear Regulatory Commission (NRC) issuing Generic Letter 89-13, "Service Water System Problems Affecting Safety Related Equipment." This letter required licensees to commit to various on-going actions to ensure thermal performance requirements were met for heat exchangers supporting the Ultimate Heat Sink (UHS) function. These on-going regulatory commitment actions provide the general basis for what is commonly referred to as the Generic Letter 89-13 program or simply the GL 89-13 program.

Efforts to achieve improved equipment and station reliability have been adopted throughout the nuclear industry, which has yielded improvements to Preventive Maintenance (PM) based actions for heat exchangers. These PM actions for heat exchangers are commonly referred to as the Balance-of-Plant (BOP) Heat Exchanger program.

This guidance document refers to two different engineering programs related to heat exchangers, the GL 89-13 program and the BOP Heat Exchanger program. This terminology is used for consistency when referring to programmatic type actions. There are various organizational structures, as well as delegation of roles and responsibilities within those structures, which can achieve the desired goal of effective implementation of programmatic actions to ensure reliable heat exchanger performance.

It is not the intent of this document to imply a specific organizational structure is required or even preferred to accomplish the objective of ensuring effective programmatic actions for heat exchanger reliability. The information provided in this guide is intended to assist the engineers responsible for implementing the program type actions for heat exchangers, regardless of their specific site's organizational structure.

1.2 Purpose

The objectives of this document are to:

1. Provide guidance for engineering program type actions related to heat exchangers.
2. Provide cross reference to the variety of nuclear industry documents, reports, and resources related to heat exchangers.
3. Provide additional technical detail related to heat exchanger programmatic actions, which may not be readily available in other documents.

1.3 Glossary of Terms and Acronyms

1.3.1 Key Definitions

BOP Heat Exchanger Program – This term refers to the programmatic actions taken on critical heat exchangers with a principal focus of ensuring structural integrity. The program addresses both safety related and operationally critical non safety related heat exchangers, primarily through the performance of eddy current testing (ECT) of tubes.

GL 89-13 Program – This term, as applied in this document, refers to the on-going commitment actions for service water (SW) heat exchangers per the site's response to GL 89-13. The focus of the GL 89-13 program is ensuring adequate thermal performance for the SW heat exchangers.

Service Water System – The term Service Water (SW) has been used generically within the nuclear industry to refer to the safety related cooling water system which is open to the environment and serves the Ultimate Heat Sink (UHS) function. The system(s) performing this role at a given station may have another name, and the system referred to as the SW system at a given site may be a non safety related open cooling water system. In this document, the term Service Water or SW will be in reference to the open cooling water system(s) performing the UHS function and the object of GL 89-13.

System Engineer – While differences in names or titles may exist, all nuclear sites typically have a system engineering group with a role of monitoring and ensuring the health of their assigned systems. Roles and responsibilities for system engineers may include part or all of the scope of the GL 89-13 program and/or BOP Heat Exchanger program.

1.3.2 Acronyms

ASME	American Society of Mechanical Engineers
BOP	Balance-of-Plant
ECT	Eddy Current Testing

EPRI	Electric Power Research Institute
FME	Foreign Material Exclusion
FWH	Feedwater Heater
GL	Generic Letter (NRC)
ID	Inside Diameter
INPO	Institute of Nuclear Power Operators
MIC	Microbiologically Influenced Corrosion
NDE	Non-Destructive Examination
NMAC	Nuclear Maintenance Application Center (EPRI)
NRC	Nuclear Regulatory Commission
O&M	Operations and Maintenance
OE	Operating Experience
OEM	Original Equipment Manufacturer
OOS	Out-of-Service
PM	Preventive Maintenance
PWR	Pressurized Water Reactor
SW	Service Water
TEMA	Tubular Exchangers Manufacturers Association
UHS	Ultimate Heat Sink
UT	Ultrasonic Testing

1.4 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. Identifies tasks which potentially consume significant resources or create scheduling problems.

Key Technical Point

Targets information that will lead to improved equipment reliability and/or program performance.

Key Human Performance Point

Denotes information associated with complex, critical, and difficult to perform tasks and content appropriate in a planning/work package to minimize human performance problems (i.e. 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
GENERIC LETTER 89-13 PROGRAM

The purpose of this section is to present an overview of the Generic Letter (GL) 89-13 program. The program focus, as presented in this guide, is to ensure adequate thermal performance for the service water (SW) heat exchangers, per the site's response to GL 89-13.

Structural integrity of heat exchanger tubes and other parts is addressed in this guide by the BOP Heat Exchanger program, described in Chapter 3.

At any given site, the GL 89-13 commitment actions for SW heat exchangers may or may not be addressed by a specific engineering program. If an engineering program exists, it may use a different name and/or the scope of the program may include actions for components other than heat exchangers, systems beyond SW or actions beyond those committed to in the site's GL 89-13 responses. This guidance document is limited to discussion of the on-going actions needed to address GL 89-13 commitments for SW heat exchangers.

2.1 GL 89-13 Program Scope

The scope of the GL 89-13 program, as presented in this guide, is limited to heat exchangers in the SW system (i.e. safety related, ultimate heat sink (UHS) function cooling system, and open to the environment).

The on-going commitment actions for the SW system heat exchangers generally involve thermal performance testing and/or periodic maintenance (i.e. visual inspections and cleaning). Other heat exchanger monitoring actions may be included in the site's commitments for GL 89-13.

2.1.1 Exclusions from Program Scope

Safety related heat exchangers cooled by closed cooling water systems are not addressed by the GL 89-13 program, as described in this document, based upon the following:

1. GL 89-13 was issued due to the additional challenges faced by open cooling water systems related to their environmental interface.
2. Closed cooling water systems have been widely shown to be capable of maintaining acceptable performance with respect to fouling by the application of appropriate chemistry treatments, monitoring and inspections.

3. Lapses or failure to maintain adequate chemistry control of closed loop systems can be addressed via the corrective action process, which is designed to correct deficient conditions and address the cause(s) of significant deficiencies.
4. NRC GL 89-13 Supplement 1 (ref. 2) clarifying guidance in Section F, Question 4 (described below).

The wording in GL 89-13 regarding closed systems stated, "*If an intermediate system is used between the safety-related items and the system rejecting heat to the UHS, it performs the function of a service water system and is thus included in the scope of this Generic Letter. A closed-cycle system is defined as a part of the service water system that is not subject to significant sources of contamination, one in which water chemistry is controlled, and one in which heat is not directly rejected to a heat sink. If all these conditions are not satisfied, the system is to be considered an open-cycle system in regard to the specific actions required below.*"

Subsequently, in Action II of GL 89-13, which specified conducting "*a test program to verify the heat transfer capability of all safety-related heat exchangers cooled by service water", the following description was included, "Operating experience and studies indicate that closed-cycle service water systems, such as component cooling water systems, have the potential for significant fouling as a consequence of aging-related in-leakage and erosion or corrosion. The need for testing of closed-cycle system heat exchangers has not been considered necessary because of the assumed high quality of existing chemistry control programs. If the adequacy of these chemistry control programs cannot be confirmed over the total operating history of the plant or if during the conduct of the total testing program any unexplained downward trend in heat exchanger performance is identified that cannot be remedied by maintenance of an open-cycle system, it may be necessary to selectively extend the test program and the routine inspection and maintenance program addressed in Action III, below, to the attached closed-cycle systems.*"

Supplement 1 to GL 89-13 was issued April 4, 1990, and provided additional guidance and clarification in the form of questions and answers regarding the requirements in the generic letter. Questions related to Action II for heat transfer testing, associated with closed systems were included in Section III.F, with question 4 of this question stating,

> *"An intermediate closed cooling water system is exempt from the GL provided it is not subject to significant sources of contamination, is chemistry controlled, and does not reject heat directly to a heat sink. However, the adequacy of the chemistry control program must be verified over the total operating history of the plant. The ACRS (Advisory Committee on Reactor Safeguards) questioned whether the absence of an adequate water chemistry control system over any part of the operating history of a closed-cycle system was adequate justification for including the system within the scope of the GL. How did the staff resolve this question?*

Answer

The staff relaxed its position on including closed-cycle cooling systems in Recommended Action II but added the precautionary recommendation that if degradation of heat transfer could not be explained or remedied by maintenance of the open-cycle part of the service water system, then testing may have to be selectively extended to the closed-cycle part of the system."

This clarification in Supplement 1 provides reasonable basis for excluding closed loop chemistry controlled systems from the scope of GL 89-13. The described response to investigating the cause of declining heat transfer which has not been explained or remedied by actions on the open-cycle part of the system is consistent with expected cause determination actions pursued by a corrective action program for a condition adverse to quality (i.e. degraded heat transfer of a SW heat exchanger). While the investigation may include closed cooling water systems in this example and the extent of condition determination may involve addressing closed loop heat exchangers, these actions are consistent with corrective action program responses and would not necessarily require implementation of an on-going test/inspection program (i.e. inclusion in GL 89-13 program) to address them in the future.

Chemistry treatment and monitoring of safety-related closed cooling water systems, which reject heat to the SW system, are indirectly credited by GL 89-13 to avoid applying the inspection and test requirements to heat exchangers in those systems. Therefore, while the selection of GL 89-13 program scope was a one-time occurrence, the basis for excluding closed system heat exchangers relies upon on-going station actions of closed loop chemistry treatment and monitoring.

The GL 89-13 program is not responsible for closed loop cooling water system chemistry. However, since the program relies upon on-going closed loop chemistry treatment and monitoring actions to exclude addressing heat exchangers in those systems, it may be beneficial for program documentation to include reference to the controls established to ensure effective chemistry treatment and monitoring of those systems is maintained. This could be in the form of reference to chemistry procedures which specify chemical control ranges, monitored parameters, and action levels consistent with those in EPRI Report 1007820 (ref. 36), described in Section 4.5.2.

Key Technical Point

Closed loop cooling systems which reject heat to the SW system rely upon chemistry controls and monitoring as the principal basis for exclusion from the GL 89-13 program. Documentation of the effectiveness of those measures and their consistency with industry guidance provided in EPRI Report 1007820 is a beneficial practice for ensuring the UHS function.

2.2 Background and Guidance Documents

2.2.1 NRC Generic Letter 89-13

The GL 89-13 program owner and SW system engineer are expected to be familiar with the content of NRC Generic Letter (GL) 89-13 (ref. 1). Familiarity with the associated Supplement 1 letter is also beneficial (ref. 2). The requirements for on-going programmatic actions from GL 89-13 are divided into three principal groups:

1. Reduce flow blockage due to biofouling via surveillance and control techniques.
2. Verify heat transfer capability via a test program or frequent regular maintenance.
3. Ensure corrosion, erosion, coating failure, silting, and biofouling cannot degrade performance of the SW system via routine inspection and maintenance.

These on-going programmatic requirements with the examples of actions noted in the GL as acceptable to the NRC, are discussed below.

2.2.1.1 Action I: Reduce Flow Blockage due to Biofouling

Acceptable actions to address this issue were described in Enclosure 1 of the GL as:

1. Intake structure visual inspection each cycle for:

   a) macroscopic fouling, b) sediment, c) corrosion.
2. Biocide treatment of SW to control macrofouling and MIC.
3. Components tested on a regular schedule to ensure they are not fouled or clogged, with infrequently used cooling loops flushed and flow tested.

Actions related to item 1 may be included within the GL 89-13 program at some utilities, but since they are system level actions versus heat exchanger actions, they are not addressed in this document other than as actions of interest for GL 89-13 program owner awareness.

2.2.1.2 Action II: Verify heat transfer capability via testing or frequent regular maintenance.

Acceptable actions to address this issue were described in Enclosure 2 of the GL as:

1. Monitor and trend SW flow when present, verifying within design limits and flow blockage or excessive fouling does not exist.
2. In addition to item 1, thermal performance testing.

The discussion of Action II in the GL acknowledges that an alternative action to thermal performance testing, which would be acceptable to the NRC is frequent regular maintenance, such as visual inspection and cleaning.

The Action II activities are the focus of the GL 89-13 program as described in this document, although the performance of SW flow balance testing is not specifically addressed. Discussion of thermal testing and visual inspection are included in Chapter 5.

2.2.1.3 Action III: Routine Inspection and Maintenance for Corrosion, Erosion, Coating Failure, Silting, and Biofouling to Ensure Required System Performance

The maintenance program is described as at least having the following purposes:

1. Removing excess accumulations.
2. Repair defective coatings and corroded SW pipe and components that could adversely affect required performance.

The Action III activities may be included within the GL 89-13 program at some utilities. Actions related to piping or other components besides heat exchangers are not addressed in this document but are recognized as commitment actions of potential interest for GL 89-13 program owner awareness. The removal of excess accumulations (i.e. debris/macrofouling), repair of defective coatings, and repair of corroded heat exchanger parts which could “adversely affect required performance” are discussed in this document, although periodic maintenance actions to address pressure boundary integrity are discussed as part of the BOP Heat Exchanger program in this guidebook.

2.2.2 NRC Inspection Procedure 71111.07

The NRC inspection procedure 71111.07 (ref. 3) provides staff guidance for annual and triennial inspections of the ultimate heat sink (UHS) complex. These inspections are focused on ensuring the required safety functions of UHS components are adequately monitored and verified, much of which is implemented by the GL 89-13 program. While the inspection procedure is not a regulatory requirement document, it provides useful insight regarding the level of monitoring, inspection, and testing expected by the NRC for UHS related components. Inspection items included in the NRC UHS inspection procedure which were not addressed by GL 89-13 are noted in Appendix H, along with associated comments.

2.2.3 Industry Documents for GL 89-13 Actions

The principal EPRI guidance documents related to GL 89-13 program implementation are TR-107397, Service Water Heat Exchanger Testing Guidelines (ref. 28), for SW heat exchanger thermal performance testing, and 1003320, Supplemental Guidance for Testing and Monitoring Service Water Heat Exchangers (ref. 29). Early guidance consisted of EPRI NP-7552, Heat Exchanger Performance Monitoring Guidelines (ref. 27), although it has largely been replaced by the additional detail in TR-107397. Guidance is provided in EPRI 1009839, Heat Exchanger Single Tube Test Device (ref. 33), for an alternative heat exchanger test method which does not require testing of the entire tube bundle. Since all GL 89-13 programs are likely to be performing heat exchanger thermal performance tests and/or visual inspections, it is beneficial for the involved engineers to be familiar with the content of applicable documents.

EPRI Report 1007248, Alternative to Thermal Performance Testing and/or Tube Side Inspections of Air-to-Water Heat Exchangers (ref. 31), provides information for actions other than heat transfer testing of room coolers. The report content has provided supporting technical basis for commitment changes at sites originally thermal testing air-to-water room coolers.

ASME OM-2009, Part 21, Inservice Performance Testing of Heat Exchangers in Light-Water Reactor Power Plants (ref. 15), is described in EPRI 1003320 (ref. 29) as, "OM Part 21 establishes the requirements for pre-service and in-service testing to assess the operational readiness of certain heat exchangers used in nuclear power plants. The heat exchangers covered are those required to perform a specific function in shutting down a reactor to safe shutdown condition, in maintaining the safe shutdown condition, or in mitigating the consequences of an accident. This part establishes test intervals, parameters to be measured and evaluated, acceptance criteria, corrective actions, and records requirements."

2.2.4 INPO Engineering Program Guide– 04

INPO's engineering program guide (EPG) EPG-04 provides guidance for successful oversight and implementation of activities to ensure a highly reliable service water system, including recommendations from NRC GL 89-13. Accordingly, it is beneficial for the GL 89-13 program owner to be familiar with this guide. [1]

The guidance in EPG-04 is generally very consistent with the information provided in this document. An exception is noted for Section 2.3.2 Item II of EPG-04, which notes thermal performance testing of all/most safety-related heat exchangers should be a GL 89-13 program goal and justification for not thermal testing should be documented in the program files. In contrast to this statement, the GL 89-13 program actions for heat exchangers are presented in this guide to accomplish two principal objectives:

1. The GL 89-13 program inspection, testing, maintenance, and monitoring actions are "singularly or in combination adequate to ensure proper heat transfer." (quotation from NRC IP 71111.07, ref. 3, section 2.02.b)
2. The GL 89-13 program actions maintain consistency with NRC commitments related to type, scope and frequency of actions performed. This includes revising the GL 89-13 commitments, as required.

These two goals are also the intent of EPG-04, however, achieving these objectives does not in most cases require thermal performance testing of all safety related heat exchangers and can be achieved without thermal performance testing any heat exchangers at many sites. Stations are therefore not expected to have a GL 89-13 program goal to thermal performance test heat exchangers beyond those committed in their GL 89-13 response, if proper heat transfer capability for those heat exchangers can be reasonably established by other means.

[1] Access to INPO reports and materials is restricted to organizations authorized by INPO. The information is confidential and for the sole use of the authorized organization.

A program document explaining the adequacy of current program actions to ensure heat exchanger performance is not explicitly required by the response to the GL, although it is implied via the NRC's allowance for "an equally effective program to ensure satisfaction of the heat removal requirements of the service water system", with the document providing the basis why the current actions are "equally effective". Appendix B provides additional discussion related to crediting various test, inspection, and design aspects related to SW heat exchangers in an integrated fashion to establish a more comprehensive understanding of system and component thermal performance. It is beneficial for GL 89-13 programs which do not directly validate thermal performance capability of all SW heat exchangers, to document how reasonable assurance of adequate heat transfer is determined for heat exchangers not tested.

Key Technical Point

Documenting the technical basis for reasonable assurance of adequate heat transfer for heat exchangers not thermal performance tested is beneficial for GL 89-13 programs not directly validating thermal performance capability of all SW heat exchangers.

2.3 Division of Responsibilities and Communications

It is beneficial for GL 89-13 program documentation to include clear divisions of responsibilities for program driven actions as well as for supporting or interfacing roles of other programs and organizations such as the BOP Heat Exchanger program and system engineers.

Key Human Performance Point

Clear and specific identification of assigned roles and responsibilities for program driven actions as well as supporting or interfacing roles of other programs is an important factor in their effective implementation. It is beneficial for each program action to have an identified responsible individual (by position). This is not intended to limit the ability to distribute or delegate work within the organization, but to remove uncertainty regarding ownership of program actions.

Recognizing there are various means to achieve effective implementation of GL 89-13 program goals, this program guide does not specify a recommended organizational structure, nor does it address the assignment of key program actions to specific positions. It is important to clearly and specifically identify assigned roles and responsibilities for program functions to ensure they are implemented. The program basis document is the most common location for identification of these roles and responsibilities.

Identification of the responsible individual(s) for program actions in program documents is a beneficial practice. Actions are performed by individuals, not organizations, departments, or groups, therefore specifically identifying the individual position responsible for ensuring an action is performed may avoid confusion, duplication of effort, and/or failure to perform the action.

The identification of a responsible individual for program actions is not intended to limit the ability to distribute or delegate work within the organization. The use of training and qualification tasks discussed in Section 2.5 provides a means to ensure support individuals are technically qualified to perform delegated work which requires specialized knowledge. Many GL 89-13 programs rely on actions performed by individuals in other groups and departments.

Considerations for distributed/delegated program work may include:

- Individuals in other groups or departments may not be familiar with program procedures (corporate and site) related to the actions being performed.
- Greater detail in program documents may be needed to support implementation by those with less subject matter expertise than the program owner.
- Temporary delegation of program actions, such as during an outage or for a specific test/inspection, may benefit from clear identification of the specific action, procedure steps, and expected documentation.
- Programs with permanently distributed work may benefit from periodic audits/assessments to check for consistency and compliance with program documents.
- Programs with permanently distributed (or long-term delegated) work may benefit from periodic meetings (such as pre-outage, post-outage, semi-annual, etc.) to review work scope, results, follow-up, and similar actions to ensure awareness and consistency of actions taken by various program implementing personnel.

2.3.1 Communication

Periodic structured meetings between the GL 89-13 program owner, SW system engineer, and personnel responsible for SW system chemistry treatment are a beneficial practice to ensure those responsible for monitoring, testing, inspection, and treatment have an integrated understanding of equipment and system conditions. Appendix F includes an example agenda for such a meeting.

Key Human Performance Point

Periodic structured meetings between various individuals performing key roles related to GL 89-13 actions, such as the GL 89-13 program owner, SW system engineer, SW chemist(s), etc., are beneficial to program performance by establishing an integrated understanding of the monitoring, testing, inspection, and treatment results for the system and components.

2.4 GL 89-13 Program Functions and Key Attributes

Many functions for engineering programs are generically defined by site/corporate procedures for all engineering programs. Brief descriptions of several of these key functions are described in this section with their application in the GL 89-13 program.

2.4.1 Program Documentation

Program notebooks are established at most utilities for engineering programs, with a site or corporate level document often outlining the general format and content expectations. Electronic notebooks may be a beneficial format to maintain program information. Connecting an electronic program notebook to an engineering department web page with a read-only link can improve access to program information for other site personnel, such as system and design engineers.

Program basis documents or procedures are also established at most utilities for engineering programs. These documents commonly provide an explanation of program scope as well as the roles and responsibilities for the program owner and other individuals/groups providing support.

2.4.1.1 GL 89-13 Program Thermal Test and Visual Inspection Documents

Procedures or guidebooks are commonly developed for thermal performance tests (if applicable) and heat exchanger visual inspection. Thermal performance tests typically utilize a field implementation procedure to direct the test process. A test protocol document may exist which provides description of the instrumentation, test uncertainty, and targeted test conditions (i.e. range of flows, temperatures, and heat loads).

2.4.2 Implementation Process for Program Actions

Use of the Preventive Maintenance (PM) process and database has been found to be a beneficial means to implement program actions. Regulatory commitments can be noted, including reference to the associated licensing commitment. Implementing GL 89-13 program actions in the PM process can provide consistency, structure, and accessibility for the following:

- Documentation basis location.
- Integrated listing of actions performed on a heat exchanger.
- Process to control changes, including their reviews.

Implementation of PM database actions is normally through the site work control process using repetitive work packages with defined intervals and due dates. This method has been found to be more effective than manual initiation of work requests by the program owner for recurring program actions such as tests and inspections.

Work scheduling grace periods commonly defined within the PM process may result in exceeding the five year maximum interval between heat exchanger tests noted in the GL. This may be addressed by adjustments to scheduling controls for the tasks or by justification of the grace period for the GL 89-13 program commitments, including a commitment update, if necessary.

Establishing an integrated database or spreadsheet for GL 89-13 heat exchangers which documents the operating cycles and refueling outages when they are scheduled to be tested or inspected, as well as when they will be opened for eddy current testing (ECT) (i.e. integrated with BOP Heat Exchanger program actions) is a beneficial practice. This spreadsheet supports budgeting, NDE service contracts, maintenance planning, test equipment calibration scheduling, and related support. Further, the GL wording for Action II to perform periodic heat transfer verification actions stated, "*A summary of the program should be documented, including the schedule for tests*" (ref. 1). Maintaining the spreadsheet in an electronic program notebook linked to the program or department web page is a means to improve accessibility and therefore awareness for delegated or shared work responsibilities.

Chapter 5 includes additional detail for heat exchanger thermal performance testing and visual inspection.

Key Human Performance Point

An integrated database or spreadsheet for program heat exchangers containing the schedule for cycles and refueling outages in which GL 89-13 tests or inspections and ECT tube inspections by the BOP Heat Exchanger program are to be conducted is a beneficial practice supporting budgeting, NDE service contracts, maintenance planning, test equipment calibration scheduling, and related actions.

2.4.3 Program Changes – Actions or Frequencies

The GL 89-13 program actions are regulatory (NRC) commitment based. The level of detail in site GL 89-13 response letters, regarding the type of actions and their frequencies for the SW heat exchangers, varies significantly across the industry. The program owner is responsible to maintain awareness of the level of detail in their site's commitment correspondence to the NRC related to GL 89-13, particularly as it relates to specific actions (i.e. thermal performance tests, dp monitoring, periodic visual inspection, etc.) and intervals for SW heat exchangers. The program basis documents and/or databases containing SW heat exchanger actions and intervals typically also references the applicable NRC commitment to ensure changes are reconciled against regulatory commitment correspondence.

A maximum interval between inspections and tests is defined in the GL as, "*The minimum final testing frequency should be once every 5 years.*" Justification of periods longer than 5 years typically involves a technical evaluation basis document and may require a commitment change prior to implementing longer intervals.

2.4.3.1 License Renewal and GL 89-13 Program Commitments

The nuclear license renewal process to extend the original 40 year operating license for an additional 20 years has been applied or is expected to be applied to most US nuclear units. While the renewed license and its associated commitment are unit specific, in general the process is applied per the guidance in NUREG-1801, Generic Aging Lessons Learned (GALL) Report (ref. 4).

The Aging Management Programs (AMPs) credited in NUREG-1801 to address license renewal issues include the "open cycle cooling water system" which credits the site's GL 89-13 program to address associated issues. The station's license renewal submittal may have identified greater level of detail in the type of actions, scope of actions and their scheduling than was originally committed by their GL 89-13 response. This may substantially reduce the GL 89-13 program owner's ability to make program adjustments without impacting regulatory commitments related to license renewal. It is important for program owners to be aware of license renewal commitments and content related to their program. Most license renewal commitments do not take effect until the period of extended operation (i.e. after initial 40 year license period). However, awareness of such commitments is important to ensure the GL 89-13 program is either operated in a manner consistent with the pending commitments or is addressing and tracking changes which may be needed prior to the period of extended operation.

2.4.4 Thermal Performance Testing

Thermal performance testing of SW heat exchangers represents a major focus of the GL 89-13 Program resources at stations committed to this action. Thermal performance tests can provide high confidence quantitative data and commonly require program documents related to test protocol, test procedures, heat exchanger thermal model software packages, and field test results analysis. Program owners may be involved with supporting contracts for test equipment rental, test personnel, software service agreements, or related items. Coordination of instrumentation calibration may be required to support test schedules. Oversight or direct involvement with field actions including installation of test instruments, coordination with Operations for required test conditions, and scheduling can require considerable program owner time.

The principal industry reference documents related to thermal performance testing are noted in Section 2.2.3. Section 2.5 discusses qualification and training considerations for thermal performance testing.

2.4.5 Heat Exchanger Visual Inspection

Visual inspections of SW heat exchangers also represent a major focus for the GL 89-13 program owner, at stations committed to this action. Coordination with others involved with the inspections may include the system engineer(s), component engineer, BOP Heat Exchanger program owner, chemistry, and maintenance. It is beneficial for the program owner to be directly involved with most SW heat exchanger visual inspections, and be familiar with all of the results. The program owner is expected to have an integrated knowledge of inspection results in order to evaluate potential implications to other heat exchangers or system parameters.

The principal industry reference documents related to thermal performance testing are noted in Section 2.2.3. Section 2.5 discusses qualification and training considerations for visual inspections. Section 5.2.2.2 includes a brief summary of technical considerations related to GL 89-13 program visual inspections.

2.4.6 Budgeting and Scheduling

Budgeting for the GL 89-13 program is often determined by the site's reliance on outside services to support thermal performance testing. Support may include contracting heat exchanger test services, rental of test equipment, and/or software maintenance service agreements. Occasional costs may involve thermal performance test equipment purchase/replacement, software purchase/replacement, support for document upgrades, etc.

The program owner is commonly relied upon to maintain an integrated schedule of program actions. This scheduling tool provides input to budgeting and similar resource allocation planning activities for the site.

2.4.7 Trending and Margins

Trending by the GL 89-13 program owner is typically limited to parameters measured by program driven actions. Example of trended parameters from thermal performance tests may include fouling factors, U-factors, heat removal capability, or heat transfer margins, while trending associated with visual inspections often includes the number or percentage of blocked tubes.

Numerous additional trends, such as SW chemistry parameters, differential pressure, flow, thermal effectiveness, tube plugging rates, and possibly peak UHS temperatures, may be of interest to the program owner.

2.4.7.1 Margin

Margin is the difference between the required or limiting value and the measured or projected value being trended. Many utilities have implemented margin management processes to identify and prioritize low margin or margin reduction issues. These processes typically are intended to increase management awareness and provide a consistent process to address margin improvement. Program owners are expected to be aware of GL 89-13 program heat exchanger margins as well as the various tools at their station for communicating and addressing low or degrading margins.

A generalization of the design basis for a GL 89-13 program heat exchanger is for it to meet heat removal requirements with simultaneous occurrence of the minimum surface area (i.e. maximum tube plugging/blockage), maximum fouling, minimum required flow (shell and tube sides), at the most limiting fluid temperature conditions. It is beneficial for the GL 89-13 program owner to be aware of the design basis requirements for program heat exchangers, although other groups or departments (e.g. system engineering, operations, etc.) are often responsible for monitoring or trending some of these parameters. The heat exchanger may remain operable (i.e. capable of achieving the required heat removal) with one or more of the supporting parameters not being met due to margin in other parameters, although the component may be identified as degraded in the site's corrective action process.

2.4.8 Performance Indicators and Health Reporting

Long-term heat exchanger issues and/or program performance issues are important to communicate to site management. Methods for communicating and addressing SW heat exchanger health issues may include some or all of the following:

- Program and/or System Health Reports
- Program Performance Indicators
- Long Range Planning Process
- Margin Management Program/Database
- Engineering Project Request Process
- Equipment Reliability "Top Ten" Process
- Corrective Action Process

These tools are not specific to the GL 89-13 program. Accordingly, the program owner is responsible for implementation of the site's health reporting processes. The program owner may help in establishing specific criteria and leading indicators applicable to performance of their program. Sites may rely on the SW system health report to provide visibility to site management for SW & UHS issues versus establishing separate program indicators and reports. Unlike many other engineering programs, the GL 89-13 program generally does not have cross-cutting aspects that impact systems beyond the SW system. The complexity of the site SW system, extent of system degradation and vulnerabilities, and GL 89-13 programmatic actions will factor into the site determination of need for a separate GL 89-13 program and/or associated performance indicators and health reports.

Regardless of the health reporting tools used by the site, communication between the program owner, the associated system engineer(s), and other affected engineering groups is important to ensure SW heat exchanger health issues and recommended actions are reported consistently.

2.4.8.1 General comments for Program Indicators and Health Reports

- Leading indicators are more beneficial than failure counting. Examples could include:
  - SW chemical treatment system out-of-service time.
  - SW chemistry out-of-tolerance events considering severity and duration.
  - Tube blockage margin.
  - Thermal performance test results could be graded according to margin versus meeting operability requirements.
- Timely documentation of program inspection/test results may be an indicator of program health via program owner availability or adequacy of resources. Tracking the number and age of open inspection or tests which are field completed but do not have engineering paperwork completed may be a leading indicator of program health.

2.4.9 Long Range Planning/Life Cycle Management

Long range planning processes are established at most sites to assist in capital budget forecasting along with major project management and outage planning. The program owner is expected to be familiar with applicable site procedures and processes needed to support the program.

Most issues detected by the GL 89-13 program tests/inspections involve short term resolution actions versus slowly degrading loss of margin issues that require significant resources. Examples of exceptions which could require long-range planning actions include:

- Retubing due to loss of tube plugging margin.
- Coating/Corrosion repairs (pending size, extent of work, and work window).
- Replacement due to tubesheet corrosion damage.
- Repair/Replacement due to shell-side corrosion damage, if SW is supplied to the shell.
- Supply header lining/coating repairs to address a deteriorating macrofouling problem.

2.4.10 Operating Experience

The GL 89-13 program owner, often in conjunction with the applicable SW system engineer, is normally responsible for review and disposition of industry SW heat exchanger thermal performance or fouling related INPO operating experience (OE).

Program owners may find it beneficial to establish automatic direct email notification from INPO[2] for OE with selected key words of interest, such as fouling, service water, 89-13, etc.

Maintaining an electronic log of GL 89-13 heat exchanger related OE reviews may be beneficial. Inclusion with an electronic program notebook allows ease of access to previous OE dispositions for the back-up program owner, system engineers, or future program owners.

2.4.11 Industry Users Groups and Peer Interaction

Industry peer communication is important to improving program and equipment health. Most GL 89-13 heat exchanger issues have occurred previously at one or more other sites. Thus, experience in correcting or avoiding the problem is often available within the industry. GL 89-13 program owners are encouraged to share their experiences to assist others in improving their program performance. There are multiple avenues available to the program owner in requesting support and sharing program experiences (see Chapter 6).

[2] Access to INPO reports and materials is restricted to organizations authorized by INPO. The information is confidential and for the sole use of the authorized organization.

Opportunities for peer communication and information exchange include:

- Annual meetings for EPRI Service Water Assistance Program (SWAP) and Heat Exchanger Performance Users Group (HXPUG).
- Periodic webcasts or teleconferences by HXPUG.
- Participation in EPRI Technical Advisory Groups for technical reports.
- Assessment support or benchmarking at other sites.
- Nuclear fleet utility periodic program owner peer phone calls (as applicable).

Program owners are encouraged to make presentations at industry conferences or webcasts to share heat exchanger failures, issues, or successes with industry peers. Program owners are also encouraged to provide Operating Experience reports to INPO to distribute to industry peers for more significant degradation or failure issues. Technical libraries and collaboration bulletin boards maintained by EPRI are additional locations to find and share documents, ask questions, review previous topic results, etc.

The site or utility benchmarking and assessment processes available to the program owner provide structure and documentation options to formally capture peer communication and information exchange.

2.5 Qualification and Training

Qualification tasks for GL 89-13 program actions are a tool which may be used to ensure adequate technical understanding of program activities. Other means such as mentoring, training programs, or similar actions may be equally effective at ensuring adequate technical knowledge and may be used in conjunction with or instead of a qualification process, as determined appropriate by the site/utility.

An experienced program owner with subject matter expertise is desirable, but it is often impractical for all program technical actions to be performed directly by the program owner. Qualification tasks or similar tools may be used to allow additional personnel to knowledgably support program actions. The most commonly implemented qualification tasks are discussed in sections 2.5.1, 2.5.2, and 2.5.3, below.

2.5.1 Training

Industry training is available periodically from EPRI for GL 89-13 heat exchanger testing. The five day course uses lecture, examples, case histories, and exercises to guide engineers in testing SW heat exchangers. The coarse goal is to provide engineers with the tools to design and implement heat exchanger test programs that yield test results with acceptable uncertainty. This training may be credited by a site qualification process for the program owner or the thermal performance testing engineer.

EPRI periodically offers a three day Microbiologically Influenced Corrosion (MIC) Course providing background and methods for its diagnosis, treatment, and prevention. The seminar targets an understanding of microorganisms and techniques to help reduce the operation and maintenance costs of plant water systems. Cleaning, treatment, and repair techniques as well as material susceptibilities are reviewed.

The EPRI Service Water Engineer Training course is a three day course addressing the function, operation, and maintenance of SW systems. Case histories and experiences highlight issues facing a SW system engineer. Available resources to assist an effective SW system maintenance program are noted, as well as information on current trends and new technologies. The course also presents how SW system issues can affect other plant systems and components.

Training applicable to heat exchangers and GL 89-13 program actions may also be available from vendors, engineering firms, or other industry or professional organizations.

2.5.2 Program Owner Qualification

Qualification requirements for the GL 89-13 program owner and backup may be established via a qualification task or a similar program turnover, mentoring, or training process, as noted above in section 2.5. Key items to consider for GL 89-13 program owner familiarity include:

- Program documents (Corporate and Site) – notebook, procedures, guides
- Design basis documents – calculations, engineering reports, specifications
- License Basis Documents – UFSAR and Technical Specifications as well as active commitments and pending License Renewal commitments
- Industry guidance and technical documents
- Regulatory documents – GL 89-13 (including Supplement 1), IP 71111.07
- Software (as applicable) for thermal performance tests
- Health reports and performance indicators
- EPRI users groups (i.e. HXPUG and SWAP)
- Industry experience

2.5.3 GL 89-13 Heat Exchanger Visual Inspection Qualification

A qualification process for individuals performing GL 89-13 visual inspections may be used to ensure their familiarity with the relevant technical issues. Visual inspections of SW heat exchangers are needed to satisfy GL 89-13 thermal performance capability. The visual inspections include qualitative and quantitative acceptance criteria, with the thermal performance acceptability conclusion often considering comparisons with previous inspections, tests, and monitoring results from SW heat exchangers, as well as consideration of design features and margins. As a result, the heat exchanger acceptability is not determined solely based on the visual inspection, but also relies upon technical understanding.

The use of photographs from previous heat exchanger inspections in the qualification or training material improves the explanation of heat exchanger fouling and degradation mechanisms. Chapter 5 includes additional discussion of GL 89-13 visual inspections.

2.5.4 GL 89-13 Heat Exchanger Thermal Test Qualification

Thermal performance tests of SW heat exchangers are normally conducted per site procedures which direct the test activities, specify instrumentation, and define limits for test conditions. Specialized data acquisition systems and software may be utilized to record the test data and support analysis of the results. Many thermal performance tests include a detailed test protocol document describing the test parameters, instrumentation, and analysis. Thermal performance software is commonly used to evaluate the test results and project heat removal capability at design limiting conditions. These factors may support development of qualification tasks related to thermal performance testing and/or data analysis. Thermal performance tests are often conducted or coordinated by the program owner (or backup), which may limit the need for task specific qualification.

3
BALANCE OF PLANT HEAT EXCHANGER PROGRAM

This section presents an overview of the Balance-of-Plant (BOP) Heat Exchanger program. The program focus, as presented in this guide, is to maximize heat exchanger pressure boundary reliability by the application of appropriate preventive maintenance actions and intervals to address material degradation prior to failure. The determination of program actions and their frequency are generally not regulatory driven but are risk-based through consideration of both failure consequences and failure probability. Thus, while it is a general program goal to minimize the occurrence of tube leaks and other pressure boundary failures, it is not an economically justifiable goal to prevent all leaks.

The program's heat exchanger inspection actions are commonly implemented through the Preventive Maintenance (PM) process. These programmatic activities may not be addressed by a separate engineering program at a given site, or an alternate name may be used.

Thermal performance is not addressed by the BOP Heat Exchanger program, as presented in this guide, for the following reasons:

1. System engineers are responsible for monitoring in-service heat exchangers, when monitoring capability exists. This includes familiarity with adverse trends from Operations monitoring or plant thermal performance monitoring, where applicable.
2. Service Water system heat exchanger thermal performance is addressed by the GL 89-13 program, which encompasses the safety related open cooling water heat exchangers.
3. Closed loop safety related heat exchangers have a low potential to foul beyond design values, particularly when appropriate chemistry controls and monitoring are established. Isolated failures are commonly addressed via the corrective action process versus establishing programmatic functions through a BOP Heat Exchanger or GL 89-13 program.

While not a primary focus of the program, thermal performance requirements are supported by various program actions, which may include:

- Visual inspection – includes criteria to detect/address fouling and bypass flow
- Tube plugging limits are often based upon thermal performance requirements. Heat exchanger remaining life projections and long-range planning actions are intended to initiate repair prior to exceeding tube plugging limits and thermal performance limits.
- Periodic cleaning actions are normally specified for heat exchangers cooled by open cooling systems and may be triggered by performance monitoring.

3.1 BOP Heat Exchanger Program Scope

A structured process to determine the components included in the scope of the BOP Heat Exchanger program is beneficial.

Key Technical Point

A structured process is beneficial for determining the scope of heat exchangers to be included in the BOP Heat Exchanger program, with clear identification of heat exchangers included and any critical/important heat exchangers excluded from the scope.

The most widely used process to determine heat exchangers to be included in the program involves classifying or ranking according to failure consequences. The term "Critical" is often applied to the components with sufficient consequences of failure to warrant preventive actions. Generally this process is applied at the site for all component types and is used by the PM process to determine which components warrant PM actions to avoid failure versus those where corrective maintenance (CM) is acceptable.

3.1.1 Exclusions from Program Scope

Clear identification of heat exchangers addressed by the BOP Heat Exchanger program, as well as any critical heat exchangers excluded from the scope, is beneficial content for program documents.

Run-to-failure (RTF) heat exchangers are excluded from the BOP Heat Exchanger program, since they do not justify programmatic actions to avoid failure. It is a good practice for criticality rankings which provide the basis for exclusion from program actions, to include review and concurrence by the system engineer, program owner, and operations.

It is a good practice for the BOP Heat Exchanger program documentation to reference the group(s) or other programs responsible for addressing reliability of critical heat exchangers not included in the BOP program. Examples include steam generators at all PWRs, which are addressed by regulatory programs. Sites may exclude other specialized heat exchanger types such as MSRs, main condensers, integral pump/motor coolers, or HVAC coils, with responsibilities assigned to system engineers, maintenance, etc. Service Water (SW) system heat exchangers addressed by GL 89-13 commitments are excluded from the BOP Heat Exchanger program at some sites due to their GL 89-13 program scope addressing both thermal performance and pressure boundary degradation issues.

Some critical heat exchangers are not designed to support performance of NDE tube inspections. In this case, it is beneficial for program documentation to include the basis for actions taken to ensure their reliability (i.e. periodic replacement).

If no actions to ensure reliability are established for critical heat exchangers, it is beneficial for these components to be presented to a plant health/reliability committee or plant management to ensure their awareness and concurrence with the lack of action.

Key Technical Point

A presentation to plant management on critical heat exchangers which do not have actions established for maintaining reliability is beneficial to ensure their awareness and concurrence with the lack of action.

In a similar manner, if new actions to ensure heat exchanger reliability are developed by the program but scheduling for initial or baseline performance is beyond that defined by PM program guidance or is beyond 10 years, then it is beneficial to present these components to a plant health/reliability committee or plant management to ensure their awareness and concurrence with the associated risk of delayed implementation of the PM actions.

3.2 Background and Guidance Documents

The BOP Heat Exchanger program is not regulatory driven and does not have regulatory background or basis documents. The License Renewal process may have credited the program and resulted in additional inspection actions and regulatory commitments as noted in Section 5.7. There are numerous industry guidance documents related to heat exchangers and their associated inspection, monitoring, and maintenance issues, but not which address the program for implementing these actions, other than as noted in Section 3.2.1.

3.2.1 INPO Engineering Program Guide 14

INPO[3] EPG-14 provides guidance for successful oversight and implementation of activities to ensure reliability of critical heat exchangers. Accordingly, it is beneficial for the BOP Heat Exchanger program owner to be familiar with its content. The guidance in EPG-14 is generally consistent with the information provided in this EPRI report. Differences include, but are not limited to, the inclusion of performance monitoring actions in EPG-14 but not in this guide and the exclusion of SW heat exchangers from EPG-14, but their inclusion for structural integrity purposes in this guide.

3.3 Division of Responsibilities and Communications

It is beneficial for the BOP Heat Exchanger program documentation to include clear division of responsibilities for program driven actions as well as for supporting or interfacing roles of other programs and organizations such as the FAC program (if responsible for inspection of feedwater heater shells), the GL 89-13 program and system engineers.

[3] Access to INPO reports and materials is restricted to organizations authorized by INPO. The information is confidential and for the sole use of the authorized organization.

Key Human Performance Point

Clear and specific identification of assigned roles and responsibilities for program driven actions as well as supporting or interfacing roles of other programs is an important factor in their effective implementation. It is beneficial for each program action to have an identified responsible individual (by position). This is not intended to limit the ability to distribute or delegate work within the organization, but to remove uncertainty regarding ownership of program actions.

This program guide does not specify a recommended organizational structure, nor does it recommend the assignment of key program type actions to specific individuals, in recognition of the various means of achieving effective implementation of the BOP Heat Exchanger program goals. However, regardless of the organizational names or alignments, an important aspect of sustaining effective implementation actions is the clear and specific definition of assigned roles and responsibilities for programmatic functions. The program basis document is the most common location for these roles and responsibilities to be identified.

Identification of the responsible individual(s) for program actions in program documents may be beneficial to avoid confusion, duplication of effort, or failure to perform the action. The identification of a responsible individual for program actions should not limit the ability to distribute or delegate work within the organization. The program may rely on actions performed by a variety of individuals in different groups or departments. Considerations for distributed/delegated program work load include:

- Individuals in other groups or departments may not be familiar with program procedures (corporate and site) related to the actions being performed.
- Greater detail in program documents may be needed to support implementation by those with less subject matter expertise than the program owner.
- Temporary delegation of program actions such as during an outage or for a specific test/inspection may benefit from clearly identifying the specific action, applicable procedural steps, and documentation expected.
- Permanently distributed program work may benefit from periodic audits/assessments to check for consistency and compliance with program documents.
- Permanently distributed (or long-term delegated) program work may benefit from periodic meetings (pre-outage, post-outage, semi-annual, etc.) to review work scope, results, follow-up, and similar actions to ensure awareness and consistency of actions taken by various program implementing personnel.

3.3.1 Communication

Periodic structured meetings between the program owner, affected system engineers, and other personnel responsible for program actions (e.g. site NDE – ECT lead) may be beneficial to address issues encountered and ensure consistency in implementation of program actions.

3.4 BOP Heat Exchanger Program Functions and Key Attributes

Many functions for engineering programs are generically defined by site/corporate procedures for all engineering programs. Brief descriptions of several of these key functions are described in this section as they relate to the BOP Heat Exchanger program.

3.4.1 Program Documentation

Program notebooks are established at most utilities for engineering programs, with a site or corporate level document often outlining the general format and content expectations. Electronic notebooks may be a beneficial format to maintain program information. An electronic program notebook on an engineering department web page with a read-only link can improve access to program information for other site personnel, such as system and design engineers.

Program basis documents or procedures are also established at most utilities for engineering programs. These documents commonly provide explanation of program scope and roles and responsibilities of the program owner and other key individuals/groups supporting the program.

The program documents commonly specify (or reference other procedures or documents which include this detail) the disposition of ECT inspection data, both electronic field data as well as the final analysis reports. It is a beneficial practice to maintain a copy of the field data at the site (or utility corporate office) versus having it kept solely by the contract NDE vendor. ECT analysis reports may not be maintained as permanent records at some stations, which can cause difficulty locating previous information.

3.4.2 Implementation Process for Program Actions

Use of the site's Preventive Maintenance (PM) processes and database have been found to be a beneficial means to implement program type actions for heat exchangers in support of the BOP Heat Exchanger program. Actions and intervals which are regulatory commitment driven can be noted accordingly with reference to the associated licensing commitment. Including program actions in the PM process provides consistency, structure, and accessibility for the following:

- Documentation basis location.
- Integrated listing of actions performed on a heat exchanger.
- Process to control changes, including their reviews.

Implementation of the PM database actions is normally through the site's work control process using repetitive work packages with defined intervals and due dates. This method has been widely adopted over manual initiation of work requests by the program owner for recurring program tests and inspections, since it improves visibility of program type actions and reduces human error potential.

An integrated database or spreadsheet for program heat exchangers containing the operating cycle and refueling outage schedule for ECT and visual inspection is beneficial. This database supports budgeting, NDE service contracts, maintenance planning, and related support. The spreadsheet may need to include the total number of tubes and/or the number of tubes to be ECT inspected. Integrating the database with GL 89-13 program visual inspection and thermal performance test schedules for SW heat exchangers provides a more complete view of inspection and test actions. Maintaining the spreadsheet in an electronic program notebook linked to the program or department web page is a means to improve accessibility and therefore awareness for delegated or shared work responsibilities. Specific PM actions are discussed in Chapter 5.

Key Human Performance Point

An integrated database or spreadsheet for program heat exchangers containing the schedule for cycles and refueling outages in which GL 89-13 tests or inspections and ECT tube inspections by the BOP Heat Exchanger program are to be conducted is a beneficial practice supporting budgeting, NDE service contracts, maintenance planning, test equipment calibration scheduling, and related actions.

3.4.3 Program Changes – Actions or Frequencies

It is a beneficial practice for both the system engineer as well as the BOP Heat Exchanger program owner to review PM changes for heat exchangers in the scope of the program. The site PM control process normally specifies other reviews/approvals needed to implement changes. Some utility PM procedures may only require the system engineer and not the affected program owner to review changes. In this case or when an individual program owner is not established (i.e. distributed responsibilities), it is beneficial for the program documents to acknowledge that engineers reviewing PM changes which impact the scope or frequency of NDE inspections be communicated to the individual responsible for the program's NDE budgeting and contracts. It may be appropriate at such sites to establish a requirement for periodic reviews of the PM actions and intervals for heat exchanges in the scope of the program to ensure awareness of changes and update of program documents, databases and budgets to accurately reflect the changes.

Key O&M Cost Point

It is important to ensure changes to BOP Heat Exchanger program PM actions which impact the scope or frequency of tube NDE inspections are communicated to the individual responsible for the program's NDE budgeting and contracts.

The program owner and the system engineer typically review the existing PM scope and frequency against the heat exchanger as-found condition to initiate justified changes. It is beneficial for the PM review to avoid focusing on maintaining the existing inspection scope and frequency, versus evaluating if the as-found conditions support changes to the resources expended, by considering these questions:

1. If no tubes required plugging, can the ECT inspection interval be extended? If not, why not?
2. If tubes required plugging, was the tube damage significantly beyond the plugging threshold such that it could be considered a "near-miss" and warrant more frequent NDE inspection to avoid future tube failures? Was the tube damage new or unexpected such that a pulled tube is warranted for metallurgical analysis to characterize the failure risk and future ECT intervals? If the damage type and progression was consistent with previous inspections, then can a longer ECT inspection interval be justified by accounting for the added progression in the plugging calculation?

Prior to making significant changes to a heat exchanger's PM actions due to the responses to the above questions, it is beneficial to consider the site's experience with this type material in the same or similar service conditions/environments. An individual heat exchanger may be an outlier relative to previous experience for various reasons, but it is beneficial to understand those reasons, to the extent possible, prior to making PM adjustments which differ significantly from those justified for other heat exchangers with similar materials and service environment.

Key O&M Cost Point

BOP Heat Exchanger program PM actions and their frequencies are best established based on the known material condition of the heat exchanger without preference to maintaining generic PM template intervals.

3.4.3.1 License Renewal and BOP Heat Exchanger Program Commitments

The nuclear license renewal process to extend the original 40 year operating license for an additional 20 years has been applied or is expected to be applied to most US nuclear units. While the renewed license and its associated commitments are unit specific, in general the process applies the guidance in NUREG-1801, Generic Aging Lessons Learned (GALL) Report (ref. 4).

The aging management credited in NUREG-1801 to support license renewal includes numerous references to heat exchangers and their degradation mechanisms. The station's license renewal submittal may have credited in the site BOP Heat Exchanger program or actions implemented by the program to address heat exchanger degradation. New actions, as described in Section 5.7, may also be attributed to the program by the license renewal submittal. It is important for program owners to be aware of license renewal commitments and content related to their program. The license renewal commitments are not in effect until the period of extended operation (i.e. after initial 40 year license period), however, it remains important to be aware of such commitments to ensure the BOP Heat Exchanger program is operated in a manner consistent with the pending commitments or is addressing and tracking changes to be addressed prior to the period of extended operation.

3.4.4 Tube Plugging Decisions per ECT Results

Tube plugging decisions often involve the program owner and system engineer, with input from the ECT analyst. Many sites utilize a tube plugging calculator to establish standardized guidance for tube plugging. Tube plugging calculators are discussed in Section 5.2.1.3. Establishing acceptance criteria for the tube inspection results of safety related heat exchangers is an NRC expectation per 10CFR50 Appendix B Item V.

Related decisions include the need for tube stabilization (see guidance in Section 5.2.1.6 and tube removal for metallurgical analysis (see guidance in Section 5.2.1.5).

3.4.5 Tube Plugging Map Configuration Control

It is beneficial for program documents to identify the responsible individual for initiating updates to configuration control records for tube plugging.

Safety related heat exchangers normally require documentation of tube plugging in permanent plant records. This may be through controlled drawings or similar means. Control of tube plugging maps for non safety related heat exchangers may vary from controlled drawings to tubesheet maps maintained in uncontrolled ECT data management software.

3.4.6 Budgeting and Scheduling

Budgeting for the BOP Heat Exchanger program commonly addresses ECT contract services and may be the responsibility of the program owner, maintenance, outage organizations, or an NDE group.

The program owner is commonly relied upon to maintain an integrated schedule of program actions. This scheduling tool provides input to budgeting and similar resource allocation planning activities for the site. The program schedule of inspections/tests is often needed 1 to 2 years in advance to provide adequate funding through the site’s budgeting process.

Since the program actions are typically implemented by the site PM program, inadequate resources to implement the scheduled program inspection scope is generally addressed by PM program processes, including consideration of grace periods and PM deferral. Budget constraints and the lack of other resources are not a technical basis for changes to heat exchanger maintenance intervals. As noted in Section 3.4.3, the PM actions and intervals established for each program heat exchanger are intended to be appropriate for their known material condition, applicable industry experience and/or changes to operating conditions. Accordingly, inadequate resources to implement the scheduled program maintenance actions is equivalent to a PM deferral by site management (given their control over budget/resource allocation), which is generally best addressed through the reviews and approvals established for that process. The deferral process should allow a documented means for the program owner to defend the basis for the current interval as well as potential risk(s) associated with deferral, and therefore allow site management to make a risk-informed decision regarding resource allocation before implementing an over-ride type deferral of program work.

3.4.7 Trending and Margins

Since the BOP Heat Exchanger program, as described in this guide, is focused on pressure boundary structural degradation versus thermal performance monitoring, there are limited parameters which provide meaningful trends. As noted in Section 3.1, the system engineer for the associated heat exchanger is responsible for tracking/trending thermal performance issues, other than for the SW heat exchangers addressed by the GL 89-13 program. Thus, trended parameters for the BOP Heat Exchanger program are generally limited to tube plugging margin, but may include corrosion progression. Flaw progression within heat exchanger tubes is evaluated as part of the tube plugging decision process and is ideally conducted in conjunction with the ECT analyst by comparing previous inspection raw data with the current inspection results. Trending of flaw progression rates in tubes is typically not performed. Trending of parameters such as general ID erosion may be beneficial for susceptible heat exchangers, although an action limit or acceptance criteria for general wall loss may be difficult to establish without access to heat exchanger vibration analysis software, as noted in Section 3.4.9.

Identification of the maximum tube plugging limit for program heat exchangers and tracking the remaining plugging margin is a beneficial practice. This is often performed with a spreadsheet or database containing plugging limits, the associated design document for the limit, current plugging totals, and remaining margins. Section 3.4.9 discusses remaining life projections.

The maximum allowable tube plugging limit for safety related heat exchangers is normally established by calculations evaluating heat removal requirements for the limiting design basis event. The site’s design engineering organization is most often responsible for these calculations and accordingly would be responsible for defining the allowable plugging limit of a safety related heat exchanger if not previously established.

Tube plugging limits for non safety related heat exchangers may not be defined in design bases documents. Generic tube plugging allowances for non-safety related heat exchangers are applied at some utilities, below which no further engineering evaluation is required for tube plugging. The thermal margin included in heat exchanger design has not been a fixed or consistent value, although general trends can be considered. Most heat exchangers (other than feedwater heaters and main condensers) designed prior to 1984 had sufficient conservatism in the design methodology for a 10% plugging margin. Heat exchangers designed since 1984 generally support at least a 5% plugging margin based on the inherent conservatism of the design methods, although lower margins could have been used in more recent production. It is a good practice for the purchaser to include a tube plugging allowance in the heat exchanger specification, if a target value is desired. Otherwise it may be unwise to assume significant excess margins exist in today's large heat exchangers.

Feedwater heater and main condenser thermal design has been well established for many decades and these components may have less tube plugging margin from a thermal design perspective. However, the thermal impact from tube plugging in these services is largely an economic impact and other issues are likely to be more technically limiting.

In addition to changes in design margin by the OEM, site issues may non-conservatively impact a generic tube plugging limit, such as:

- Higher maximum cooling water temperatures than originally specified.
- Increased heat load (i.e. due to power uprates or other changes).
- Design fouling factor which does not bound system conditions.

Coordination with the system engineer on tube plugging decisions may help identify existing thermal performance margin issues which require more restrictive plugging limits.

3.4.8 Health Reporting

Long-term heat exchanger health issues and the need for major repair or replacement actions are important to be communicated to site management. Methods for communicating health issues and addressing them with the site's funding and prioritization processes may include:

- Program and/or System Health Reports
- Program Performance Indicators
- Long Range Planning Process
- Margin Management Program/Database
- Engineering Project Request Process
- Equipment Reliability "Top Ten" Process

Communication between the BOP Heat Exchanger program owner, the associated system engineers, and other affected engineering groups is important to ensure consistency when communicating heat exchanger health issues and recommended actions.

The performance indicator process is used by many engineering programs as a means of reporting program and equipment health issues. Some sites may not utilize a separate performance indicator for the BOP Heat Exchanger program, relying instead on the system engineering health reporting process to provide visibility to site management.

3.4.9 Long Range Planning/Life Cycle Management

Structured program guidance for performing heat exchanger life projection is beneficial to avoid late identification of major repair or replacement needs relative to the site's long range planning process. Guidance may specify a life projection review when tube plugging reaches an administrative limit, with updates when new ECT data is acquired.

Heat exchanger remaining life projections are commonly performed by a simple methodology, such as dividing the remaining tube plugging margin by the expected or projected future tube plugging rate to determine the remaining years or operating cycles. The accuracy of the tube plugging limit and the projected tube plugging rate both increase in importance according to the resources and impact associated with the repair or replacement project. Considerations when making remaining life projections include:

- Changes in plugging thresholds (i.e. may temporarily skew trends).
- Conservative insurance plugging applied in response to a leak, particularly if insurance plugged tubes are not follow-up inspected by NDE to validate their need to remain plugged.
- Rate of change for degradation of in-service tubes may provide a more accurate picture of anticipated future tube plugging than historical plugging data.
- Active degradation leading to recent tube plugging may be relatively localized to tubes already removed from service and not challenge nearby tubes.
- Corrective measures taken in response to tube damage may significantly reduce the rate of future tube degradation. Examples include tube-side flow reduction to reduce ID erosion damage; changes in lay-up and flushes to address aggressive pitting environments; limits to shell-side overload operation or maximum flows to reduce vibration damage; increases in feedwater heater operating level or repair/tuning of level control equipment to address periodic steam entry into a drain cooler.

A potential remaining life consideration for copper alloy tubed heat exchangers in open cooling water service is general wall thinning. This is often accompanied by pitting or localized erosion wall loss. The resulting tube plugging may continue to drive replacement, but general wall loss could require derating of the maximum allowable shell-side flow to avoid acute tube vibration damage, with the projected drop in allowable shell flow becoming unacceptable prior to the tube plugging limit being reached. Determining the reduced maximum shell-side flow limits associated with general wall thinning requires analysis software normally only available from heat exchanger vendors.

The results of remaining life projections are intended to be communicated to site personnel and management via the health reporting options discussed in Section 3.4.8.

Key O&M Cost Point

Structured guidance for performing heat exchanger remaining life projection is beneficial to avoid late identification of major repair or replacement needs relative to the site's long range planning cycle. Administrative limits, such as exceeding 50% of the tube plugging limit, can be used to trigger remaining life evaluations.

3.4.10 Operating Experience

The BOP Heat Exchanger program owner, often in conjunction with the system engineer, is normally responsible for review and disposition of industry heat exchanger operating experience (OE) from INPO[4].

Program owners may find it beneficial to maintain an electronic log of heat exchanger OE reviews. Use of an electronic program notebook allows ease of access and review of previous OE dispositions for the back-up program owner, system engineers or future program owners.

3.4.11 Industry Users Groups and Peer Interaction

Industry peer communication can provide valuable information to support improvements to program and equipment health. Most heat exchanger issues have occurred previously at one or more other sites. Thus, experience in addressing heat exchanger problems is often available in the industry. Heat exchanger program owners are encouraged to share their experiences to assist others in improving program performance. There are multiple avenues available to the program owner to request support and share information (see also Section 6), which include but are not limited to the following:

- Annual meetings/webcasts with HXPUG
- Industry conferences (i.e. EPRI BOP Heat Exchanger NDE, EPRI Feedwater Heater Technology, EPRI Condenser Technology, ASME conferences, etc.)
- Participation in EPRI Technical Advisory Groups (TAG) for technical reports
- Operating Experience reports
- Assessment support or benchmarking at other sites
- Nuclear fleet utility periodic program owner peer phone calls (as applicable)

Program owners are encouraged to make presentations at industry conferences and webcasts to share heat exchanger failures, issues, or successes with industry peers. Program owners are also encouraged to provide Operating Experience reports to INPO to distribute to industry peers for more significant degradation or failure issues. Technical libraries and collaboration bulletin boards are additional available opportunities to find and share documents, ask questions, review previous topic results, etc.

[4] Access to INPO reports and materials is restricted to organizations authorized by INPO. The information is confidential and for the sole use of the authorized organization.

The site or utility benchmarking and assessment processes available to the program owner provide structure and documentation options to formally capture peer communication and information exchange.

3.5 Qualification and Training

Qualification tasks for BOP Heat Exchanger program actions may be used to ensure adequate technical understanding of program activities. Other means such as mentoring, training programs, or similar actions may be equally effective at ensuring adequate technical knowledge and may be used in conjunction with or instead of a qualification process, as determined appropriate by the site/utility.

An experienced program owner with subject matter expertise is desirable, but it is often impractical for all program technical actions to be performed directly by the program owner. Qualification tasks or similar tools may be used to allow additional personnel to knowledgably support program actions. The most commonly implemented qualification tasks are:

1. Program Owner/Back-up Qualification
2. Program Task Specific Qualifications

Program owner qualification addresses all aspects of the program, including basis documents, design and licensing basis, site program history and operating experience, regulatory and industry guidance documents, and industry experience.

The need for task specific qualification is determined based upon several factors, including the level of detail in the procedure or work document for the activity, the complexity of the action, and the extent technical background is needed to complete the action. It is not practical to have all program technical actions performed directly by the program owner or backup engineer. Therefore, additional support capability may warrant development of qualification tasks, training, or similar tools. Actions such as computer based training modules, just-in-time training by the program owner, or similar means may be employed in addition to or instead of a task specific qualification. A BOP Heat Exchanger program less frequently requires task specific qualifications, although they may be established for visual inspections, tube plugging based on ECT results, or other actions.

3.5.1 Training

In general, the availability of industry training related to BOP Heat Exchanger programs has been limited. Communication with industry peer groups is beneficial to remain aware of training opportunities which become available. Vendor training may be periodically offered by NDE companies performing eddy current testing of heat exchanger tubes. Heat exchanger training may also be available from other professional organizations, manufacturers, suppliers, engineering firms, etc.

3.5.2 Program Owner Qualification

Qualification requirements for the program owner and their backup may consist of a qualification task or an equivalent program turnover, mentoring, or training process. Key items to consider for BOP Heat Exchanger program owner familiarity include:

- Program Documents (Corporate and Site) – Notebook, procedures, guides
- Design Basis Documents – Calculations, Engineering Reports, Specifications
- License Basis Documents – UFSAR and Technical Specifications as well as commitments and License Renewal commitments
- Industry Guidance and Technical Documents
- Health Reports and Performance Indicators
- EPRI Users Groups (i.e. HXPUG)
- Industry Experience

4
HEAT EXCHANGER TECHNICAL TOPICS

This section provides an overview of key technical topics related to heat exchanger programs. Summary information and references for additional information is presented for the following:

- Heat Exchanger Design
- Thermal Performance Degradation Mechanisms
- Mechanical Degradation Mechanisms
- Heat Exchanger Corrosion Mechanisms
- Cooling Water System Chemical Treatment
- Industry Issues – Awareness Points

4.1 Heat Exchanger Design

This section provides a brief overview of design standards and codes and the three principal heat exchanger types: shell and tube, air-to-water, and plate and frame. Heat exchanger program owners are directed to reference sources for additional information, with the EPRI Heat Exchanger Maintenance Guide (ref. 20) providing detailed discussion of heat exchanger design and the EPRI Materials Handbook for Nuclear Plant Pressure Boundary Applications (ref. 21) providing detail on materials of construction.

4.1.1 Design Codes and Standards

4.1.1.1 Design Code

American Society of Mechanical Engineers (ASME), Boiler and Pressure Vessel Code (B&PV): The ASME B&PV Code, Section VIII, Div. 1 addresses pressure vessels applicable to power plants. This section covers the physical and mechanical design requirements for pressure retaining parts in the heat exchanger including the shell, channel wall thickness, weld design, fabrication, test requirements, and allowable stress. Other sections of the Code address material standards and properties, material processing, quality of finish specification (Section II), nondestructive test methods (Section V), and welding and brazing qualifications (Section IX), nuclear power plant components (Section III), and rules for in-service inspection of nuclear power plant components (Section XI).

The ASME Code is noted for reference only, with the BOP Heat Exchanger program owner typically having limited need for the design details in the Code. The heat exchanger design and construction requirements contained in Section VIII (or Section III for some safety related applications) are applicable to new construction, although the requirements may be referenced by the Design Engineering group, National Board inspectors, or others for specific applications. Refer to Section 7.1 of reference 20 for a brief discussion related to repairs and alterations to Code heat exchangers.

4.1.1.2 Heat Exchange Institute

The Heat Exchange Institute (HEI) is a trade association for utility and industrial-scale heat exchange and vacuum apparatus. The Institute concentrates its efforts on the manufacturing and engineering aspects of steam surface condensers, closed feedwater heaters, power plant heat exchangers, liquid ring vacuum pumps, steam jet ejectors and deaerators. The primary purpose of HEI is to develop standards for heat exchange and vacuum apparatus. HEI standards of interest to the BOP Heat Exchanger engineer include:

- HEI – Standards for Power Plant Heat Exchangers
- HEI – Standards for Closed Feedwater Heaters
- HEI – Standards for Steam Surface Condensers

As noted in EPRI report 1003470 (ref. 50), the HEI standards address thermal performance design, analysis, and specific physical design requirements. This includes the tube velocity, nozzle locations, temperature limitations on expanded joints, design bases consistent with but not specifically covered by ASME, allowable nozzle loads, and velocities not specified by the owner.

The HEI standards combine present industry standards, typical purchaser requirements, and manufacturer's experience to provide design criteria. The standards outline practical information on equipment nomenclature, dimensions, testing, and performance. Use of the standards enables effective communication between the purchaser and the manufacturer. The standards represent the collective experience of the member manufacturers and provide a guide in the preparation of heat exchanger specifications. The standards provide definitions of technical terms, a discussion on performance, a listing of mechanical design standards for sub-components (including code requirements), material design standards, guidance on replacement specifications, discussion of heat exchanger protection, discussion of typical installations, an overview of channel types, and an outline of typical heat exchanger internals. Appendices address issues such as operation and maintenance.

4.1.1.3 Tubular Exchanger Manufacturers Association

The Tubular Exchanger Manufacturers Association, Inc. (TEMA) is a trade association for manufacturers of shell and tube heat exchangers. TEMA Standards and software are widely used for shell and tube heat exchanger mechanical design.

The publication, “Standards of the Tubular Exchanger Manufacturers Association”, is available at www.tema.org. A table of contents for the current standards is available at their website.

The four principal topics covered include:

1. Nomenclature
2. Fabrication Tolerances
3. Mechanical Practices (tube thickness for different pressures, recommended gaskets, types of end covers, and fouling effects on heat transfer)
4. Recommended Practices (supports, lifting lugs, wind and seismic considerations)

The TEMA Standards are presented in three classes, for “R”, “C”, and “B”, each reflecting acceptable designs for various service applications (power plant heat exchangers fall into the “C” category). The standards present information on the nomenclature for heat exchangers, data on fabrication tolerances, general fabrication and performance information, a discussion on installation, operation, and maintenance, mechanical standards for the three different classes described, materials specifications, thermal standards, data on physical properties of fluids, general technical information, and recommended good practices for heat exchangers. The standards also address topics such as tube orientation, thermal expansion, heat exchanger supports, impingement protection, and heat exchanger testing.

4.1.2 Shell and Tube Heat Exchangers

The shell and tube design is the most common heat exchanger type in a power plant. Accordingly, it is important for the engineers involved with the heat exchanger programs to be familiar with the basics of this design. Diagrams and a summary of the key components of shell and tube heat exchangers are presented in EPRI report 1018089, Heat Exchanger Maintenance Guide (ref. 20). This reference provides additional detail and discussion related to basic shell and tube heat exchanger design.

4.1.3 Air-to-Water Heat Exchangers

Air-to-water heat exchangers are used in nuclear plants as room coolers, containment cooling, main turbine generators (hydrogen coolers), isolated phase electrical bus duct coolers, and other applications. Many Service Water Systems include air-to-water heat exchangers, resulting in them being associated with the GL 89-13 program. Essentially all BOP Heat Exchanger programs will include air-to-water heat exchangers.

A key design issue with some air-to-water heat exchangers is the ability to access tubes for visual inspection, ECT, or cleaning. Many cooling coils for HVAC and similar applications are constructed with copper alloy materials and brazed tubing connected to supply/return header pipes and u-bend fittings as shown in Figure 4-1. This design does not support access for inspection or cleaning and is not considered desirable for open cooling water systems due to this lack of access. Designs with removable bolted waterboxes, as shown in Figure 4-2, on each end of the tubes allow access for inspection and maintenance.

Key Technical Point

A key design aspect of some air-to-water heat exchangers is tube access for NDE and visual inspection. Designs with header pipes and u-bend fittings are not accessible for maintenance actions.

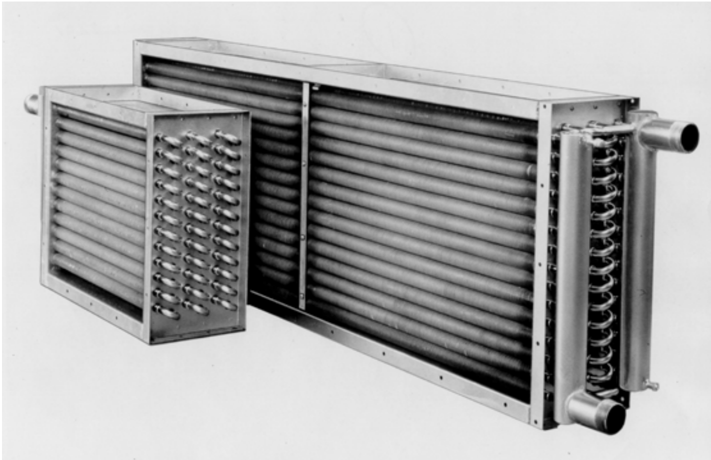

Figure 4-1
Air-to-water heat exchanger design without tube access

Figure 4-2
Air-to-water heat exchanger with removable end/cover plate

4.1.3.1 Air-to-Water Heat Exchangers – GL 89-13 Program Considerations

EPRI report 1007248, Alternative to Thermal Performance Testing and/or Tube Side Inspections of Air-to-Water Heat Exchangers (ref. 31), provides beneficial information for GL 89-13 program owners with air-to-water SW heat exchangers. The report contains pertinent information for HVAC cooling coils regardless of the method used to address GL 89-13 commitments for thermal performance monitoring (i.e. inspection/cleaning, thermal performance testing, etc.). The report describes the principal reasons difficulty is encountered when conducting thermal performance tests.

Limited access for visual inspection/cleaning is an issue for serpentine or header pipe coils. This may limit the available options and quality of results relative to ensuring required thermal performance capability. The considerations in Appendix B may be useful in establishing a basis for acceptable thermal performance as well as establishing action limits for videoprobe inspections through connection flanges, thermography of coils to detect blocked inlet pass tubes, or chemical cleaning of the coils.

The use of thermography imaging of HVAC cooling coils has been effectively used at some stations to detect inlet pass (i.e. outermost row) tube blockage due to macrofouling. The differences in tube temperatures between tubes with and without flow are evident in the thermal image of the coil. The inlet pass has a much higher susceptibility to macrofouling tube blockage in cooling coils, allowing thermography monitoring to provide reasonable in-service detection capability of tube blockage status. This tool could be used in combination with or as follow-up to periodic flow/dp monitoring of the coils.

Coils with a waterbox design with uncoated carbon steel tubesheets may be more prone to corrosion nodule occlusion/restriction issues as well as debris accumulation on tubesheet ligaments (i.e. string-like organic material such as dead filamentous algae strands, bissell threads, etc.), galvanic corrosion issues, and bypass flow issues.

4.1.3.2 Air-to-Water Heat Exchangers – BOP Heat Exchanger Program Considerations

Header pipe cooling coil design does not support access for visual inspection, ECT, or tube plugging. Typically PM actions to ensure reliability consist of periodic replacement. An “autopsy” of the initial replacement to determine material condition of the tubes and u-bends can be used to establish appropriate replacement intervals for remaining coils.

HVAC cooling coils are often constructed with copper or copper alloy tube materials, which are subject to inside diameter (ID) erosion damage (see Section 4.3.1.3), particularly in open cooling water systems. The erosion problems are often most prevalent at return bends (if applicable) and near tube inlets, with general ID erosion sometimes occurring through the full tube length.

4.1.4 Plate and Frame Heat Exchangers

Plate and frame heat exchangers are relatively new to the nuclear industry in the United States, with initial installations occurring in the mid-1980’s to replace original shell and tube heat exchangers or in new service applications. This section briefly discusses plate heat exchanger design and considerations for heat exchanger programs.

Additional information on the design of plate and frame heat exchangers is available in section 2.2 of reference 20.

4.1.4.1 Plate Heat Exchangers – GL 89-13 Program Considerations

The application of plate heat exchangers in SW systems remains limited; accordingly it is of increased benefit for program owners with this design and service combination to communicate experiences and lessons learned. Two key considerations for plate heat exchangers in GL 89-13 programs are:

- Increased macrofouling potential exists due to smaller flow passageways. The frequency and type of monitoring/testing/inspection may need to be different from that applied to tube type heat exchangers in order to achieve comparable assurance of thermal performance capability for plate heat exchangers.
- Thermal performance monitoring techniques and response actions have been developed based on experience with tube type heat exchangers. The responsible engineer should recognize the potential for differences in the fouling materials and response characteristics (i.e. rate of change) for plate heat exchangers.

Key Technical Point

Plate heat exchangers have smaller flow passageways than shell-and-tube heat exchangers, which may increase their macrofouling or blockage risk pending the adequacy of filtration. This increased macrofouling risk is their principle design limitation for open cooling water system service.

4.1.4.2 Plate Heat Exchangers – BOP Heat Exchanger Program Considerations

- ECT is not applicable since no tubes exist.
- Plate material is ideally very corrosion resistant for open cooling water service. It is important to minimize risk of MIC and/or crevice corrosion issues.
- PM actions address elastomeric gasket aging issues either via periodic replacement, monitoring techniques, and/or evaluation of acceptable consequences if addressed by corrective maintenance after leaks develop.

4.1.5 Feedwater Heaters

Feedwater heaters are specialized shell and tube heat exchangers in the regenerative power cycle which improve overall plant thermal efficiency. They are not within the scope of GL 89-13 programs, but are a significant focus for BOP Heat Exchanger programs. A summary of the design and key components of feedwater heaters is presented in EPRI Report 1003470, Feedwater Heater Maintenance Guide (ref. 50). This reference as well as the grouping of additional feedwater heater related documents in the reference section provides additional detail and discussion. EPRI sponsored industry meetings or groups which address issues related to feedwater heater are noted in Sections 6.1, 6.3, and 6.5.

4.1.6 Main Condensers

The condenser for the main turbine is another specialized shell and tube heat exchanger and is by far the largest heat exchanger in the BOP Heat Exchanger program. Main condensers are not in the GL 89-13 program. Main condenser design varies considerably from other shell-and-tube heat exchangers. This program guide focuses on tube integrity issues and does not address condenser expansion joints (commonly referred to as the “dog bone”), spargers, deflector or shield plates, air removal support equipment, waterbox vacuum support equipment, or various related main condenser topics. Program owners and system engineers responsible for main condensers are referred to EPRI Report 1003088, Condenser Application and Maintenance Guide (ref. 68), as well as the grouping of additional condenser related documents in the reference section. EPRI sponsored industry meetings or groups which may address condenser topics are noted in Sections 6.1, 6.3, and 6.4.

4.1.7 Moisture Separator Reheaters (MSRs)

Moisture separator reheaters (MSRs) are another specialized shell-and-tube heat exchanger in nuclear power plants. They function to remove moisture from the wet exhaust steam from the high pressure turbine and to reheat the dried steam into the superheat region before it flows to the low pressure turbines. Some plants have only moisture separators without reheat capability.

MSRs are not in the GL 89-13 program. They may be in the BOP Heat Exchanger program, but may be delegated to the system engineer, turbine group, and/or plant performance engineer due to their specialized design. Most MSRs in US nuclear plants have 439 stainless steel tubes, which is considerably more difficult to obtain high-quality and cost-effective NDE data compared to many other materials. The responsible engineer is directed to EPRI Report TR-106345, Moisture Separator Reheater Source Book (ref. 43) for additional information. The EPRI sponsored periodic industry meetings noted in Section 6.3 often include discussion on NDE technology related to inspection of ferritic stainless steels such as type 439.

4.2 Heat Exchanger Thermal Performance Degradation Mechanisms

Thermal degradation in nuclear plant heat exchangers occurs primarily due to fouling, less frequently due to bypass flow, and occasionally due to maintenance assembly errors or operational issues such as inadequate venting. The most common causes of thermal degradation related to fouling and bypass flow are discussed in additional detail in the sections below.

Both the GL 89-13 program and BOP Heat Exchanger program rely upon System Engineering as the responsible engineering group to monitor in-service heat exchanger performance, if monitoring capability exists. This includes review of data gathered by Operations and other groups. The plant thermal performance engineer also monitors the principal steam cycle heat exchangers such as the main condenser, feedwater heaters, and MSRs.

Chemistry controls are relied upon by the GL 89-13 program and BOP Heat Exchanger program to directly or indirectly address many potential causes of thermal performance degradation. Chemistry parameters provide indirect monitoring of heat exchanger thermal performance since the chemical treatment is a vital part of maintaining fouling within design limits.

4.2.1 Macrofouling

The definition of macrofouling in EPRI report 1003320 (ref. 29) is as follows:

Macrofouling – Fouling with large materials, such as the collection of debris (leaves, sticks, plastics), biomass, macroorganisms, corrosion products, and eventually non-suspended solids (solids coming out of suspension due to the reduction in flow velocity caused by the blockage of the primary macro-foulants). This type of fouling reduces flow through heat exchanger tubes, and may eventually prevent flow and reduce the active surface area of the heat exchanger, thereby lowering total heat transfer (Q).

Macrofouling consists of large material, most often at the tubesheet but possibly lodged down the tube(s) or deposited in the tubes due to sedimentation of suspended solids. Some macrofouling materials can be present in any heat exchanger application, but many are exclusive to open cooling systems, where macrofouling is most widely seen. Macrofouling sufficient to noticeably reduce thermal performance is normally accompanied by other system effects such as reduced flow and increased pressure drop.

Debris or foreign material fouling may be biological (sea grass, sticks, fish) or non-biological (rocks, silt, coatings) with sources external or within the system. Sources of debris and foreign materials from within the system may include the following:

- Delaminated coatings or liners from pumps, piping, or intake bays.
- Dislodged corrosion nodules or tubercles (more common in intermittent service systems).
- Failed component parts such as rubber valve seat liners or gasket material.
- Flashlights, tools, FME barrier materials, or other items in the system due to poor FME practices.

Macrofouling sources such as live bi-valves may be present in the system or heat exchanger, due to ineffective chemistry controls, without initially causing a large pressure drop or other symptoms. This material may become an acute problem following a sudden mortality event such as chemical treatment or thermal shock which releases large numbers of shells, or a high velocity alignment which picks up settled shells, either of which may allow them to accumulate on tubesheets. Biological related macrofouling may also result from string-like materials which are individually capable of passing through pump discharge strainers and the heat exchanger tubes (i.e. grass, dead filamentous algae strands, bissell threads from zebra mussels, etc.), but catch and accumulate on the tubesheet ligaments between tubes. The material buildup may occlude the tube opening fully or allow material to bridge the tube opening with a porous layer (Figure 4-3).

Figure 4-3
Example of macrofouling buildup on tubesheet ligaments

4.2.1.1 Sedimentation

Sedimentation is a type of macrofouling in open cooling water systems caused by the deposition of suspended matter in the heat exchanger tubes. Once-through systems may experience periods of high suspended solids loading due to environmental changes such as high river flows, while recirculating systems, which rely on evaporative cooling from cooling towers or sprays, can experience high suspended solids due to evaporative cycle-up of make-up water solids.

Throttling cooling water system flow in response to low water temperatures can cause sedimentation due to reduced tube velocities. Sedimentation of normally isolated heat exchangers may occur due to leakage past isolation valves. Sedimentation of individual tubes may be the result of reduced velocity due to partial blockage of flow through the tube.

4.2.1.2 Program Strategies for Macrofouling

- Chemical treatment to minimize growth of biological macrofoulants (e.g. bi-valves).
- Pump discharge strainers to prevent entry of materials capable of blocking tubes.
- FME controls to avoid debris entry during maintenance.
- PM of upstream components to reduce the risk of component part failure debris.
- Application of coatings and inspection programs on upstream piping and components.

Maintaining fluid velocity >3 ft/s (0.9 m/s) is generally recommended to avoid sedimentation, although variations in the suspended solid size and loading both influence the velocities needed to maintain materials in suspension. Periodic high velocity flushes, if possible, can help reduce or minimize sedimentation load in tubes.

Chemical treatments may be added to assist in maintaining suspended solids in suspension. Blowdown and makeup are normally used in recirculating open systems to reduce the suspended solids loading of open cooling systems.

Key Technical Point

Maintaining tube fluid velocity >3 ft/sec (0.9 m/s) is recommended to avoid sedimentation, although variations in suspended solid size and concentration both influence the velocity needed to maintain materials in suspension. Sedimentation may be a seasonal occurrence due to cooling water flow reductions during periods of low water temperatures.

4.2.1.3 Susceptible Designs/Materials

- Heat exchangers with tube velocities <3 ft/s (0.9 m/s) have higher susceptibility to sedimentation.
- Smaller tube sizes are more susceptible to macrofouling blockage.
- System piping configuration can influence the distribution of macrofouling materials. Heat exchangers receiving flow from bottom tapping tee or branch connections or flow through straight legs of tees may experience higher macrofouling than those receiving flow from upward branching tees.
- Heat exchangers in intermittently operated open cooling water systems with carbon steel pipe may experience higher incidence of corrosion nodule macrofouling than seen in normally operating systems.

- Recirculating open systems using a spray pond or cooling tower are less vulnerable to many of the macrofouling debris issues in once-through cooling water systems. However, recirculating systems which do not include pump discharge strainers may warrant additional actions such as increased inspections and heightened awareness for foreign material exclusion at the UHS reservoir to reduce macrofouling risks.
- Cooling systems with internal bi-valve growth and reliance on periodic shock treatments to control excessive infestations are likely to experience higher macrofouling blockage.

4.2.1.4 Plate Heat Exchangers

Plate heat exchangers generally have higher macrofouling susceptibility than shell-and-tube heat exchangers due to the small flow passageways between plates compared to the commonly used ¾ inch or 5/8 inch (19 or 16 mm) outside diameter (OD) tube sizes. Improved strainer or filtration capabilities as well as dp and flow monitoring often accompany plate heat exchanger installations to reduce the macrofouling potential and accommodate more frequent monitoring.

4.2.2 Microfouling

The definition of microfouling in EPRI report 1003320 (ref. 29) is as follows:

Microfouling – Deposits on the tube ID surface nominally comprising a film of a combination of microorganisms, their associated slime, and entrapped solids. Another common form of microfouling is scale. Microfouling deposits can reduce the overall heat transfer coefficient (U), and lower total heat transfer (Q) by the heat exchanger.

In addition to degrading heat exchanger thermal performance, microfouling can also be damaging to the tubes (with the exception of titanium and the most highly alloyed stainless steels) via waste byproducts, under deposit corrosion, or related corrosion dynamics.

Open cooling systems experience microfouling from biological agents such as slime or bacteria, from scaling mineral deposition, and potentially from chemical precipitates associated with the chemical treatment of a recirculating system (i.e. cooling tower or spray pond). Biological microfouling may occur in lube oil systems subject to water intrusion (such as turbine seal oil) and has occurred in closed loop systems where chemical treatments may provide a nutrient source for microorganisms. The INPO[5] operating experience (OE) database contains examples.

Mineral scale microfouling occurs when the solubility limit is exceeded based on elevated tube wall temperature, causing solids to plate onto the tube wall. Typically, the resulting scale deposits cause significant thermal performance losses and are hard to clean, calling for chemicals, high pressure water jets, or aggressive mechanical means. Scaling susceptibility is dependent on the mineral content of the cooling water source.

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[5] Access to INPO reports and materials is restricted to organizations authorized by INPO. The information is confidential and for the sole use of the authorized organization.

4.2.2.1 Program Strategies for Microfouling

Chemical treatment is relied upon to minimize growth of biological microfoulants (e.g. bacteria and slimes) in heat exchanger tubes. (see Section 4.5)

GL 89-13 programs normally rely on thermal performance tests if microfouling is an issue. Visual inspection for GL 89-13 thermal performance assumes fouling caused by macrofouling or it relies on thermal tests with visual inspection to validate microfouling acceptability.

Mineral scale microfouling is controlled via a combination of chemistry monitoring, chemical treatment, thermal testing/monitoring, and periodic inspection/cleaning.

Maintaining tube velocities of 6-7 ft/sec (1.9-2.1 m/s) or more has been found to significantly reduce microfouling in open cooling water systems compared to lower velocities.

> **Key Technical Point**
>
> Maintaining tube velocities of 6-7 ft/sec (1.9-2.1 m/s) or higher has been found to significantly reduce microfouling in open cooling water systems compared to lower velocities, although velocities in this range may be detrimental to long-term service life for copper and brass tubes.

4.2.2.2 Susceptible Designs/Materials

- Low tube velocities have higher susceptibility to biological microfouling.
- Copper, arsenical copper, and 90-10 copper-nickel tubes have lower biological microfouling susceptibility due to copper's bio-toxicity.
- Mineral scaling potential is increased at elevated service temperatures due to the inverse solubility of materials such as calcium.

4.2.3 Bypass Flow

Bypass flow on the tube side is only applicable to multi-pass heat exchangers and refers to leakage past divider or partition plates, which are intended to separate the flow chambers and force flow through the tubes. Bypass is most often due to gasket leakage or gasket failure, but may occur at the divider plate due to through-wall corrosion, weld cracks, plate bowing or plate failure. In small heat exchangers with dividers in a removable head, improper positioning of the head during assembly can block or bypass flow passages (see Section 4.6.3).

4.2.3.1 Program Strategies for Bypass Flow

- Detection of reduced thermal performance due to bypass flow can be through temperature effectiveness monitoring or thermal performance testing. Reduced thermal performance due to bypass flow can't be differentiated from fouling until the heat exchanger is opened.
- Monitoring for bypass flow at gaskets sealed by the external cover may be possible with thermography or surface temperature indications across the cover.
- Visual inspection for evidence of gasket failure or leakage paths around divider/partition plates is a principal means of detecting bypass flow.
- Since bypass flow does not degrade flow or dp, hydraulic monitoring is ineffective.

4.2.3.2 Susceptible Designs/Materials

- Bypass flow from gasket leakage generally does not result in significant loss of thermal performance other than in applications with high tube-side temperature changes.
- Most multi-pass heat exchangers rely on the cover to compress and seal the partition plate gasket versus using a separate internal bolted pass partition cover. Loss of gasket sealing between the divider plate and cover/head may be caused by a combination of:
- Corrosion damage to the edge of the carbon steel divider plate
- Poor or marginal gasket surface facing/fit-up (original or post-maintenance/repair)
- Failure to maintain gasket position during assembly (i.e. rotation, slippage, etc.)
- Low gasket compressive load in the cover mid-span due to flange rotation effects
- High dp or hydraulic shock events
- Marginal or improper gasket selection for the application
- Improper installation of the reversing head of small four-pass heat exchangers has occurred in the industry resulting in bypass flow (see Section 4.6.3).
- Plate heat exchangers are not susceptible to bypass flow, since gasket leakage is external.
- Air-to-water heat exchangers with bolted waterboxes (Figure 4-2) may be susceptible to bypass flow. The air side may also be subject to bypass at failed or improperly installed coil air dams.

4.3 Heat Exchanger Mechanical Degradation Mechanisms

This section addresses common mechanical or structural degradation mechanisms for tube-type heat exchangers. (For plate heat exchangers, see reference 20, Section 4.3)

4.3.1 Tube Damage

Tube damage is the most prevalent cause of heat exchanger failures, heat exchanger corrective maintenance, and heat exchanger replacement. Preventing tube leaks is the primary function of ECT inspections and of the BOP Heat Exchanger program.

Tube damage types are briefly described in this section. Discussion of the response actions to tube damage commonly reported in ECT inspections is provided in Appendix E.

Tube material significantly influences the damage mechanisms and associated failure potential for a given service application. An overview of the most commonly used heat exchanger tubing materials, their properties and failure modes is provided in Section III of reference 21. It is beneficial for the BOP Heat Exchanger program owner to understand the damage mechanisms applicable to the tube material and service combinations at their station. Table 4-1 provides a comparison of general susceptibility to degradation for commonly used tube materials. Table 4-2 provides a similar comparison including the major service applications.

Table 4-1
Heat exchanger tube material failure susceptibility

	Component Materials				
Type of Failure	**Brass**	**Copper Nickel (CuNi)**	**Types 304/316 Stainless**	**AL6XN High-Alloy Stainless**	**Titanium**
ID Erosion	Susceptible	Good	Better	Best	Best
OD/Impingement Erosion (condensers)	Susceptible	Good	Better	Best	Good
Stress Corrosion	Susceptible	Low Susceptible	Susceptible	Better	Resistant
Pitting	Susceptible	Low Susceptible	Good*	Best	Best

*304 and 316 stainless steels are susceptible to MIC and MnO_2 pitting

Table 4-2
Tube material susceptibility to common degradation types by service application

	Support Wear	Pitting (Corrosion, MIC, Mn)	ID Erosion	OD Erosion (Cond-enser)	Cracking	Tube-to-Tube Wear	Ammonia Grooving
Open Cooling Water							(Condenser Only)
Titanium	*					*	
304/316 SS	x	X			*	*	
High Alloy SS	*					*	
Brass/Copper	X	XX	XX		x	*	
90-10/70-30	X	X	*		x	*	
Closed Cooling Water							
304/316 SS	x				*	*	
Brass/Copper	x	*	x		x	*	
90-10/70-30	x	*			x	*	
FWH							
304/316 SS	X			*	*	X	
Condenser							
Brass	X	XX	XX	XX	X	x	XX
90-10/70-30	X	XX	*	XX	x	x	
304ss	*	X		x	*	x	
Titanium	*			X		*	
High Alloy SS	*			*(rare)	*	*	
PM Action	ECT	ECT	ID Measure	ECT & Vis.	ECT (special)	ECT	ECT

Key: XX=common/prevalent; X=moderately frequent; x=occasionally; *=rare; blank= not applicable

4.3.1.1 Cracking

Tube cracking represents a potentially significant structural threat. Crack progression rates can be difficult to predict. Tube failures due to cracking may occur as circumferential breaks with larger leakage compared to other tube failures. Additional cracked tubes in the vicinity increase the risk of rapid failure progression. Circumferential cracks are generally not detectable with the commonly used eddy current bobbin probes since only the axial extent of the flaw influences the signal. Alternative probe types or probe combinations can be used if cracking is suspected.

Cracking from high-cycle fatigue occurs most frequently at rigid attachments such as tubesheets and supports and at stress risers. Fatigue failure of a tube near the tubesheet may be due to hardening from tube movement. Stresses at the tubesheet roll transition region can provide a source of residual stress or the stress riser from the fixed node point of the tube restraint under high vibratory excitation may generate the necessary stresses. Cracking near the back of the tubesheet may also be due to tube rolling errors during assembly, such as if the roll extended past the tubesheet or if the roll in the tubesheet was excessive and over expanded the tube.

Figure 4-4
Sheared tube due to stress corrosion cracking

4.3.1.1.1 Susceptible Materials and Service

Chloride stress corrosion cracking may occur in austenitic stainless steel tubes. Stress corrosion cracking of Admiralty brass tube material has been reported in open cooling water systems. Ammonia is a recognized accelerant for brass tube cracking, although it is typically limited to condenser service. Putrification of decaying organic matter, such as following shock treatment kills of significant bi-valve infestations, is suspected of being capable of releasing sufficient ammonia to cause rapid cracking and failure of brass tubes. Additional discussion of cracking susceptibility and causes for the most commonly used heat exchanger tubing materials is provided in Section III of reference 21.

> **Key Technical Point**
>
> Specialized ECT probes may be needed to detect tube circumferential cracking. Cracking has a higher progression uncertainty, may cause larger initial leaks due to sheared tubes and leakage may progress rapidly if adjacent tubes are also cracked.

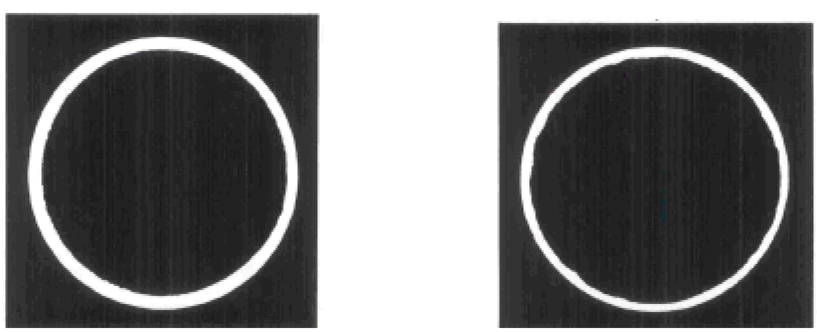
4.3.1.2 Dents

Dents may result from heat exchanger manufacturing and handling, leaving numerous affected tubes grouped at one or more support plates. Dents may also be due to loose parts or foreign material, and occasionally due to high thermal stresses in straight tube heat exchangers or even due to shell-side water hammer transients.

4.3.1.3 Erosion – ID General Wall Loss

Tube ID erosion commonly occurs in copper based (i.e. copper, brass, copper-nickel) tube materials in open cooling water systems. Erosion damage may occur as localized metal loss similar to pitting, which is readily detected by ECT, or as general wall loss, which is not easily detected. Tables 4-3 and 4-4 provide comparisons of velocity effects and ID erosion susceptibility for various common tube materials.

As noted in Section 5.1.1, the PM actions for copper based tubes in open cooling water systems include periodic ID measurements to check for general ID wall loss. Visual inspection at the tubesheet may indicate the presence of tube erosion. Figure 4-5 shows the differences in the appearance of tube ends with and without ID general erosion.



w/o ID erosion   with ID erosion

Figure 4-5
General ID erosion at tube outlet

Key Technical Point

Tube ID erosion commonly occurs in copper based tube materials in open cooling water systems and is strongly influenced by water velocity. Localized metal loss, similar to pitting, is readily detected by ECT, but general wall loss is often not detected without ID measurements. General wall loss, if present, may vary significantly within the tube bundle as well as within individual tubes. It is often most severe within the first several inches of the tube but may extend full length.

4.3.1.3.1 Susceptible Materials and Service

Tube material strongly influences the susceptibility to ID erosion, as evidenced by the data in Tables 4-3 and 4-4. The location, orientation, and geometry of the heat exchanger inlet piping may also influence ID erosion. A short distance between the inlet pipe nozzle and the tubesheet (<6 inches or <15 cm) also increases susceptibility to tube inlet end erosion. Orientation of the inlet pipe which directs the flow toward the face of the tubesheet at close range, can lead to severe erosion. A sharp turn (i.e. 90º elbow) in the inlet pipe immediately before entering the channel may result in turbulence causing increased tube inlet erosion. Tubes protruding from the tubesheet face can generate local eddy effects and erosion problems extending into the tubesheet.

Erosion resistant coatings, thin-wall erosion resistant tube inserts, and inlet nozzle flow diffusers have all been used successfully to reduce tube end erosion. These approaches are less likely to be effective in addressing full tube length general erosion.

High water velocity is a significant factor in tube erosion. Susceptibility to erosion can be reduced by maintaining velocities below industry guidance for the tube material, although variations in that guidance exist, as noted in Table 4-3. Acceptable tube velocities in open cooling water systems are affected by the amount of suspended solids and sediment in the water, potentially resulting in erosion damage even with tube velocities below industry guidance values.

Table 4-3
Tube ID erosion velocity thresholds

Material	ID Erosion Velocity Limit (ft/s)	Sources (reference #)
Copper, Arsenical	6-freshwater (1.8 m/s)	EPRI Matl. Handbook (21)
Admir. Brass	3 to 5 (0.9-1.5 m/s) 5 (1.5 m/s) 6 – freshwater (1.8 m/s) 8 – freshwater (2.4 m/s)	(98) (67) Olin Fineweld Tube Co. (21)
90-10 Cu-Ni	8 – salt water (2.4 m/s) 9 – salt water (2.7 m/s) 10 – freshwater (3 m/s) (minimum 6 ft/s (1.8m/s) to avoid fouling/pitting)	Olin Fineweld Tube Co. (21) (21) & (67) (21)
70-30 Cu-Ni	10 – salt water (3 m/s) 12 – salt water (3.6 m/s) 15 – fresh water (4.6m/s)	Plymouth Tube Co. (21) (21)
304/316 SS	30+ (9+ m/s)	Plymouth Tube Co.
Super SS	100+ (30+ m/s)	Plymouth Tube Co.
Ti Gr2	100 (30 m/s)	Plymouth Tube Co.

The results of sand erosion testing at 45 ft/s (13.7 m/s) velocity are presented in Table 4-4 below:

Table 4-4
Tube ID erosion from solids

Material	90-10 Cu-Ni	AL6XN	Sea-Cure	Ti – Gr2
Weight loss (mg)	18	6.1	4.3	2.4

4.3.1.4 Erosion – OD Water Droplet Impingement Wall Loss

Tube OD erosion occurs in steam condensing service with entrained moisture, and is therefore primarily restricted to condenser tubes (sometimes seen in FWH with non-stainless steel tubes).

4.3.1.4.1 Susceptible Materials and Service

Table 4-5 presents a comparison of the susceptibility for common materials to OD impingement erosion damage. Since industry OE reports have included OD erosion even in Sea-Cure stainless steel condenser tubes, which per Table 4-5 has the highest relative resistance to impingement erosion, essentially all materials have some susceptibility to this issue, pending the severity of the impingement.

Table 4-5
OD erosion resistance based on water droplet impingement tests

Material	Admiralty Brass	70-30 Cu-Ni	Ti – Gr2	304/316 SS	AL6XN	Sea-Cure
Hardness Value (HV)	60	135	145	165	200	240
Relative OD Erosion Resistance	0.4	0.8	1.0	2.0	7.0	7.2

4.3.1.5 Pitting

<u>ID pitting is the most common tube degradation mechanism in open cooling water systems.</u> Pitting damage is often not structural in nature, meaning the flaw must progress to 100% depth before there is risk of failure/leakage. Isolated pitting does not structurally weaken the tube due to strength provided by the shoulder effect of surrounding nominal thickness tube wall. Tightly clustered or bridged pitting can degrade or in extreme cases eliminate the shouldering effect due to the reduction in surrounding sound metal. Cases of very high density pitting are less frequently seen and are often associated with improper metal selection for the service conditions and/or significant loss of chemistry controls.

In soft metal tubes (i.e. Admiralty brass, copper, and sometimes 90-10 Cu-Ni), ID tube damage similar to pitting may be due to localized erosion (see Figure 4-6 and Chapter 11 pictures in ref. 98).

Figure 4-6
Copper alloy tube with ID pitting and erosion

4.3.1.5.1 Susceptible Materials and Service

Admiralty brass is the most susceptible material for pitting degradation. Titanium and highly alloyed stainless steels are largely immune to ID pitting in nuclear plant cooling water service. Type 304 or 316 stainless steels are fairly resistant to pitting, but when conditions exist to initiate pitting such as MIC or manganese pitting in open loop cooling systems, it may progress rapidly. Pitting in susceptible stainless steels is generally characterized by very small openings, with larger sub-surface volume (see Figure 4-7). The associated leak rates are normally very small.

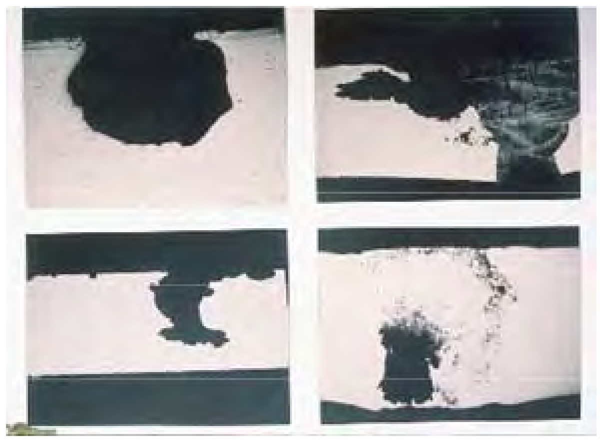


Figure 4-7
Pitting corrosion damage of stainless steel

Pitting should not be an issue in properly controlled closed loop cooling water systems. The resistance to corrosion pitting attack in stainless steel materials is often compared using the Pitting Resistance Equivalent number (PRE or PREn). The susceptibility to pitting and crevice corrosion decreases as alloy content increases, specifically chromium, molybdenum, and nitrogen content. Susceptibility increases as temperature and impurity content in the water increase. Reference 21, Section 10.4 provides additional detail on stainless steel tubing material corrosion susceptibility with the PREn values for commonly used materials in Table 3-13 of that document. Sections 4.4.2.3 and 4.4.2.5 include additional discussion of pitting corrosion and MIC/manganese corrosion.

4.3.1.6 Manufacturing Defects

It is often not possible to definitively prove a defect has been present since original construction and whether it was subjected to hydrostatic pressure testing. Baseline ECT examination of all tubes is beneficial prior to placing a new heat exchanger in service to identify the initial manufacturing related tube indications. Older heat exchangers are unlikely to have baseline ECT data, or if performed, the raw data may not be available, in a readable format, or of sufficient quality to validate the presence of an original defect.

Many heat exchanger tubes, even when new, may have imperfections detectable by ECT, but not rejectable by the tube mill or heat exchanger manufacturer unless additional quality control requirements are specified by the purchaser. These imperfections include incomplete fusion in the seam weld, nicks or buff marks from grinding, weld spatter, dents, scratches, gouges, or abrasions from handling or assembly. Most of these imperfections do not represent a threat to tube integrity since the damage mechanism is not active and the defect size is small (i.e. not structurally significant even if a high reported through-wall depth).

4.3.1.7 OD Impact/Damage

There are multiple possible sources of tube OD damage, many are manufacturing related as discussed in Section 4.3.1.6, with only a few caused by active mechanisms. Loose parts or debris can result in OD tube damage, and if wedged in close proximity to the tube can cause on-going damage. OD indications may be due to pitting damage if open cooling water is supplied to the shell side of the heat exchanger, although this is not a common or recommended design.

4.3.1.8 Tube Wear

4.3.1.8.1 Tube Wear at Support or Baffle Plates

Wear at support or baffle plates may occur in normally operating heat exchangers. Wear at plates typically affects sufficient tube volume to be structurally significant. Wear is often associated with high local tube vibrations. Heat exchangers with tube material that is more wear resistant than the plate material (i.e. 304 SS tubes with carbon steel support plates) will often experience greater loss of the plate material than tube material. The loss of plate metal allows larger tube movement or displacement due to the increased annular gaps at the plates. As the tube becomes less restrained and is able to deflect more, the wear rates may subsequently increase. The high vibrations associated with the wear may also cause work hardening of susceptible tube materials at restraint points such as support plates where the tube is bending and flexing. Tube degradation may include a more dynamic set of local conditions than simple loss of tube wall thickness where support or baffle plate wear is occurring and these dynamic interactions may result in fatigue or stress cracking which can rapidly lead to failure.

Figure 4-8
Tube wear at support or baffle plates

4.3.1.8.2 Tube-to-Tube Wear:

Tube-to-tube wear is not an expected condition for a heat exchanger operated within normal design limits. It indicates one or more of the following likely exists:

- Excessive cross-flow velocities or tube excitation
- Tube spans are excessive per original design
- Tube supports have changed such as due to ligament wear allowing greater movement
- Tube supports have shifted due to failure of the cage restraints
- Tube stiffness has changed due to thinning

Associated complications could include localized work-hardening or embrittlement of the tube, which increases the susceptibility to cracking and failure. Similar to the discussion above for wear at plates, the tube wear may not be the ultimate cause of failure, but may combine with related dynamic degradation conditions such as a fatigue crack at the stress riser created by the tube wear. Predicting progression rates is less accurate when multiple related degradation actions are present. Tube-to-tube wear affects multiple tubes and may be accompanied by tube wear at plates, partial or missing plates, signal drift (ADI), or other related damage.

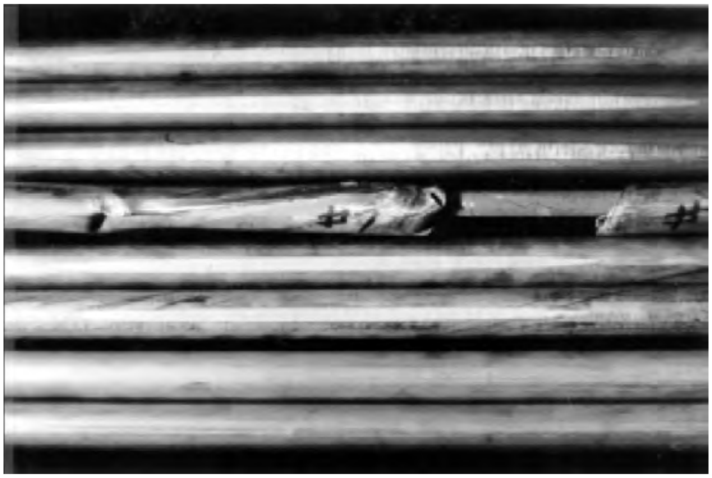


Figure 4-9
Tube-to-tube wear damage adjacent to a tube failure

4.3.2 Shell and Internal Structure Damage

4.3.2.1 Shell Damage

Damage to heat exchanger shells is avoided in most applications by the proper selection of materials and chemistry controls applied to the process fluid. Shell damage has occurred in:

- Feedwater Heaters.
- Open cooling water on the shell side of a heat exchanger w/ a carbon steel shell.
- Blowdown heat exchangers with steam condensing on the shell side.

4.3.2.2 Support/Baffle Plate Wear

Support or baffle plate wear is normally the result of tube vibration. The wear increases the hole ID, can change the damping and natural frequency of the tube for vibration effects, and increase the displacement range of the vibrating tube. In severe cases, tube vibration may cause complete loss of the plate ligaments separating tubes. Degraded or missing baffle plates can be detected during the ECT inspection, although since it is not a tube defect, it may not be reported unless this expectation is clearly communicated to the NDE service provider. This type of damage is most commonly seen in feedwater heaters, but can occur in other heat exchangers, particularly where high tube vibrations exist with tube materials that are harder than plate materials.

Severe plate wear at multiple adjacent tubes may allow star shaped sections of plate to become disconnected from the rest of the plate and move or be washed out of the tube bundle. The ligament stars may remain intact around part of the tube but be missing in others. In some cases the outer edge of the plate remains in place, but the interior connecting ligaments are missing as shown in Figures 4-10, 4-11, and 4-12.

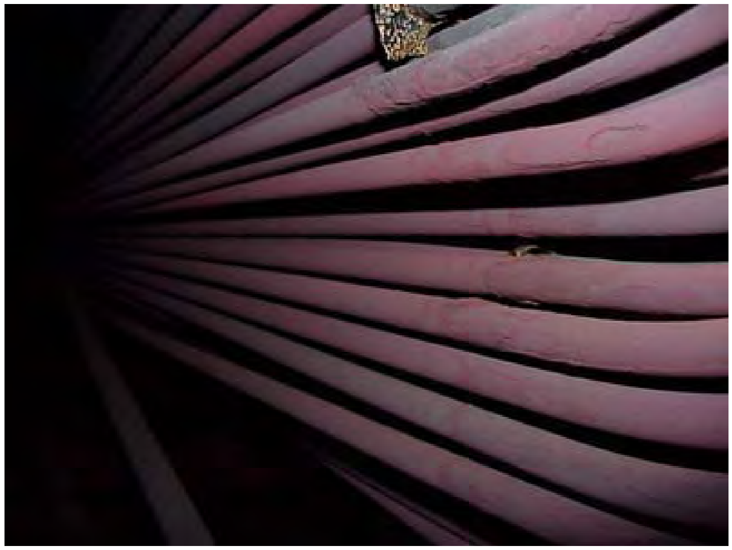


Figure 4-10
Missing support plate

Figure 4-11
Partial support or baffle plate

Figure 4-12
Baffle plate degradation

4.3.2.3 Drain Cooler End Plate Wear

This is exclusive to feedwater heaters and is similar to the partial or missing support plate condition, but occurs at the thicker drain cooler end plate. Drain cooler end plates were typically 1 to 1-1/2 inches (2.5-3.8 cm) thick in older feedwater heaters, but are >3 inches (>7.6 cm) thick in more recently built (last 20 years) heaters. The thicker end plate allows steam drawn into the lower pressure drain cooler through the annulus around the tube to be condensed by the cooler tube wall. This minimizes steam entering the drain cooler and associated local tube excitation caused by steam bubble collapse. The end plates experience erosion, corrosion, and wear from the steam/condensate flow drawn into the drain cooler around the tubes as well as abrasion wear caused by tube vibration.

The plates provide tube support and direct water across the tubes for maximum thermal efficiency. The drain cooler end plate is not a baffle plate to direct flow, but is an internal pressure boundary for the drain cooler. As such, the consequences of end plate damage can be more severe than support or baffle plate damage, since the end plate opening allows unquenched steam to enter the drain cooler region. This can contribute to elevated drain outlet temperatures and more significantly, increase tube vibration where the steam collapses as it is cooled by the tubes or the sub-cooled drain flow. If the drain cooler has been sufficiently breached such that there is not a pressure difference across the plate, then the associated vibration problems may diminish, although drain cooler approach temperatures will be correspondingly high with only limited sub-cooling of the exiting drain flow occurring.

4.3.2.4 Impingement Plates

Impingement plates are located below shell-side inlet nozzles to distribute the incoming flow and avoid direct impingement of the tubes immediately below the nozzle. Plates with welded seams may experience weld failure due to the high vibration conditions. Plate attachment welds have also experienced failures, as well as failures of plate supporting rods. A failed impingement plate may damage tubes directly by wearing against tubes, or indirectly by allowing tube damage from excess cross-flow vibration or direct impingement erosion due to the inlet flow stream no longer being deflected and redistributed. Failures are most commonly seen in feedwater heaters, but can occur in other heat exchangers.

4.3.2.5 Tube Bundle Cage Structure

Tube bundle cage structure failures have occurred, allowing baffle plates to shift from their original position. The tie-rods between the plates establish the spacing needed to avoid damaging tube vibrations and excessive pressure drop (Figure 4-14). The rods may fail due to vibration fatigue cracking, impingement from high velocity shell inlet flows (or tube leaks), or weld/fastener failures. Plate movement is more likely if high tube vibration conditions are present along with associated reduced plate ligament thickness. Plates out of position can be detected by ECT, but may not be recognized or reported.

Figure 4-13
Impingement plate with degraded attachment weld

Figure 4-14
Tube bundle cage structure prior to tube insertion

4.3.2.6 Feedwater Heater Vent Header Failure

Vent headers to remove non-condensable gas from feedwater heaters have frequently been found detached on non-functional when internal inspections were performed. The failures were most commonly associated with weld failures at attachments to the shell or internal manifolds such as shown in Figure 4-15.

Figure 4-15
Feedwater heater vent manifold failure

4.3.2.7 Shell-Side Expansion Joint

Shellside expansion joints are not common, but may be used in applications such as straight tube feedwater heaters to absorb thermal stresses between the fixed tube bundle and shell. The manufacturer is often the best source for information and experience. Thin-walled joints are fragile, damage easily, and often not repairable and must be replaced. Thick-walled joints are only slightly more repairable. Shell expansion joint failures are most often due to cracking and are initially detected by external leakage.

4.3.2.8 Other/Miscellaneous

Essentially all shell internal components are potentially subject to failure over time. Failures due to weld cracking may go undetected for internal non-pressure boundary welds. Failure of sealing strips or shell-side divider plates can result in thermal performance degradation due to bypass flow paths. Failures of erosion resistant liners at shell side inlets to feedwater heaters have been found, with the liner fragments in the bottom of the shell. The effects from failures of internal parts can be benign or they may reduce thermal efficiency, increase tube or shell degradation rates, and/or reduce capability to accommodate overload operation.

The difficulty in detecting shell-side internal damage mechanisms or failures emphasizes the importance of conducting shell inspections when access opportunities exist such as when shell relief valves are removed for maintenance or if shell cuts are made to repair erosion damage. This is particularly true for high velocity applications, such as steam condensing service.

4.3.2.9 Main Condenser Internals

Main condensers have a significant variety of internal structures beyond those associated with the tube bundles. These internal parts are not discussed in this document. Since access to the main condenser internals is typically available each refueling outage, a detailed inspection is normally performed. The use of detailed work scope instructions and/or an inspection checklist may be used to improve the quality and consistency of condenser internal inspections. See section 9.2 of reference 68 for additional information on condenser internals inspections.

4.3.2.10 MSR Internals

Similar to the discussion above for main condensers, MSR have unique internal design features which are not discussed in this document. Periodic shell-side inspections are routinely performed and the use of detailed work instructions and/or an inspection checklist may be used to improve the quality and consistency of MSR internal inspections. The responsible engineer is directed to reference 43 for additional information and guidance related to MSRs.

4.3.3 Channel and Tube-side Degradation Issues

Degradation of tube-side components, excluding the tubes, is briefly discussed in this section. Appendix I also contains visual inspection guidance related to many of these potential tube-side degradation issues.

4.3.3.1 Channel

The channel is located between the tubesheet and the cover or manway and includes the supply/return nozzles. Smaller shell-and-tube heat exchangers or coils may be designed with a removable bolted cover including flanged pipe connections. Significant damage to the channels or heads is generally due to corrosion damage to carbon steel or dealloying (graphitic corrosion) of cast iron materials in open cooling water systems.

4.3.3.2 Tubesheet

Tubesheet joint leakage is not a common problem, although conditions of inadequate original joint integrity, damage to tubesheet ligaments or roll joints sufficient to result in leakage have all occurred. The original tubesheet joint is hydrostatically tested, although the test purpose is verification of structural integrity and may not ensure the absence of very small leaks without additional requirements. Damage to the ligaments or tubesheet joint integrity could be due to cracking (of welds or from plug installation with excessive force), corrosion damage (i.e. galvanic, crevice, pitting, dealloying), or hydrolaze tubesheet cleaning (such as to remove corrosion or old coatings to sound metal). This damage primarily relies upon visual inspection for initial detection. Once damage is sufficient to allow leakage between the two systems, detection may occur while the heat exchanger is in-service.

Carbon steel is the most common tubesheet material, although copper alloy materials (e.g. Muntz metal) are also frequently used to match tube materials. Tubesheets may be carbon steel which is clad with a material matching the tube material (e.g. stainless steel or titanium cladding) and a welded tube-to-tubesheet joint applied to reduce the potential for corrosion damage and/or tubesheet joint leakage. Corrosion of uncoated carbon steel tubesheets may be accelerated by the galvanic and crevice corrosion in open cooling water systems. Muntz metal tubesheets may experience dealloying corrosion damage in open systems.

4.3.3.3 Tube Plugs

Tube plugs are not expected to fail. Detection of plug failures relies on leak detection actions and to a limited extent on visual inspections. Visual inspection verifies the total number and correct location of plugged tubes. While failures of essentially all tube plug types have been reported, plug failures are most prevalent with elastomeric plugs and one-piece tapered plugs, commonly due to aging or cracking of elastomeric materials, and thermal cycle loosening. Section 5.5 includes additional discussion on tube plug selection.

4.3.3.4 Coatings

Tubesheet materials which are potentially susceptible to corrosion or dealloying damage are often coated in open cooling water systems. In some cases, such as coated carbon steel in seawater or brackish water service, the coating permits use of an otherwise unsuitable material for the service environment.

All coatings will degrade over time. Epoxy coatings applied to internal components of heat exchangers will eventually crack, flake, or detach from the metal surface. Corrosion damage at areas of coating failure can proceed rapidly. Coating failure may also create a source of macrofouling debris and contribute to tube blockage. Ideally, coating failure will be in small pieces rather than in large sections. Visual inspection is relied upon to detect coating degradation, and when found, it is relied upon to assess the condition of the underlying metal and determine the potential for tube blockage and other impacts.

4.3.3.5 Dissimilar Metals

Dissimilar metal joints are a source of increased problem potential. Welded dissimilar metals may have increased cracking risk which warrants special inspection attention. Adjacent dissimilar metals at bolted joints, tubesheets, or tube plugs are locations with increased risk of galvanic corrosion to the less noble metal in open cooling water systems.

4.4 Corrosion

Corrosion damage of various types is a common cause of heat exchanger degradation. This section includes a brief summary of the major corrosion types from EPRI report 1018089, Heat Exchanger Maintenance Guide (ref. 20), as well as comments on where the heat exchanger engineer is most likely to encounter the corrosion type. Additional information on corrosion can be found in references 21, 38, 39, 42, and 98.

4.4.1 General Corrosion

General corrosion is the uniform loss of the metal surface. All structural alloys are susceptible to general corrosion; however, the corrosion rates can vary by many orders of magnitude. Corrosion resistance usually refers to resistance to general corrosion. Consequently, corrosion-resistant alloys may be subject to localized attack and failure in environments where their general corrosion or total metal loss is quite low. 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 heat exchangers.

This form of corrosion is responsible for the greatest destruction of metal by weight, but it is not as problematic as other types that lack uniformity and predictability. General corrosion attacks are the most evident in carbon steel. **<u>General corrosion does not often result in the need for heat exchanger repair</u>** since open cooling water system designs normally specify corrosion resistant materials, coatings, and/or sufficient corrosion allowances to address general corrosion.

4.4.2 Localized Corrosion

The remaining corrosion types are localized corrosion, which as its name implies occurs at specific locations rather than over the entire surface. Unlike general corrosion, where metal loss is distributed, dissolution occurs at only a few sites in localized corrosion. The impact on component life and reliability can be significant since localized corrosion may not be anticipated and through-wall penetration can occur rapidly in comparison to general corrosion rates.

4.4.2.1 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 in heat exchangers is most prevalent in open cooling water systems due to oxygenated and more conductive water. In heat exchangers supplied with open cooling water, common galvanic corrosion locations include:

- Carbon steel tubesheets, where carbon steel is less noble than the tube material.
- Dissimilar metal joints, either welded or bolted.
- Gasketed joints with graphite gaskets, since graphite is high in the galvanic series.
- Welds in carbon steel may experience accelerated metal loss assisted by galvanic corrosion due to differences in metallurgy between the weld filler and adjacent metal.

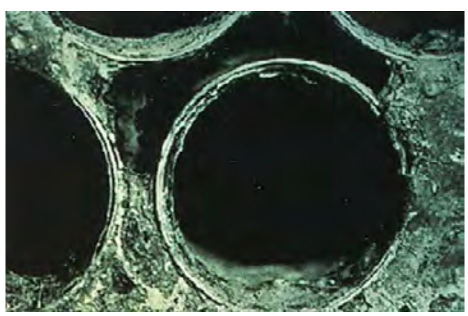


Figure 4-16
Galvanic corrosion of a muntz metal tubesheet with stainless tubes

4.4.2.2 Crevice Corrosion

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

Crevice corrosion often requires a long incubation period, however, once the corrosion starts, it can proceed at a rapid rate. Crevice corrosion may occur in combination with galvanic corrosion in carbon steel tubesheets or adjacent to graphite gasket materials in bolted connections.

4.4.2.3 Pitting Corrosion

Pitting corrosion is similar to crevice corrosion in that a local anodic site supports metal dissolution reactions on the remainder of the surface. The inside of the pit often develops very different water chemistry than the bulk water outside of 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. Similar to crevice corrosion, pitting may require a long incubation period to develop. Once started, the pit can penetrate the metal at a relatively rapid rate. Low fluid velocities and/or stagnation are conditions often associated with pitting.

Pitting corrosion is the most prevalent tube damage mechanism in open cooling water systems and is discussed in Section 4.3.1.5 as a tube damage mechanism. It is also commonly seen in carbon steel parts such as channels and heads in open cooling water.

4.4.2.4 Stress Corrosion Cracking

Stress corrosion cracking (SCC) 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 and 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 is generally associated with ammonia attack, which may be present in the main condenser or as the result of organic material decay or purification in open cooling water systems. SCC is discussed in Section 4.3.1.1 as a tube damage mechanism.

4.4.2.5 Microbiologically Influenced Corrosion (MIC)

Microbiologically influenced 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 the environments in a crevice. As a result, MIC can initiate and proceed very rapidly. MIC is normally controlled by chemical treatment of open cooling water systems. Failure or inability to establish control of microbiological agents may challenge both heat exchanger thermal performance and tube integrity due to microfouling and MIC pitting damage.

Multiple EPRI documents related to MIC are available, including references 37, 38, 39, and 40. EPRI sponsored training on MIC is also available as noted in Section 2.3.

4.4.2.5.1 Manganese Dioxide (MnO_2) Pitting

Reference 42 provides additional detail on manganese pitting, which can be aggressive with stainless steel tube materials. The pit characteristics associated with MnO_2 pitting are essentially the same as those with MIC, resulting in both often being classified simply as MIC. However, manganese pitting can occur with or without microbiological activity. Open cooling systems capable of continuous biocide treatment with excellent control of microbiological fouling and MIC may still be susceptible to manganese pitting damage. Ironically, the strong oxidizing biocides such as sodium hypochlorite, used to minimize the risk of MIC damage, also oxidize soluble manganese into an insoluble substance which tends to deposit on piping and heat exchanger tubing. The effect of MnO_2 on the corrosion rate of active metals, such as carbon steel, is normally quite small. However, the effect on passive metals, such as stainless steel and the copper alloys, can be quite significant. For these metals, conditions are created for establishing pitting corrosion through a process called ennoblement.

Microbiological Mn(II) oxidation occurs in waters containing as little as 20 ppb Mn, producing dark-brown to black precipitate that can accumulate very quickly on passive metals. Visible MnO_2 deposits have been reported to develop in less than 48 hours on stainless coupons in fresh river water. These deposits were sufficient to shift the open circuit potential (OCP) above +300 millivolt (mV_{sce}), increasing the potential for corrosion in an otherwise non-aggressive environment. This illustrates that the impacts from MnO_2 require only a very small amount of deposition, a very short time, and a very low concentration of soluble Mn in the bulk water.

Concentration of Mn(II) in the bulk water is an important determinant of the manganese dioxide fouling and deposition potential in a given system. The following three fouling thresholds are proposed in reference 42:

- Waters containing less than 10 ppb Mn(II) have low MnO_2 fouling potential.
- Waters containing between 10 and 50 ppb Mn(II) may produce fouling if manganese oxidizing bacteria are present, or if excessive levels of oxidizing biocide are in the water.
- Waters containing more than 50 ppb Mn(II) have a high potential for deposition due to microbiological oxidation or chemical oxidation if oxidizing biocide is used.

4.5 Cooling Water System Chemical Treatment

All heat exchangers in the GL 89-13 program and the majority in most BOP Heat Exchanger programs are associated with cooling water systems. Chemical treatment of SW systems is critical to satisfactory performance of GL 89-13 programs. Treatment of other non safety related open cooling water systems is also typically vital for satisfactory heat exchanger thermal performance and can significantly affect structural degradation mechanisms. Proper chemical treatment of closed cooling water systems is also of great importance. Therefore, information is provided for engineers involved with heat exchanger programs to have some familiarity with chemistry treatment and monitoring guidance for cooling water systems.

While engineering personnel are not expected to be directly involved with monitoring chemistry control parameters, it is beneficial for chemistry personnel to promptly notify the GL 89-13 program owner and SW system engineer of chemistry control lapses and out-of-specification conditions. The SW system relies upon chemistry monitoring and controls as a first line of defense for several potential fouling issues. The GL 89-13 program owner is expected to be aware of lapses or failures of SW chemical control well in advance of finding their consequences via thermal performance tests or visual inspections.

Key Technical Point

It is beneficial for the GL 89-13 program owner and SW system engineer to be aware of chemistry control lapses and out-of-specification conditions. The SW system relies upon chemistry monitoring and controls as a first line of defense for several potential fouling issues.

4.5.1 Open Cooling Water Systems

EPRI Report TR-106229, Service Water System Chemical Addition Guideline (ref. 35), provides guidance for chemical treatment and monitoring of SW systems. Due to the much wider variations in water quality, system design, environmental permitting, and related factors, this guide does not include the specific monitoring parameters, actions levels, and frequencies contained in the EPRI Closed Cooling Water Chemistry Guideline (ref. 36). The document discusses chemical selection for micro- and macro- biological control, corrosion control, fouling control, and scale control as well as general considerations for a total water treatment program. This report is in revision, with an updated guide for open cooling water system chemistry expected to be issued in the late 2011/2012 time period.

Additional EPRI information and guidance related to SW system chemistry issues can be found in references 37, 38, 39, and 40.

4.5.1.1 GL 89-13 Program

Chemistry biocide treatment is a GL 89-13 commitment at most facilities (GL 89-13 Action I – “implement and maintain an ongoing program of surveillance and control techniques to significantly reduce the incidence of flow blockage problems as a result of biofouling.”). The overall SW chemistry control and monitoring actions perform a vital function for the success of the GL 89-13 program. Due to the significance of chemistry controls in maintaining SW heat exchanger performance, communication between chemistry and engineering personnel is vital.

As noted in Section 2.3, periodic meetings between engineering and chemistry personnel are beneficial to ensure both groups are aware of information related to the effectiveness of SW chemistry controls. Appendix F contains an example agenda for such meetings.

It is also beneficial for chemistry personnel to be sufficiently involved with the SW heat exchanger and internal inspections, to have a detailed understanding of as-found conditions. This provides treatment effectiveness feedback to chemistry and promotes communication and consistent understanding of system conditions.

Monitoring of SW chemistry control is discussed in Section 5.5 of reference 35. Robust water chemistry monitoring, particularly in the area of bio-fouling control, allows early detection of potential problems and therefore timely correction prior to challenging heat exchanger performance. While high quality thermal performance tests are useful to show heat exchanger performance requirements are met, they are relatively infrequent at most stations (i.e. once/cycle) compared to the time periods for biological fouling to develop. Thermal performance tests and visual inspections are in most cases confirmatory actions for the effectiveness of other barriers, such as biocide/chemical treatment. Therefore, GL 89-13 program monitoring and awareness may also involve items addressed by the Chemistry department, such as:

- Chemical concentration monitoring for each train, including residual concentrations at back end of system.
- Effectiveness monitors such as bio-boxes and fouling probes (scale/fouling monitors) to provide a results oriented measure of chemical treatment.
- Normally isolated parts of systems, which are addressed by requiring lay-up with properly treated water following tests or in-service periods.
- Robust performance indicators and multi-tiered actions to escalate responses to out-of-specification conditions or out-of-service time for chemical treatment systems. SW chemistry performance indicators can be reflected in both chemistry and engineering (i.e. GL 89-13 program and SW System) health indicators.

4.5.1.2 BOP Heat Exchanger Program

The BOP Heat Exchanger program involvement with open cooling water chemistry control (SW, circulating water, other non safety related open cooling water systems) is generally only indirect. The following considerations are provided:

Notable changes in pitting rates or activity in copper alloy tubes can be reviewed with chemistry for consistency with corrosion monitoring data and to determine if condition has been caused by or can be improved with changes to chemistry controls.

Unexpected pitting or changes to pitting in austenitic stainless steel (i.e. types 304 or 316) tubes warrant review with chemistry regarding MIC and MnO2 (the two principal sources of stainless steel pitting in freshwater plants). Additional chemistry sampling and analysis of ID deposits or films can help determine if chemistry adjustments are needed.

Changes in tube deposits or buildup may be detected by or interfere with ECT data analysis. These changes may be associated with changes in cleaning methods or intervals, but could also be due to changes in chemistry control or occasionally due to unrecognized changes in the raw water source.

Internal visual inspections of non-SW heat exchangers are conducted as part of the BOP Heat Exchanger program (i.e. PM actions), and may detect changes in macro- or micro-fouling materials prior to being noted by GL 89-13 program inspections. These observed changes may be related to chemistry control (i.e. caused by or preventable by) and are therefore appropriate to review with chemistry personnel.

4.5.2 Closed Cooling Water Systems

EPRI Report 1007820, Closed Cooling Water Chemistry Guideline, Revision 1 (ref. 36), as its name implies, provides guidance for chemical treatment and monitoring of closed cooling water systems. Closed cooling water chemistry controls are credited by the GL 89-13 program, the BOP Heat Exchanger program, and license renewal evaluations (if applicable).

4.5.2.1 GL 89-13 Programs – Closed Cooling Systems

Heat exchangers cooled by closed cooling systems are normally excluded from GL 89-13 programs (see Section 2.1.1). Implementation of chemistry controls and monitoring consistent with that described in 1007820 (Ref. 36) provides a reasonable basis for fouling to be maintained within design limits.

4.5.2.2 BOP Heat Exchanger Programs – Closed Cooling Systems

BOP Heat Exchanger program preventive maintenance actions credit closed cooling water system chemistry and corrosion control programs, at least initially, with the assignment of appropriate inspection tasks and intervals for heat exchangers. The PM actions and/or their intervals may be adjusted following each task performance based upon as-found conditions.

4.5.2.3 License Renewal – Closed Cooling Systems

NUREG-1801, Generic Aging Lessons Learned (GALL) Report (ref. 4) provides the technical guidance for the license renewal process applied at most sites. The report credits various Aging Management Programs (AMP) to address the effects of aging, including Closed Treated Water Systems (M21A) in Section XI. This AMP credits chemistry control provided to closed cooling water systems in accordance with EPRI Report 1007820 to address corrosion and fouling issues. The chemistry parameters monitored and their frequencies are directed to be in accordance with the EPRI guidance.

Since the GL 89-13 program, BOP Heat Exchanger program, and license renewal process all include some credit for closed cooling water system chemistry control, it is beneficial for utilities to consider the following:

1. Justify or eliminate potentially non-conservative differences from 1007820 Chapter 5 (Ref. 36), guidance for monitored parameters, action levels, and frequency.
2. Establish a mechanism for periodic audit, review, or assessment of closed loop cooling water chemical control methods compared to the guidance in EPRI Report 1007820 (Ref 36).
3. Establish performance indicators and/or other mechanisms to elevate visibility and station response for out-of-specification closed cooling water chemistry parameters. The site corrective action process is sufficient to address actions needed for evaluation and to maintain operability for heat exchangers affected by out-of-specification chemistry items.

The above considerations may be addressed by the site chemistry program versus an engineering program.

4.6 Heat Exchanger Industry Issues – Awareness Points

The following summary items are based upon industry events which have had significant consequences and been found to be applicable to multiple stations. The items are noted for general awareness by the program owner, since reviews of the applicable industry notification reports may have been performed by previous program owners. Heat exchanger program owners are encouraged to be aware of the actions taken or conditions credited at their site in response to these issues to ensure any associated vulnerability has been properly addressed.

4.6.1 Tube Plug Ejection Events

Two types of tube plug ejection events are considered noteworthy for general awareness by program owners. These are the ejection of one-piece tapered plugs from feedwater heaters, which occurred during maintenance actions to remove the plugs, and the ejection of significant quantities of elastomeric plugs from condenser tubes, which have occurred in response to a loss of offsite power or a loss of circulating water.

<u>Plugs may have trapped pressurized fluid behind them.</u>

One-piece tapered plugs have ejected violently from feedwater heaters when being removed.

- Personnel injury has resulted, with the potential for permanent injuries or death.
- Occurrences at two different stations have been associated with plug removal activities.
- The presence of pressurized fluid behind the feedwater heater tube plugs removed was not widespread at the sites, but it was also NOT limited to a single tube.

Elastomeric plugs have ejected from condenser tubes when they were being checked for tightness as well as during plant operational transients. Sufficient pressure is not likely to be trapped behind a condenser tube plug to cause serious injury provided normal personnel protective equipment is used (i.e. safety glasses, hard hat, and gloves). However, due to the risk of secondary injury caused by worker reflex actions from being startled by a plug ejection, precautions may be warranted for worker awareness of the potential as well as avoiding being in the path of plugs being checked for tightness. The inclusion of industry events related to condenser tube plug ejections may be beneficial to include in work packages which involve checking condenser plug tightness.

Multiple elastomeric plugs have ejected from condenser tubes during loss of offsite power events or when circulating water flow is lost.

4.6.1.1 Items for Program Owner Consideration/Awareness

- Fluid at the tube-side system operating pressure may be trapped behind a tube plug.
- Are appropriate precautions and communication of plug ejection events included with plug removal activities?
- Plug removal in a FWH at elevated temperatures may also release steam and hot water.
- Tapered plug ejection from non-leaking tubes may be possible during activities other than plug removal; however, no industry experience reports are noted with other actions.
- The decision to puncture non-leaking FWH or high pressure service tubes prior to plugging is a site-specific decision based on reviews by maintenance and engineering with consideration given to the robustness of the plug design being used.
- Removal of existing tapered plugs in high pressure service to avoid risk of plug ejection is a site-specific decision and may be pursued in conjunction with related actions such as plug removal for condition assessment, sleeving, and/or margin recovery.
- Precautions may be warranted for work documents (work packages, plugging procedures, etc.) involving feedwater heater tube plug removal, noting: 1) High energy fluid may be trapped behind the plug; 2) Actions to capture or restrain the plug if ejection occurs; 3) Plug removal at elevated tube temperatures may result in release of steam and hot water.
- Consider condenser tube plug verification following a loss of circulating water if elastomeric plugs are in use.

Key Human Performance Point

Fluid at the tube-side operating pressure may be trapped behind a tube plug. Injuries have resulted from tapered plug ejections while attempting to remove one-piece tapered plugs. Precautions may be warranted in documents directing work which could dislodge tube plugs (intentionally or inadvertently) notifying the workers of the potential for fluid to be trapped behind the tubes and the need to capture or restrain the plug.

Key Technical Point

Ejection of multiple elastomeric tube plugs following a loss of circulating water has occurred on several occasions. Consider condenser tube plug verification as a response action to a loss of circulating water, if using elastomeric plugs.

Additional information on plug selection is included in Section 5.5. Additional information on industry experience with plug ejection events is available through INPO.

4.6.2 Shell-side Flow Induced Vibration Damage Events

Multiple stations have encountered significant vibration induced damage due to excessive shell-side flow. These events have occurred in spite of the heat exchanger vendor technical manuals providing maximum shell side flow limits, due to failure to effectively implement procedural or physical controls to protect those limits.

Key Technical Point

Significant vibration induced tube damage related to excessive shell-side flow may result from ineffective implementation of controls to protect vendor specified maximum flow values.

In addition to events where vendor specified shell-side flow limits were not observed, other cases of flow induced vibration damage have occurred due to poor original design. Heat exchangers designed and built prior to 1980 may include tube support spans and/or maximum allowed flows which exceed those allowed by current design standards and modeling software. While not all heat exchangers built before 1980 will have unacceptable tube spans and maximum flow combinations, the design limits used by the heat exchanger industry have been changed since that time period to address tube vibration induced failures. Heat exchangers with larger shell diameters may have a higher risk of marginal design. (See related Flow Limits discussion in Section 5.6.4)

4.6.3 Multi-Pass Heat Exchanger Head – Incorrect Installation Events

Installation errors on small four-pass heat exchangers, such as pump lube oil coolers or chiller condensers with removable heads containing integral partition dividers, have occurred at several stations resulting in reduced thermal capacity. The heat exchanger design contributes to the susceptibility of this human performance error due to the absence of match marks or alignment guides for correct orientation of the reversing head. However, this error has been repeated in the industry in spite of a series of industry reports and notifications on the topic over a multi-year span. It is beneficial for program owners to document the susceptible heat exchangers for this issue and the barriers established to ensure correct end bell orientation during maintenance (i.e. procedure/work order cautions and steps, match marking cover flanges, independent verification steps, etc.).

Key Human Performance Point

Incorrectly installed reversing heads on small four-pass heat exchangers have caused a reduction in active tubes and thermal capacity. Establishing multiple barriers to ensure correct head orientation for susceptible heat exchangers is a beneficial action to avoid future occurrences.

4.6.4 Feedwater Heater Shell Rupture

A feedwater heater shell rupture occurred in 1999 leading to shell inspection actions in the nuclear industry, which found significant shell damage at multiple additional stations. In addition to the one-time inspection actions performed in response to this event, programmatic oversight and controls were typically implemented, often through the Flow Accelerated Corrosion (FAC) program. It is beneficial for the BOP Heat Exchanger program documents (or PM database, as applicable) to specify the responsible group for periodic FWH shell inspections.

5
PREVENTIVE MAINTENANCE, TESTING, AND MONITORING

This section addresses the role of heat exchanger preventive maintenance in maximizing heat exchanger reliability. The following sections provide an overview of information on preventive maintenance and reference where more detail can be found in other guidance documents.

5.1 Preventive Maintenance Templates

EPRI provides PM templates for various types of heat exchangers. The PM templates provide a generic outline of commonly performed monitoring and maintenance actions, with associated recommended intervals. The templates are widely used as an initial starting point for PM actions.

5.1.1 PM Component Classifications

Heat exchangers along with other components in critical systems are classified per standard PM nomenclature to assist in prioritizing maintenance with the use of generic templates.

Criticality – This relates to the consequences of heat exchanger failure and considers factors such as safety-related component impacts, power generation impacts, and other parameters. Typical classifications include:

- Critical – may be sub-divided into High Critical and Low Critical
- Non-critical
- Run-to-Failure (RTF)

Duty Cycle – Duty cycle relates to in-service time or run hours and is normally classified as High or Low. Heat exchangers are divided between normally having flow versus normally in standby.

Service Conditions – Service conditions typically are classified as Severe or Mild. For heat exchangers this relates to water quality, operating pressure, and similar fluid considerations.

5.1.2 PM Performance Intervals

The tasks listed in the templates are intended to have an identified periodic interval at which they are required to be performed or noted as “Not Applicable” or “Not Required”. Some tasks are listed with an undefined interval of “As-Required (AR)”. Since “as required” does not represent a time interval, it would not be expected to initiate performance of the associated task, unless condition monitoring provides the determination of when the action is needed.

5.1.3 PM Template Adjustments

Deviations from the base PM templates are to be expected. These deviations are a normal and healthy aspect of a “living” PM program, which is adjusted to address variations in material condition, operating conditions, materials of construction, quality of construction, industry operating experience, site operating experiences, and related variables.

5.1.3.1 PM Template Adjustments – Site Operating Experience and Inspection Results

<u>Site operating experience and inspection results are the most influential items for a “living” heat exchanger PM process</u>, since they reflect the culmination of the various weaknesses in the heat exchanger design, fabrication, operation, service conditions, and related variables. <u>**The current condition of a heat exchanger as indicated by previous inspection data is the best basis for establishing future PM actions, scope, and intervals**</u>. The **suggested** intervals in the heat exchanger PM templates are based on initial performance.

Key O&M Cost Point

Heat exchanger PM actions, scope, and frequencies adjustments from those in generic templates are expected based upon inspection and test results.

Since PM actions and intervals in a “living” PM Program are adjusted to reflect as-found conditions and past failures, the initial duty cycle selection and classification of service severity for the PM template may have minimal future impact on the maintenance intervals and actions. The duty cycle and service severity selections only impact the initial inspection interval; feedback from as-found conditions will dictate future intervals.

5.1.3.2 PM Template Adjustments – Regulatory Requirements

Additional actions or action intervals, beyond those required by the PM templates implemented by the BOP Heat Exchanger program, may be required for safety-related heat exchangers due to regulatory requirements:

- License Basis Documents (LBD) – specific test or inspection activities may be specified in the LBDs and should be credited by applicable PM activities. Scheduling of other PM actions should consider the regulatory required action frequency.
- NRC Commitments – The most common regulatory commitment for heat exchangers are those for GL 89-13 to ensure SW heat exchangers remain capable of performing their intended safety function through one or more of the following periodic actions:
  - Thermal Performance Tests
  - Periodic Maintenance (Open, Inspect, Clean)
  - An “Equally Effective Program”

These actions were specified to be performed no less frequently than 5 years and may be required more frequently depending on trends from previous as-found inspections or tests.

- License Renewal (based on the GALL Report – NUREG-1801, for most of the license renewal applicants) – license renewal approvals may include various heat exchanger commitments, including:
  - One-time inspections of closed loop heat exchangers to validate their condition.
  - Replace small heat exchangers prior to the period of extended operation.
  - Inspections for dealloying of cast iron or brass heat exchanger materials.

5.1.3.3 PM Template Adjustments – Industry Operating Experience

Not all heat exchanger issues in INPO OE reports or NRC Information Notices are applicable to each site, but it is reasonably accurate to state essentially all heat exchanger problems, have occurred previously. Thus, there is much to be learned from industry experience. Due to the wide variations in heat exchanger designs and service conditions (e.g. water quality), the applicability determination when reviewing another site's heat exchanger problem often requires more than summary data of an event or failure. A potentially useful initial screening question for PM impact is, "If this event was applicable to my site, would it potentially challenge or impact the basis for existing heat exchanger PMs?" Many failures may be interesting, but if the response to this question is "No", then pursuing the details may not be warranted.

The INPO OE database is a useful source of heat exchanger operating experience. Other sources of industry data include NRC Information Notices, NRC Licensee Event Reports, EPRI users groups (NDE, SWAP, HXPUG), and utility papers/presentations relating successes and failures.

5.1.3.4 PM Template Adjustments – Power Uprates/Off-Normal Operation/Replacement

Significant changes from past operating conditions are appropriate triggers to review the need to reset heat exchanger PM intervals, scope, or baseline occurrence. The ability of degraded heat exchangers to handle increased service demands can be diminished, sometimes significantly. Therefore, the current material condition of the heat exchanger is an important factor when evaluating operational changes or events for heat exchanger PM impacts.

Sustained operation under conditions which are potentially more challenging (i.e. higher shell flow, higher dp, higher delta-T) or brief but significant transients such as water hammer or severe temperature excursions are generally evaluated for potential equipment impacts by the engineering change process for planned actions or by the corrective action process for unplanned occurrences. The responsible heat exchanger engineer is often tasked with evaluating the potential impact of such events for impact to PM actions and scheduling.

Power uprates are discussed in Section 5.8. Industry experience with larger power uprates has included several cases of accelerated wear and damage to feedwater heater and/or condenser tubes. Resetting PM inspection schedules for feedwater heaters and condensers with staggered reinspection dates provides opportunities to check degradation rates from the increased flow.

Temporary operating conditions or events may warrant PM schedule resets such as: condenser operation with normally closed high level dump valves in service (reinspection of condenser tubes in vicinity of sparger); feedwater heater overload operation (reinspect degraded FWHs or if none, sample overload heaters in next outage); shell-side flows exceeded OEM maximum limit for a sustained period (i.e. not start/stop evolution for pump swap); failures in condenser of internal expansion bellows, spargers, turbine blades or other metal debris generating events (thorough visual of lanes combined with ECT of open lanes in vicinity).

Replacement of a heat exchanger is another event which may warrant reset of the PM inspection interval. If multiple heat exchangers are replaced, then staggering the inspections (i.e. if 6Y is the default ECT interval, then perform one inspection at 3Y) to confirm the expected material condition may provide for earlier detection of issues.

5.2 Preventive Maintenance Actions

This section discusses the principal preventive maintenance actions implemented by the BOP Heat Exchanger program.

Tube NDE and visual inspection PM actions are the two base PM actions typically specified for all program heat exchangers, unless tube inspection is not possible or periodic replacement is more cost effective than PM actions. Additional PM actions may be justified, such as:

- Tube cleaning.
- Shell NDE inspections.
- Tube ID measurements for general wall loss of erosion susceptible materials.
- Sacrificial anode replacement.
- Elastomeric plug retightening/replacement.
- Videoprobe inspection at the transition between tube material and sleeves/coatings in erosion susceptible tube materials.

5.2.1 Tube NDE Inspection – Eddy Current Testing

Tube NDE inspection is the most important PM activity with respect to avoiding leaks. In addition to improving reliability, they provide information on the health and life expectancy of the heat exchanger via the extent, type, and progression of tube damage. This PM action is normally performed on all critical (i.e. non run-to-failure) heat exchangers where tube inspection is possible. Eddy Current Testing (ECT) is the most widely used tube inspection NDE technique and is used as a generic term in this document for the various tube inspection methods.

Performing ECT and analyzing the data requires considerable technical understanding and training. This section briefly discusses the technology within the context of information needed by the BOP Heat Exchanger program owner. Reference 89 provides additional detail on heat exchanger ECT inspections. Figure 5-1 illustrates typical tube degradation types, many of which can be detected via ECT.

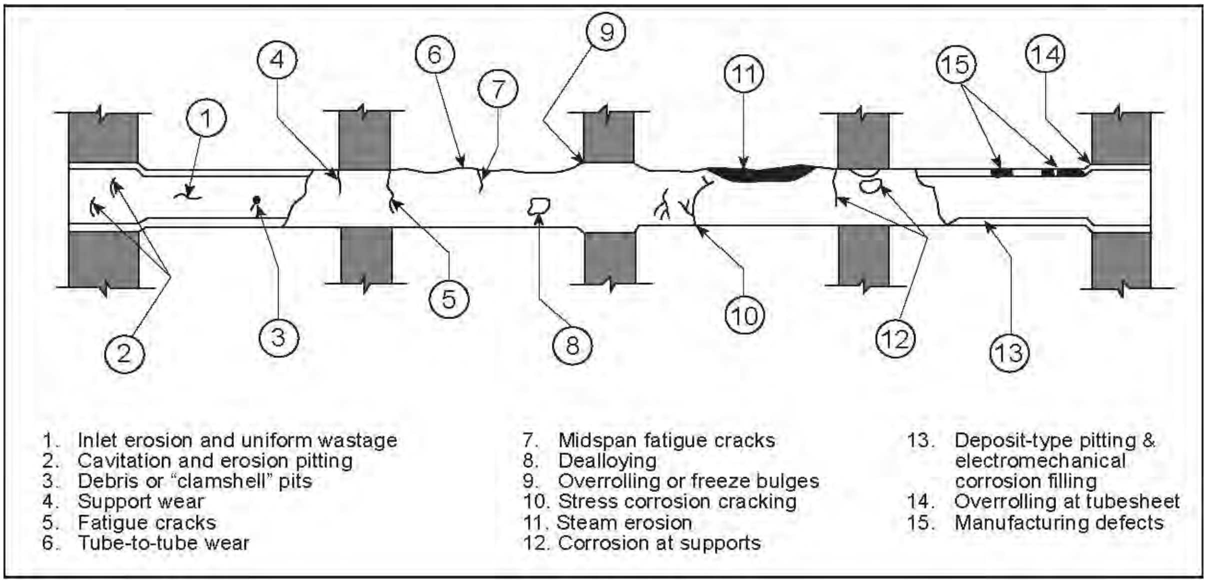


Figure 5-1
Typical heat exchanger tube degradation

Eddy current testing (ECT) employs a probe designed for the tube inside diameter and material. The probe consists of a coil used to establish an electrical field which produces eddy currents in the tube. Flaws in the tube wall such as wall thinning, cracks, or pits interrupt this field, and the interruptions cause an impedance change in the coil. These changes to the signal are compared to signal changes caused by the reference or calibration standard flaws to determine the flaw size. Therefore, ECT flaw analysis is comparison based and the quality of the flaw characterization is greatly influenced by similarity to flaws in the calibration standard.

The typical industry practice is to use an ASME calibration standard. The specifications for ASME-type standards are found in the ASME B&PV Code – Section V, Article 8, Appendix I. Figure 5-2 is a drawing of the reference standard containing representative flaw types.

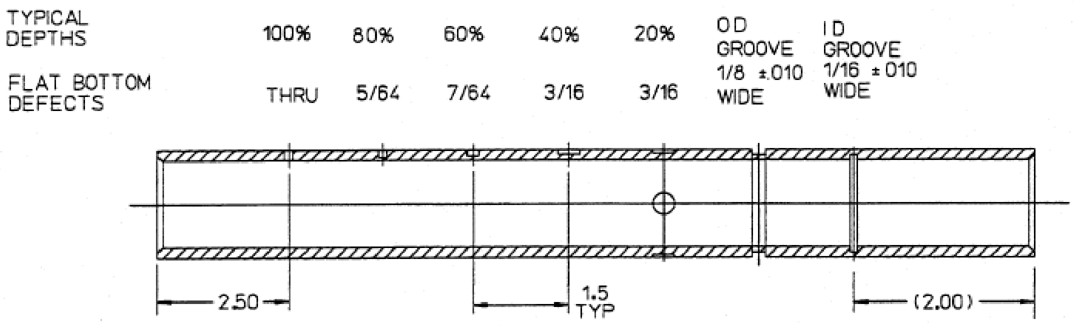


Figure 5-2
ASME type ECT reference standard

The probe is calibrated in a tube standard containing simulated defects, such as holes and notches. As the probe is withdrawn, differences detected by the coils are displayed as eddy current signal responses. An ASME calibration standard by itself may not be the best standard for sizing ID pits. As the name implies, an ID pit standard, as shown in Figure 5-3, is used to improve sizing of ID pits. Calibration standards can also include other expected damage types such as OD wear at support plates. **<u>Calibration standards with defects similar to expected damage improves the accuracy of ECT flaw classification and sizing.</u>**

Flaw	A	B	C	D	E	F	G	H	I	J	K	L
% TW	25%	50%	75%	100%	25%	50%	75%	100%	25%	50%	75%	100%
Flaw Type	PIT	PIT	PIT	TWH	PIT	PIT	PIT	TWH	PIT	PIT	PIT	TWH
Flaw Diameter	1/16	1/16	1/16	1/16	1/8	1/8	1/8	1/8	3/16	3/16	3/16	3/16
Depth	0.0123	0.0245	0.0368	TWH	0.0123	0.0245	0.0368	TWH	0.0123	0.0245	0.0368	TWH

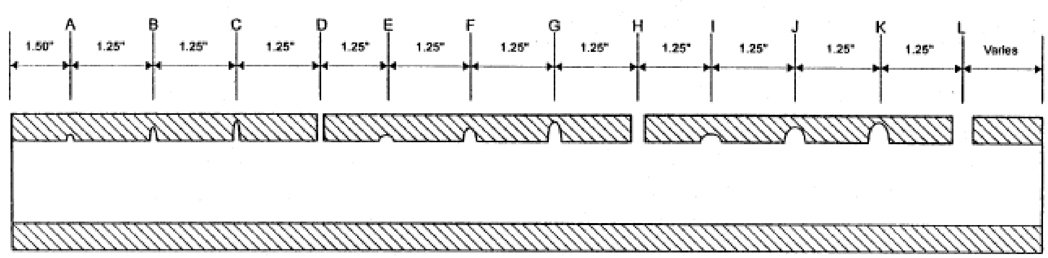


Figure 5-3
Example ID pit calibration standard containing rounded-bottom holes

Key Technical Point

The most commonly used NDE technique for heat exchanger tubes is ECT. It is relatively fast, repeatable, and accurate in sizing defects, but it also relies on skilled analyst for subjective interpretation. Detection of some types and locations of defects can be difficult or require specialized equipment.

Cost, speed, accuracy, repeatability, detection capability are all factors in selecting the NDE technique to be applied. Some advantages of ECT to test for tube damage include:

- Proven technology.
- Relatively fast with automated examination capability.
- Differentiation between various flaw types as well as ID vs. OD indications.
- Repeatability allows changes to be detected and flaw progression determined.
- Detection of baffle plates and other metal in contact with the tubes.
- Sensitive to material property changes.
- Flaw sizing accuracy is good if closely matched to calibration standard flaws.

Disadvantages of ECT include:

- Many variables can lead to inaccurate interpretations of the ECT signals.
- Subjective – technicians must have extensive training and practical expertise.
- Affected by material property variations such as conductivity, permeability, and geometry.
- Eddy currents are influenced by flaw orientations that make the testing directional.
- Flaw detection sensitivity is not uniform, with optimum detection at the surface closest to the test coil and decreasing exponentially below the surface.

5.2.1.1 Magnetic Tube Materials

Conventional eddy current testing cannot be performed on magnetic tubing material such as ferritic stainless steels (i.e. type 439, Sea-Cure™, E-brite™, etc.). Alternative methods similar to eddy current testing such as remote field, full-saturation, and flux leakage inspections are available, or different NDE techniques can be performed. These alternative techniques may include drawbacks such as loss of inspection resolution, added costs, added time, or other issues impacting selection of the optimum inspection method.

Key points for the BOP Heat Exchanger program engineer related to ECT inspections include:

1. Eddy current testing is a comparative technology.
2. The quality of flaw characterization and sizing is strongly influenced by their similarity to fabricated defects in the calibration standard.

3. Additional flaw types added to an ASME calibration standard can improve sizing accuracy for those flaws.
4. Gradual (i.e. non-sharp edged) defects are not readily detected.
5. Special probe types may be required to detect some flaws, such as circumferential cracks.
6. Skilled analysts are needed to evaluate ECT data. The analyst's experience with similar defects, tube material, and service conditions can influence their characterization of flaw indications, particularly those that vary from the reference standard flaws.

Section 4.3.1 discusses the various tube damage types, including ECT inspection issues. Appendix E addresses response actions for tube damage indications detected by ECT. Appendix G provides an example checklist for a pre-inspection meeting with the ECT analyst.

5.2.1.2 Inspection Scope

100% inspection is optimum, but not always justified or necessary to maintain reliability. For heat exchangers with relatively few tubes, inspection of all tubes requires little additional time. Some utilities establish a minimum tube count (e.g. 500 tubes) below which 100% ECT is normally performed, with <100% inspection scope performed on larger heat exchangers.

When less than full inspection scope is implemented, it is beneficial to select tubes for inspection considered most likely to be degraded given the service conditions and tube material. In addition to this targeted tube selection, some rows may be checked to confirm damage is not occurring in the bundle interior. Most partial inspections also specify scope expansion to adjacent tubes when significant degradation is found on the edge of the inspection scope.

Additional Comments on Inspection Scope:

- Randomly distributed tube damage, such as pitting in open cooling water service, may justify 100% inspection of heat exchangers with high leakage consequences.
- Most damage mechanisms are not random, allowing a limited inspection scope to target areas of greatest risk.
- The tube bundle periphery has a higher likelihood for tube damage due to both shell-side debris and higher vibration levels causing accelerated wear. Thus, inspecting the outer 2-3 tubes and rows is commonly performed in partial inspections.
- Sampling of interior tube rows provides confirmation of expected damage distribution.
- Review of past inspection results, tube plug locations, causes for plugging in both the inspected and other related heat exchangers (i.e. similar service conditions and tube materials) can help identify the highest risk tube locations for partial inspection scope.

Key Human Performance Point

When selecting an ECT inspection scope of <100%, tubes most likely to be degraded are chosen combined with random sampling. A common approach is to test periphery tubes, around plugged tubes, and other randomly selected tubes, with scope expansion as needed to bound significant degradation.

5.2.1.3 ECT Report Content

Before the start of the ECT examination, it is beneficial to discuss the report content expectations with the NDE service provider. The inspection report or related records typically include the following information:

- For each heat exchanger examined:
  - Total number of tubes, tubes examined, and tubes plugged.
  - Tubesheet map showing, row/tube numbering, plugged tubes and indications.
  - Tube material(s), size, and gauge(s).
  - Probe selection, set-up, test instrument and calibration standard information.
  - Tube defect indication listing.
- A glossary of acronyms, terms, and indication nomenclature.
- Tube plugging recommendations, notable defect indications, changes from previous inspections, and tube pulling recommendations due to analysis uncertainty.
- Reference to previous inspection reports used for data comparison.
- Certification records for data acquisition and analysis personnel.
- Index of data acquisition calibration groups.

The ECT data and analysis files are normally retained by the utility for future reference and access. The NDE service provider may also maintain a copy of the data files.

5.2.1.3.1 ECT Report Format

Eddy current results are commonly provided in a spreadsheet format similar to that in Table 5-1, although a standardized format is not established in the industry. Variations in the report columns, layout and nomenclature may exist between ECT service providers. Understanding the content of the various columns is beneficial for the engineer reviewing the ECT results.

It may be beneficial for the heat exchanger engineer to review the report content and terminology in previous ECT reports from the NDE service provider, to allow questions to be addressed prior to receiving the inspection results. It is a good practice for ECT vendors to include definitions or explanations for the abbreviations, acronyms and terms used in their reports. A brief explanation for the columns in the composite ECT report example in Table 5-1 follows.

Table 5-1
Composite example of ECT test reports

ID	Row	Col	Volts	Deg	%	Ind	Chn	Location	Extent
6AI	1	27	1.03	0	18	WAR	P2	B6 + 0.53	IUB
6AI	4	54	60.56	181		DNT	P1	5TSP + 0.02	08-IT
6AI	4	54				OBS			08-IT
6AI	26	19	5.67	108	65	MO	1	5TSP + 0.92	IUB
6AI	26	19	2.86	63	90	MO	1	5TSP + 3.23	IUB
6AO	16	45	11.95	89	76	SD	1	4TSP + 7.48	OUB
7A	4	2	1.09		12	TT	2	9TSP + 19.0	OUB
7A	5	2	1.11		12	TT	2	9TSP + 20.1	OUB
2E28	8	40	58.23	14	35	MI	1	TES + 262.4	TENTES

5.2.1.3.2 ID Column

Identifies the tested component, normally using the site component numbering convention. The inlet/outlet designation may be included, or the results provided separately for each pass.

NOTE: The ECT analyst may interchangeably use inlet and hot as well as outlet and cold, based on steam generator experience, although these designations may be backwards for a feedwater heater or other heat exchangers. Use of inlet/outlet instead of hot/cold can help avoid confusion.

5.2.1.3.3 Row and Col Columns

The second and third columns are the row and tube designations established for the heat exchanger. Look at previous numbering conventions if data is to be compared. Normally there is less confusion in u-tube bundles, but in a straight-tube bundle review which end is referenced, particularly if previous data is being compared. The supply piping connection end of a straight-tube bundle is normally the reference end.

5.2.1.3.4 Volts Column

The fourth column in Figure 5-4 is the voltage of the flaw indication. Voltage is most closely correlated to the volume of the flaw. Voltage is assigned to the calibration standard defects. Thus, consistency in the calibration set-up is important to allow data from previous inspections to be compared for changes.

Voltages assigned to the calibration standard defects, drilled holes and wear grooves, do not correlate to the absolute volume differences between the two types of indications. Voltage comparisons can only be made between similar types of defects, which are analyzed using the same data channel.

Since voltage is associated with the flaw's volume, it can be related to the structural significance and therefore potential for failure of the defect. This is particularly true for higher pressure service, where greater hoop stress is present, and the defect volume may correlate to its probability of rupture.

5.2.1.3.5 Deg – Degree Column

The degrees of the indication establishes if it is ID (<40 degrees) or OD (>40 degrees). The uncertainty of this indication may increase as the flaw approaches through wall.

5.2.1.3.6 % – Percentage Through-Wall Depth Column

The percentage through-wall reading is self explanatory. The accuracy is nominally considered to be +/- 10%. Numerous factors can influence the nominal accuracy, including appropriate calibration standards, analysis software configuration, probe fill factor, and differences in flaw morphology from flaws in the calibration standard.

5.2.1.3.7 Ind – Indication Column

These abbreviations classify the defects per the descriptions in Section 4.3.1 and Appendix E.

5.2.1.3.8 Chn – Channel Column

The channel used for analysis is primarily of interest to the analyst to compare past inspection results. Since a flaw analyzed using different channels can yield different sizing results, determining the rate of change between inspections requires use of consistent analysis channels.

5.2.1.3.9 Location Column

The flaw axial location in the tube can be important in understanding the most likely cause of the defect. The tube bundle layout and shell drawings can help determine features in the vicinity of the defect such as shell inlets, impingement plates, drain cooler entrance, etc. Flaw axial locations are beneficial for recognizing patterns within the bundle. Comparisons with previous inspection data rely on the location data as well. Errors or inconsistencies in landmarks/locations are not uncommon due to information provided to the analyst or mistakes during the analysis. Review of raw data is sometimes required to verify if the indication is the same as one previously reported. When multiple defects are present, all of them may not be reported unless they are significant enough in size and/or reasonably limited in quantity. When large numbers of defects are present, often only the largest indications are reported.

5.2.1.3.10 Extent Column

This column indicates the length of tube examined (i.e. Table 5-1 data: IUB-inlet to u-bend, OUB – outlet to u-bend, TENTES – tube end north to tube end south). If the entire tube was not inspected, then the partial extent such as 003TES indicating support plate 3 to tube end south, are normally indicated in the extent column with the Indication column noting the tube as blocked.

5.2.1.4 Tube Plugging Calculator

The EPRI Tube Plugging Calculator (ref. 25) provides general guidance for tube plugging considerations. It is beneficial for the BOP Heat Exchanger program to have defined tube plugging criteria, either via the EPRI calculator, or other similar methodology. For safety related heat exchangers, establishing acceptance criteria for the heat exchanger tube inspection results is an NRC expectation per 10CFR50 Appendix B Item V.

The benefits of a tube plugging calculator may includes:

- Incorporating past experience to prioritize damage mechanisms relative to failure probability considering service conditions, tube materials, and related variables.
- Prioritizing plugging based on leak consequences.
- Prioritizing consistency of plugging decisions by varied users.
- Prioritizing a basis from which deviations may be allowed with justification.

Adjustments to the EPRI plugging calculator may be desired to address:

- Damage progression, which is an important consideration that is significantly under weighted.
- High-risk damage mechanism of cracking is under weighted (allows 44% to 64% depth cracks to remain for safety-related heat exchangers; higher for non-safety)
- Under weights wear damage (i.e. FWH wear of 57% allowed regardless of growth rate)
- Lumps damage mechanisms into groups for weighting with considerable variations in the group relative to progression uncertainty (i.e. wear/corrosion/loose part)
- Under weights risk contribution of high energy service compared to cooling water systems (i.e. HP FWH 4% and LP FWH 2% lower plugging limit than cooling water systems).
- Overly conservative plugging threshold for pitting in cooling water service (i.e. max allowed size is 68% for pit in brass tubes, SR, even with no growth rate)
- Many inputs have low weighting and are therefore of limited impact on the plugging threshold. (Some inputs are unrelated to tube leak potential or consequences.)

5.2.1.4.1 Tube Plugging Calculator Program Controls

Tube plugging thresholds are generally conservative, but generically established values cannot factor in variables such as past component operating history, changes in NDE inspection (probes, analysis software, calibration standards, etc.), operational changes, tube plugging margins, etc.

Allowing deviations from a tube plugging calculator is often desired, and can be addressed by establishing controls for the deviation process. Examples of controls may include:

- Conservative deviations are at the discretion of the responsible engineer.
- Less conservative plugging decisions for non safety-related heat exchangers are at the program owner's discretion and noted in the tube plugging report.
- Less conservative plugging decisions for safety related program heat exchangers require concurrence from Design Engineering.

It is beneficial to document the basis for tube plugging decisions as well as deviations from generic tube plugging criteria (if used), even if such documentation is not required by program documents. Documented explanations of tube plugging decisions, versus total numbers or percentage of plugged tubes, helps other individuals understand the basis for actions. This documentation may be in the form of a summary sheet included with the inspection record.

5.2.1.4.2 Tube Plugging Considerations

Tube plugging decisions generally seek to maximize reliability by avoiding tube leaks. However, this must be balanced with additional considerations, such as:

- High leak consequence heat exchangers warrant cautious plugging, while lower consequence applications may justify less stringent plugging.
- Thermal Margin – Safety related heat exchanger thermal performance requirements also define the maximum number of tubes which can be plugged. BOP heat exchangers have functional limits to support equipment operation. Low margin heat exchangers may warrant added NDE follow-up verification actions (i.e. reacquire data, alternate probe type, reanalysis, etc.), as well as other actions to avoid plugging.
- Replacement Cost – Overly cautious plugging can lead to premature replacement.

5.2.1.4.3 Options to Support Reliable Heat Exchanger Operation and Avoid/Limit Tube Plugging

A conservative plugging criteria which maximizes reliability could result in excessive reductions in thermal capability causing unit derating or failure to meet operability requirements. Options to improve confidence in degraded tubes to remain in service may include:

- Pressure Testing – Tubes can be individually pressure tested at design, hydrostatic test, or even bursting pressure to gain information. Primarily for damage thought to be inactive, but with a depth or sizing uncertainty of concern. If applied to crack indications, consider repeated pressure tests on some tubes followed by additional ECT.
- Additional Inspections – reprobe with standard or alternate probes, update calibration standards to improve classification/sizing, or use video probe for more information.
- Tube Pulls – Tubes can be removed for metallurgical analysis of damage type, size, contaminants, etc. This can prove useful for new defect types, unexpected indications, and confirmation of sizing. (See Appendix D for tube pulling considerations)
- Sleeving – Addition of sleeves over the damaged area of the tube can address the damage mechanism and allow tubes to remain in service or be returned to service.
- More Frequent Inspection – May allow less stringent plugging thresholds since potential future degradation is projected over a shorter time period.

Schedule and budget limitations may not support some of the above options during the outage a flaw is detected, but actions in a future outage could support returning tubes to service.

5.2.1.5 Tube Sample Removal

Destructive failure analysis of a removed tube may be beneficial to determine or verify the associated failure mechanism(s). Removal of a tube sample allows confirmation of ECT flaw types, reported depths, and may support improvements to calibration standard defects to better match the flaw morphology as well as ECT set-up and analysis techniques. Tube sample removal is not considered a routine or normal activity, but may be justified to support cause analysis for tube failures or significant degradation. Appendix D includes tube pulling considerations for the responsible heat exchanger engineer.

5.2.1.6 Tube Stabilization

Tube stabilizers are most commonly installed in conjunction with the following conditions:

- Tube is sheared (if stabilization can capture both ends of the sheared tube), to avoid potential damage to surrounding tubes as well as tube breakage foreign material.
- Tube has circumferential cracking or similar risk of shear failure.

- Tubes to be strengthened to provide a physical barrier or support for conditions such as a dropped impingement plate in contact with the tubes, a missing/dislodged impingement plate allowing excess tube vibration below the inlet nozzle, or for tubes subject to significant erosion impingement damage.
- Response to a large tube leak, indicating potentially sheared tubes, stabilization of the surrounding tubes may be performed as a precaution due to risk of damage to adjacent tubes from unsupported failed tube ends and/or potential damage to adjacent tubes due to the leak and/or susceptibility to similar failure modes. When tube inspections are performed with the leak response, the improved understanding of the failure cause and condition of surrounding tubes, then plugging without stabilizers may be sufficient to contain potential damage from a sheared tube.

Tube stabilizers most often consist of bar stock or wire rope (cable). Heat exchangers with manway openings will have a limited number of tubes directly in-line with the manway opening which can potentially be stabilized with longer sections of round bar. Tubes not in-line with the manway require use of wire rope or segmented bar stock pieces with lengths as limited by the distance from the tubesheet before obstructions are encountered. The use of segmented round bar normally requires a means to securely connect the pieces as they are being assembled in the head. The presence of dents in the tubes and sometimes even dips or displacement of the tubes can create difficulty when inserting stabilizers with a high ID fill factor.

Preceding stabilization of failed tubes with a videoprobe inspection allows the condition of the failed tube to be determined as well as the alignment of the tube ends, if sheared, to verify the stabilizing bar can capture both tube ends.

Anchoring the end of the tube stabilizer is an issue to be addressed, unless the full length of the tube is being stabilized (or if using round bar in a u-tube, the full straight length of the tube). An unanchored partial tube length stabilizer may move in the tube due to tube vibrations and could potentially leave the intended target region of the tube unstabilized.

It is advisable for the responsible engineer to assume the stabilizer will eventually be exposed to the shell-side fluid, even if the stabilized tube is not presently failed or breached, and select materials and cleanliness requirements appropriate for the shell-side system. The presence of grease, an oil film or coating is common on wire rope and may also be on bar stock material. Oils or greases are incompatible contaminants in most systems. The presence of an oil or grease film is also believed to be causal for the flash-fire occurring in conjunction with a plug ejection event involving a stabilized feedwater heater tube. Compatibility of the stabilizer material with shell-side fluids, both from a corrosion perspective as well as a contamination perspective for impact on system chemistry, is another consideration.

5.2.2 Heat Exchanger Visual Inspections

The following sections address heat exchanger visual inspections. The first section covers general inspections performed as part of the BOP Heat Exchanger program, and the second discusses safety-related SW heat exchanger visual inspections for the GL 89-13 program.

5.2.2.1 General Heat Exchanger Visual Inspections

Visual inspection is an important PM action along with the tube NDE inspections. Normally the tube ECT interval dictates the schedule for opening the heat exchanger, with visual inspection performed whenever it is opened. In the case of SW heat exchangers, which are subject to GL 89-13, visual inspections may require them to be opened more frequently than ECT inspections. An itemized visual inspection checklist, or similar, is beneficial to maximize effectiveness, and ensure thoroughness and consistency.

Other than the tubes, which rely on ECT, the rest of the heat exchanger primarily relies on visual inspection to verify acceptability or determine if additional actions are needed. Guidance is provided in Appendix I for general heat exchanger visual inspections.

5.2.2.1.1 Inspection Documentation

Thorough documentation of heat exchanger visual inspection is beneficial. A visual inspection checklist provides a means to document inspection findings. Including a copy of the completed checklist in the maintenance work package provides a permanent record for future review.

Digital photographs are often very beneficial. Maintaining an electronic copy of visual inspection records, including photos, on a shared network drive can improve accessibility for future reviews.

Since most general visual inspections are performed in conjunction with ECT inspections, the visual inspection records may be combined in an overall inspection record with the ECT results.

5.2.2.1.2 Borescope or Videoprobe Inspections

Videoprobe inspection equipment can be a very effective tool to augment visual inspections. Their use is not generally a required PM action versus a follow-up or contingency action. Videoprobe inspections are sometimes warranted for follow-up of ECT ID indications, as well as verification of tube cleaning effectiveness, such as for scale or tenacious deposits. Videoprobe inspections of failed tubes often provide beneficial detail.

Special conditions may warrant PM driven videoprobe inspections, such as inspections for erosion damage in softer metal tubes (i.e. copper alloys) at epoxy or sleeve transitions, since damage at this location is difficult for ECT to detect.

5.2.2.1.3 NDE – MT/PT/RT/VT/UT Inspections

NDE inspections other than tube ECT (and possibly shell UT) are not routine PM actions. They may be required as follow-up actions for visual inspections, such as a possible crack at a partition plate weld or to quantify corrosion depth.

5.2.2.2 GL 89-13 Program Heat Exchanger Visual Inspections

The GL 89-13 heat exchanger visual inspection is focused on thermal performance verification, although it includes the structural integrity checks of a general visual inspection. Additional information regarding GL 89-13 is provided in Section 2.1.1.1.

Detailed guidance on GL 89-13 visual inspections, including checklists and acceptance criteria, is provided in Reference 29, Section 3. It is beneficial for GL 89-13 program visual inspections to use an inspection checklist and acceptance criteria, as appropriate for the site.

Appendix B includes considerations for integrating GL 89-13 program visual inspections with other inspections, tests, monitoring, and program actions.

Appendix H includes additional items from NRC inspection procedure 71111.07 (ref. 3) which may need to be addressed in visual inspection procedures.

Heat exchanger visual inspections are performed in lieu of thermal performance testing for GL 89-13 commitments at most stations for some or all of their SW heat exchangers. The NRC Inspection Procedure 71111.07 (ref. 3) for annual and triennial UHS inspections includes the statements noted below related to visual inspections. As noted in Section 2.2.2, the inspection procedure is not a regulatory requirement, but does reflect compliance expectations for the GL 89-13 program and related actions for the SW system and UHS function.

> 2.02.b *"…. Verify that testing, inspection, maintenance, and monitoring of biotic fouling and macrofouling programs are singularly or in combination adequate to ensure proper heat transfer."*
>
> 2.02.b.2.a For inspection/cleaning: methods are consistent with *"as-found conditions identified and expected degradation trends and industry standards"*
>
> 2.02.b.2.b *"Inspection and cleaning activities have established acceptance criteria and are consistent with industry standards."*

The NRC's inspection procedure notes visual inspection activities should be consistent with "industry standards". EPRI technical reports may serve the function of an industry standard in the absence of other guidance. Visual inspection guidance documents and field checklists which are consistent with the information in reference 29 are not requirements to satisfy GL 89-13 commitments, but they are generally beneficial for the GL 89-13 program.

5.2.3 Tube Cleaning for Open Cooling Water System Heat Exchangers

Tube cleaning is a commonly specified PM activity for heat exchangers with open cooling water supplied to the tube side. Tube cleaning removes thin bio-films and deposits (e.g. manganese) which can cause accelerated corrosion of susceptible materials and/or thermal degradation.

Cleaning tubes in closed loop service is not a typical PM action. The need to clean closed loop heat exchanger tubes generally represents a failure or problem with the water chemistry control, and would therefore be a corrective maintenance action. Visual inspection of the heat exchanger is capable of detecting most abnormal conditions warranting tube cleaning. Excess buildup of corrosion products in FWH tubes, to the extent it interferes with ECT data quality and/or acquisition, has occurred at several stations. Chemistry involvement in such cases can help determine if the corrosion product buildup represents a condition to be expected in the future and therefore if cleaning is justified as a FWH PM action.

The frequency at which tube cleaning is needed in open cooling systems can vary greatly based on water quality, chemistry treatment, seasonal disruptions, and related factors. The best guidance is often based on site-specific experience. In addition to cleaning open cooling water heat exchanger tubes when opened for a scheduled ECT inspection, cleaning may be required as corrective maintenance or as a condition monitoring triggered PM action.

The appropriate tube cleaning method also varies greatly, based on water quality, chemistry treatment, and similar site-specific parameters. The tools needed to effectively remove existing bio-films and deposits can vary from relatively simple scrapers/balls/brushes propelled through the tubes by air/water, to rotating brushes, hydrolance equipment, or chemical cleaning. The optimum cleaning method is the simplest, fastest, safest and least expensive action which effectively cleans the tubes. Ideally previous cleaning actions and results are sufficiently documented to provide a basis for selection of the currently used cleaning methods. More aggressive cleaning methods sometimes continue to be used out of custom or habit versus use of more economical, faster, or safer options which may be equally effective. Additional information on tube cleaning can be found in Section 6.2.5 of reference 20 and Chapter 7 of reference 37.

5.2.4 PM Actions for Heat Exchangers without ECT Capability

Some heat exchangers do not allow reasonable access for tube ECT or in some cases for tube-side visual inspection. The leak consequences may justify action to maintain high reliability and avoid tube leaks. A common example is HVAC room cooling coils of the serpentine design shown in Figure 4-1. Other examples may include regenerative heat exchangers, seal coolers, sample coolers, and pump or motor lube oil coolers.

PM options to maintain tube integrity are limited when NDE is not possible. The potential damage mechanisms can be determined based on the heat exchanger materials of construction, water quality, design and operation. Comparison of tube degradation rates observed in accessible heat exchangers with similar materials and service may provide reasonable guidance on expected degradation rates to establish periodic replacement intervals, if justified.

Relatively inexpensive heat exchangers such as sample coolers or small pump coolers may be addressed by maintaining a spare in stock, if leakage consequences are acceptable. Maintaining spares of larger and more expensive heat exchangers may be justified.

Maintaining a spare does not provide reliability, but may allow sufficiently quick return to service in response to a leak for some applications to avoid replacement prior to leakage. The initial leak may also serve as a PM trigger to replace similar heat exchangers. Future intervals could be established to bound the initial failure interval if reliability improvements are not made to materials, design, water quality, flow rate, and other variables.

Heat exchangers with moderate to high installed costs may warrant destructive examination of the first replacement for a detailed condition assessment. This information could then be used to guide the replacement decisions for the remaining similar heat exchangers.

License renewal commitments may result in the need for one-time replacement of some critical heat exchangers with designs that do not support NDE examination.

5.2.5 Shell-Side Inspections and NDE

As noted in Section 4.3.2, damage to heat exchanger shells is not common in most applications. Heat exchanger PMs to check shell wall thickness are normally not required other than for:

- Feedwater Heaters – Significant OE has been issued on this topic following the rupture of a feedwater heater shell at a nuclear plant in 1999 (See Section 4.6.4). Shell erosion damage was subsequently found at numerous additional plants performing inspections in response to this event. Erosion from steam impingement and occasionally from tube leak impingement can damage the heater shell. These inspections are often part of the Flow Accelerated Corrosion (FAC) program, but may be addressed by FWH PM actions.
- Open cooling water supplied to the shell side with carbon steel materials may warrant additional PM actions. Corrosion damage to carbon steel components on the tube-side of an open cooling water heat exchanger can be monitored by visual inspections when the heat exchanger is opened for cleaning or ECT. Open cooling water supplied to the shell-side generally does not have a similar inspection opportunity. External UT or similar NDE methods may be appropriate. If internal baffle plates are also carbon steel (generally a design error for open cooling water service), then ECT inspections may detect partial or missing baffle plates. The loss of baffle plates degrades thermal performance and may reduce the acceptable shell-side flow allowed to avoid damaging tube vibration.
- PWR blowdown heat exchangers, if steam condensing on shell side, depending on the heat exchanger design and the pressure reduction location. Reference 20 notes that laminations on older shells are common and they are not wall loss.

5.2.5.1 Shell-Side Internal Inspection

The shell-side of most heat exchangers is not accessible for internal inspection. Exceptions include the main condensers and MSRs. The use of a detailed inspection checklist or guidance documentation is beneficial.

Shell-side inspections are beneficial when opportunity exists. Examples include when a tube bundle is pulled or performing limited inspections with videoprobe equipment when shell relief valves are removed or similar access is available.

Required shell-side internals inspections would normally only be condition driven in response to a specific issue or event. Examples might include inspections of carbon steel baffle plates in raw water service (design error), or inspection of support plates or drain cooler shrouds in response to active tube degradation and/or plate ligament debris in the drain system.

5.2.6 Pressure/Leak Testing

Pressure testing has been widely debated and applied over the years. It is by definition only useful after a leak has occurred. Small leaks in some applications do not have sufficient adverse consequences to be a considered a failure or cause a loss of function, although a larger leak might be unacceptable. Pressure leak testing has many applications as a corrective maintenance practice to detect indicated leaks, but is discussed in this section related to its use as a PM action.

Pressure leak testing is not generally performed as a PM action due to the following principal reasons:

1. ECT is a preferred PM action for tubes due to damage detection prior to a leak occurring.
2. Monitoring, either during operation or shutdowns, can detect a leak, often including a small leak. This monitoring provides a less expensive and on-going opportunity for leak detection compared to periodic pressure tests, in many applications. Some sites may classify monitoring actions such as FWH level checks, performed while the unit is off-line with condensate in service, as pressure/leak testing, but it is discussed as a monitoring action in this guide. Actions not requiring the heat exchanger to be isolated and opened are generally considered monitoring versus testing.

For many heat exchangers both of the above reasons for not pressure leak testing are true. When only one of the reasons is applicable, additional basis may include a very low probability of leaks, such as due to superior materials of construction (i.e. AL6XN tubes), design features (i.e. welded tube-to-tubesheet joints), and operating history (absence of leaks after years of service).

For some heat exchangers neither reason applies, or they have limited applicability. Considerations which may justify pressure/leak testing include:

- Small leaks are not readily detectable with current monitoring methods AND consequences of a small leak could be significant.
- Tube NDE may have lower reliability due to materials, design, or degraded conditions.
- Pressure/leak testing of an entire heat exchanger may be possible as a go/no-go test with little additional expense or resources.
- Leakage history has included problems with plugs, tube-to-tubesheet joints, sleeve sealing, or other locations not addressed by ECT.

5.2.6.1 Small Leak Detection and Consequences

Small leaks may not be readily detectable with current monitoring methods due to:

- Tube and shell side operating pressures are similar, providing minimal leakage during normal operation. Increased leakage during shutdown may be mistakenly attributed to shutdown conditions (component cooling water, hydrogen coolers, etc.).
- Process fluid has automatic method for removal of cooling water in-leakage (lube oil system with water removal skid or hydrogen cooler with hydrogen dryer).
- Minimal difference in shell and tube side process fluids (e.g. feedwater heater).
- Small leakage of process fluid into cooling water loop is difficult to detect.

Some of these examples can be addressed by careful monitoring of shutdown parameters by chemistry, operations, and/or engineering, although changes to current monitoring methods or their timing may be needed. Correctly interpreting leakage data from shutdown/startup periods is more difficult due to the large number of changed conditions.

The consequences of small leaks would generally not be considered significant if a standby heat exchanger was available, or if a safety-related heat exchanger remained capable of performing its intended safety function and could be repaired in less than half the allowed out-of-service time per Technical Specifications. (NOTE: These consequences being “not significant” are only in context of justifying additional actions beyond performance of tube NDE to address detection of a low probability leak.)

5.2.6.2 Tube NDE of Low Quality/Reliability

Tube NDE may be of lower quality or reliability due to:

- Tube materials such as ferritic stainless steels (Ebrite™, Sea-Cure™, Type 439) requiring alternative NDE methods which may yield lower quality data results.
- Tube designs such as finned tubes (integral or external) are more difficult to analyze and have increased “blind spots” (i.e. integral finned tubes). The incidence of missed leak locations is notably higher in finned tube applications. Heat exchangers with finned tubes and a past history of or high susceptibility to leakage may warrant pressure testing as a back-up to ECT, if monitoring detection capability is not good.
- Degraded tube conditions such as heavy pitting, OD erosion, or cracking, if detected and left in-service, significantly increase the risk of missing a through-wall defect. Heavily pitted tubes are more likely to also experience ID thinning (if copper alloy) which reduces the accuracy of size comparisons with the calibration standard. Large numbers of pits may also include pits of different aspect ratios, including those different from the calibration standard. Cracking is not normally left in-service, but if indicated, increases the risk of undetected cracks (i.e. circumferential cracks) unless specialized probes are used.

5.2.6.3 Summary

Pressure leak testing is not justified for most heat exchangers due to in-service monitoring leak detection capability and the ability of ECT to detect tube damage prior to leaks developing. Where these are not applicable or do not address sources of past leakage, pressure leak testing may be an appropriate PM action. Reference 20, Section 6.2.4, includes additional information on various pressure leak testing methods.

5.2.7 Other Heat Exchanger PM Actions

5.2.7.1 Tube ID Measurement

Heat exchangers with copper, 90-10 copper-nickel or Admiralty brass tubes in open cooling water systems are potentially susceptible to tube ID general erosion, discussed in Section 4.3.1.3. Periodic measurements of the tube internal diameter (ID) with a tube hole gauge can check for this condition. A tube sample pattern can be used to check different areas of the tube bundle and provide statistically meaningful data. Measurements at both tubesheets (most low pressure heat exchangers are straight tube) are beneficial.

5.2.7.2 Elastomeric Plug Retightening/Replacement

Tube plugs containing non-metallic material may be present in low pressure heat exchangers and have been widely used in condensers. The term “elastomeric plug” is applied generically, although some plugs may be primarily metal or include a variety of non-metallic materials. Elastomeric plugs have a sufficient history of age-related leakage problems to warrant the PM actions listed below, if they are installed in a high leak consequence application.

1. Retighten the plugs periodically to address relaxation/creep of the elastomeric material.
2. Replace the plugs periodically to address age-related deterioration of the elastomers.

See Section 5.5 for a discussion on tube plug selection. See Section 4.6.1 for discussion of industry experience involving ejection of elastomeric condenser tube plugs.

5.2.7.3 Removable Tube Bundle Gaskets

Gaskets are normally replaced when a heat exchanger is opened for inspection. Removable tube bundles include an additional gasket(s) beyond those associated with removal of the cover for tube-side maintenance. Removable tube bundle gasket materials and designs vary widely and may include soft iron, neoprene, or traditional sheet gasket material depending on straight tube or u-tube design, service conditions, and related variables. The BOP Heat Exchanger program PM evaluations can address the suitability of the additional gaskets for long-term service, the potential consequences of gasket leakage, and any associated PM actions which may be justified.

5.3 Thermal Performance Testing

Thermal performance tests of SW heat exchangers are conducted at many sites per their GL 89-13 response commitments. Thermal performance testing of other heat exchangers may also be conducted due to licensing requirements or other regulatory commitments besides GL 89-13. EPRI guidance for thermal performances testing is noted in Section 2.2.3. Heat exchanger thermal performance tests are also described in various ASME Performance Test Codes (PTCs), which are similar in nature to the heat transfer method described in the EPRI references and provide comparable high confidence results.

Performing a heat exchanger thermal performance test which achieves low test uncertainty often requires significant resources. Testing of closed loop heat exchangers for thermal performance capability on a periodic basis is typically not warranted due to extensive experience supporting the ability to maintain fouling within normal design values with standard closed loop chemistry control practices. Thermal performance tests may be a useful confirmatory action tool, but they are generally not justified on a periodic basis as a programmatic action unless regulatory requirements apply.

5.4 Heat Exchanger Monitoring

System engineering is traditionally the engineering group responsible for monitoring and trending of parameters for in-service heat exchangers. Monitoring heat exchangers and their associated systems are intertwined, since changes in heat exchanger parameters may be symptoms of a system problem and vice versa. Thus, system engineering is normally the lead engineering group for heat exchanger monitoring, with operations, and chemistry also performing important monitoring actions.

The principal thermal performance monitoring methods applicable to heat exchangers are described in EPRI Heat Exchanger Performance Monitoring Guidelines, EPRI NP-7552 (ref. 27), with additional information in references 28 and 29. These references present the details of each method and explain their strengths and weaknesses.

An additional potential thermal performance monitoring method for macrofouling tube blockage of cooling coils is the use of thermography images. These images are capable of detecting the differences in tube temperatures associated with flowing versus obstructed tubes on the outer tube rows of accessible room coolers. This predictive maintenance or monitoring tool may be warranted in open cooling water systems with room cooling coils where a history of macrofouling issues exists.

In addition to thermal performance issues, heat exchanger monitoring for tube leaks may also be performed, either directly or indirectly.

5.4.1 System Engineering Monitoring

System engineering monitoring involves data obtained from field observations (walkdowns), plant computer data points, and may include review of operations and chemistry data.

Heat exchangers such as feedwater heaters (FWHs), moisture separator reheaters (MSRs), and the main condenser are well instrumented, providing a variety of direct trending parameters. These components have EPRI reference handbooks providing information regarding monitoring. (see ref.s 43, 50, 68) Routinely monitored parameters for FWHs include inlet/outlet temperatures on the tube and shell sides, shell pressures, terminal temperature difference (TTD), drain cooler approach (DCA), operating level, level control valve position (and air supply signal, if pneumatic), heater drain flow (if available), and main feedwater pump suction pressure. Additional detail for these components can be found in the noted references.

Other heat exchangers may have lesser quantity and quality of trendable parameters. Difficulties trending heat exchanger parameters may result from variable heat loads, variable cooling water temperatures, varying flows due to temperature control valves (TCV), or system alignment changes, and operation at conditions well below design values. The availability of temperature, pressure, and flow data as well as related parameters such as control valve position can all affect if trending is possible. Monitoring non-meaningful data points wastes effort and could result in a false confidence of acceptable operation which may be inappropriately used to refute or dismiss valid warning signals from other components or elsewhere in the system.

5.4.2 Chemistry Monitoring

Chemistry monitoring of both open and closed loop cooling water systems is important for maintaining proper heat exchanger thermal performance. The type of chemistry monitoring performed, the monitoring results, and its importance to heat exchanger performance are all beneficial for the heat exchanger engineer to understand. Chemistry monitoring can also have significant impact on tube integrity via the avoidance of pitting conducive environments.

Chemistry monitoring of open cooling water systems typically includes the following:

- Biocide concentrations in supply header and at remote components and/or return headers.
- Side-stream biological monitoring (bio-growth box, fouling monitor, etc.).
- Corrosion coupon rack.

Closed cooling water system chemistry monitoring of interest to the engineer includes:

- Conductivity – may provide early indication of in-leakage from a tube leak.
- Iron and Copper – indication of effectiveness of corrosion inhibitors (if closed system includes copper alloy heat exchanger tubes).
- Microbiological Content – controlled to avoid fouling and MIC.

The active engagement of chemistry and engineering personnel is beneficial to ensuring reliable heat exchanger performance. Periodic meetings between chemistry and engineers responsible for SW heat exchangers (system engineers and program engineer) are a beneficial practice. An example of a meeting agenda is provided in Appendix F. Closed system chemistry control is normally more stable and issues are addressed on an as-needed basis.

5.4.3 Operations Monitoring

Monitoring by operations often provides the initial detection of heat exchanger problems, due to the frequency of data collection. The system engineer is typically aware of the parameters trended by operations and their action thresholds. Examples of operations trends related to heat exchangers include FWH level, approach temperatures, differential pressures, flows, makeup/surge tank levels, as well as drain checks for cooling water contamination of lube oil, hydrogen and other systems. Operations monitoring of two-zone FWHs may also include level checks when the condensate system is in service but the turbine is off-line (i.e. shutdown, startup, or post-trip). This monitoring can detect FWH tube or plug leaks.

Operator rounds provide opportunity to detect unusual noises or external leaks from heat exchangers.

5.4.4 Operations Tests/Surveillances

Operations tests are generally due to regulatory/licensing requirements, such as Technical Specification surveillances and In-Service Testing (IST). Operations tests and surveillances involving heat exchangers are often less comprehensive than thermal performance tests, and may only confirm a single parameter such as a minimum flow value. Pump IST tests in SW systems with one set of heat exchangers may provide data to ensure minimum required flow to the heat exchanger is maintained.

5.4.5 Plant Thermal Performance Monitoring

Plant thermal performance monitoring is another potential source of heat exchanger data for the system engineers responsible for the FWHs, MSRs, and main condensers.

5.4.6 Flow Tests

Flow tests may be a source of monitoring data related to heat exchangers, although it is most often the responsibility of system engineers and not the heat exchanger programs.

Periodic flow tests are commonly performed for SW systems. Flow testing ensures required minimum flows are provided to each heat exchanger in the system. Once-through open loop plants with multiple heat exchanger types may perform flow balance/verification tests each outage, while plants with recirculating SW systems may justify less frequent tests.

Closed systems do not normally warrant periodic system flow tests, due to their chemistry control and the absence of macrofouling debris sources and corrosion nodule buildup often seen in open systems.

Non-safety related open cooling water systems are normally in service supporting plant operation. Routine heat exchanger monitoring is generally relied upon to provide evidence of adequate flow. Flow checks may be performed as a follow-up to adverse trends, or as operating experience warrants.

Flow testing is primarily focused on ensuring minimum required flows. Additional considerations include if measured flow is excessive and contributing to ID erosion of copper alloy tubes, or if flow velocity is too low (even if above required minimum) allowing sedimentation fouling. Flow tests performed with all safety related heat exchangers aligned may not be representative of flows during normal operation or surveillance tests (if some heat exchangers are normally in standby).

5.5 Tube Plug Selection

The selection of tube plugs is normally left to the heat exchanger engineer and/or mechanical maintenance department. Some considerations, observations and comments are noted below.

5.5.1 Plug Leakage Considerations

The robustness of the selected plug design should reflect the consequences of plug leakage. Similarly, the installation guidance, training, and verification activities should also reflect the consequences of leakage as well as the complexity of plug installation requirements.

> **Key Technical Point**
>
> The consequences of tube plug leakage should be factored into tube plug selection, as well as the level of detail provided in plug installation guidance, training, and verification actions.

5.5.2 Plug Failure Mechanisms

Sudden/catastrophic plug failure is less frequent but may occur due to:

- Debris impact (dense, heavy object) to a tapered plug or pop-a-plug center pin.
- Water hammer (although uncommon for the pressure wave to reflect off of the tubesheet).
- Sudden thermal and/or pressure transient with trapped water in tube.

Leakage is the most commonly seen plug failure mode, often related to the following:

- Preventive plugs lacking initial seal or loosened, followed by subsequent tube wall failure.
- Elastomeric seals – aging/cracking, creep, loss of preload.
- Transients – pressure/temperature may loosen seal allowing leakage.

Since action generally can't be taken to reduce the consequences of plug leakage, risk reduction actions involve reducing the probability of plug leakage by considering the following:

1. Robust plug designs – provide margin for credible transients and off-normal conditions (i.e. consider sealing area, plug capture, ability to maintain sealing force, etc.).
2. Plug installation instruction detail in accordance with the complexity of the plugging method used (i.e. installation details in WO or procedure).
3. Plug installation training for maintenance (pending complexity of plug type). May include "just-in-time" training prior to outages.
4. Validation steps to ensure plugs are properly installed in the correct locations. (could include tube ID validation; inspection for issues which could affect plug sizing or sealing such as rough ID, coated tubesheets, welded tubesheet joint, tube end projecting past tubesheet, plug tooling set-up, and break-away piece removal verification, as applicable).

5.5.3 Plug Design Considerations

- What is tube ID range for installation?
- Compare pressure/temperature rating for plug to design ratings (exclude tapered metal plug). Consider factor of safety for plug pressure rating versus tube design pressure.
- If plug installation risks damaging the tube-to-tubesheet joint integrity, tubesheet ligaments, or sealing of plugs in adjacent tubes. What precautions are in place to avoid the potential damage and to detect it if it occurs?
- Is plug material compatible with system water chemistry?
- In open cooling water, does plug material create a galvanic cell with tube or tubesheet?
- If plug design life is limited (i.e. includes non-metallic or elastomeric material), then are actions established to periodically retighten (if applicable to design) and replace?
- Has ability to remove plug in the future been considered if plugging a non-leaking tube?
- If a tapered plug is planned for use in > 300 psig (20.7 bar) service with a non-leaking tube, has industry plug ejection operating experience been considered? (See Section 4.6.1)

5.5.4 Temporary/Limited Duration Plugging

Tube plugging performed during forced power reductions or shutdowns may warrant the use of lower quality plugs due to availability of plugs or support equipment, speed/ease of installation, and ease of removal for insurance plugs installed in the absence of ECT data and more definitive causal information for the leak. Follow-up actions can be initiated to remove these plugs to support detailed failure investigation, potential tube recovery (insurance plugged tubes), and installation of higher quality or more permanent plug designs. See Section 3 of Reference 20 for discussion of various tube plug types.

5.6 Operations Actions

Various actions performed by Operations which are important to heat exchanger reliability, performance and service life are briefly noted in this section.

5.6.1 Fill and Vent

This is a routine action when placing a heat exchanger or system in service. Heat exchangers can be susceptible to retaining air pockets which may include leaving tubes air bound. Heat exchangers at high points in the system are at greater risk of accumulating air from the system.

5.6.2 Alignment Sequence to Avoid Thermal Shock

Placing heat exchangers in service with elevated process fluid temperatures requires the precaution of placing the cooling water in service first and slowly initiating the hot process fluid flow. This minimizes thermal shock which can cause cracked welds, tube-to-tubesheet joint damage in straight tube bundles, and potentially gasket leaks. The greater the differential temperature between the process and cooling water fluids, the greater the need for controlled introduction of the process fluid (e.g. decay heat, shutdown cooling or RHR heat exchangers are examples which could have large initial temperature differentials). Thermal stress damage may result in immediate cracking or cumulative thermal stress ratcheting may result in cracking after multiple thermal cycles.

5.6.3 Temperature Rate-of-Change Limits

Temperature change limits, similar to the initial alignment controls above, are specified for some heat exchangers to maintain thermal stresses within design limits. If the heat exchanger OEM has provided these limits, they should be incorporated into Operations procedures.

It is highly beneficial when specifying a heat exchanger to provide the OEM with the full range of operating conditions for both the shell and tube side fluids, versus a single thermally limiting design point, which was historically a common practice.

5.6.4 Flow Limits

Operational control of maximum shell-side flow can be very important to avoid damaging vibration of heat exchanger tubes. The damage progression time to tube failure can be reduced to days with high vibrations caused by excessive shell flow. Maximum flow limits specified by the heat exchanger OEM should be incorporated into operating procedures for systems capable of supplying greater flow than the limit. See Section 4.6.2 for related industry events discussion.

Clarifications or additional comments for shell side flow limits:

- Maximum flow limits or analyzed overload values may not be intended to support long-term operation just below those limits, versus representing a threshold for temporary loading. The design point on the heat exchanger data sheet represents the flow condition evaluated by the OEM for vibration. Prior to operation at or near the maximum flow value or evaluated overload limit for an extended time period, it is prudent to contact the OEM for concurrence regarding the suitability of the predicted vibrations for sustained operation, and to reset the PM schedule for ECT inspection to the next outage to confirm wear and vibration damage remain acceptable.
- Degraded heat exchanger tubes or internals were NOT considered in the OEM overload or maximum flow limits. The potential for degradation detected by heat exchanger inspection and ECT (i.e. support/baffle plate wear, tube-to-tube wear, ID erosion, etc.) to adversely affect the originally specified overload or maximum flow limits is a consideration for the responsible engineer. Heat exchangers with notable vibration related damage may not be suitable for overload operation, since not only will damage rates increase significantly, but the ability of the tubes to withstand this damage may be lower with preexisting degradation.
- Improvements in heat exchanger modeling to address shell-side flow induced tube vibration have been made since the 1970's. Heat exchangers built prior to 1980 are less likely to have had tube vibration analysis or if performed, it may have been with less rigorous analysis methods and acceptance limits than those used in more recent design.

Maximum tube side flows are not specified for most heat exchangers, even if a maximum limit for shell side flow was provided. Tube side flow in nuclear plant heat exchangers is generally only a concern for long-term damage with copper-alloy tubes (carbon steel tubes may also be susceptible, but are rarely used in nuclear units). If tube-side velocities above the flow erosion thresholds noted in Section 4.3.1.3 are possible, precautions to limit service time under those conditions may be warranted.

5.6.5 Lay-Up

Practices for lay-up of standby heat exchangers in open cooling water systems vary widely. Actions to reduce fouling and corrosion environments during lay-up may include ensuring the layup water was treated with biocides or draining the heat exchanger and leaving in air, inert gas, or clean water for lay-up. Leaving a heat exchanger drained is generally limited to those manually placed in service versus standby safety-related heat exchangers which may be automatically aligned. The need for special layup is strongly influenced by:

- Tube Material – titanium and high alloy SS are generally resistant to corrosion related problems, but are susceptible to biological fouling. Copper alloy tubes and low alloy SS (304/316) can be susceptible to MIC and under deposit corrosion, with 90-10 Cu-Ni sometimes experiencing aggressive pitting in lay-up if the protective oxide layer is lost.
- Water Quality and Treatment – untreated or minimally treated raw water in once-through open cooling systems may include high biological content. Systems that biocide treat intermittently are at increased risk of lay-up with untreated water, unless heat exchanger isolation is synchronized with biocide injection.
- Poor Isolation/Valve Leakage – Low volume leakage past isolation valves is generally acknowledged as the worst lay-up condition in open cooling systems. Leakage past valves results in low velocity conditions allowing sedimentation of suspended materials and replenishment of oxygen to speed corrosion. The water leaking past the isolation valve may be biocide treated, but the biocide may not penetrate the sediment layers, allowing unchecked biological activity. Valve leakage may cause problems in continuously treated systems, which do not have a history of significant layup problems, due to biological ingress during brief out-of-service (OOS) periods for the chemical treatment system. The sludge or sediment deposit may shield biological material entering while the biocide system is OOS. Since most heat exchanger isolation valves are not frequently checked or repaired for leakby, the development of seat leakage may result in increased fouling and tube damage (i.e. pitting) compared to historical norms.

Layup decisions are site-specific, and consider variables such as water quality, plant experience and tube materials. Related PM actions can include maintenance of isolation valves. Plants with intermittent biocide treatment may use procedure precautions to isolate heat exchangers when the biocide system is in service. Plants with a high frequency of OOS time for their biocide treatment systems may warrant similar precautions. Establishing heat exchanger lay-up practices is not an on-going program function or a normal responsibility of the BOP Heat Exchanger program. The program owner may provide technical input if lay-up practices or tube materials are being changed. The program can provide feedback to those responsible for lay-up actions such as changes in heat exchanger degradation noted by visual inspection and/or ECT.

5.6.6 High Velocity Flushes

Flushes may be performed to reduce biofilm and sedimentation, and occasionally macrofouling (i.e. shell buildup) from heat exchanger tubes and surfaces in open cooling systems. The need for periodic flushes is commonly associated with flow throttling either manually or by flow/temperature control valves due to seasonal temperature variations of the cooling water. It is often not desirable for the process fluid stream to have large temperature swings. Bypassing the heat exchanger with a portion of the clean process fluid is a preferred design for temperature control over throttling flow from an open cooling water system due to sedimentation issues.

Low tube velocities associated with throttling may result in increased bio-film growth on the tubes and sedimentation of suspended solids. This accumulation has detrimental thermal effects regardless of tube material and detrimental tube integrity impacts unless highly pitting resistant tube materials (i.e. titanium and high alloy SS) are present. High velocity flushes may not restore tube cleanliness to previous unfouled values. However, flushes may be effective in restoring protective oxide films on the tube materials and significantly reduce pitting rates.

Flushes are not practical in all applications. If a back-up heat exchanger is not available, then the increased tube flow may cause undesirable process fluid temperature swings.

5.7 License Renewal

As described in sections 2.4.3.1 and 3.4.3.1, the nuclear license renewal process to extend the original 40 year operating license for an additional 20 years has been applied or is expected to be applied to most US nuclear units. Those sections note that it is beneficial for license renewal commitments which impact the programs to either be incorporated into applicable program documents and databases or tracked for future implementation. Examples of heat exchanger degradation mechanisms addressed in the license renewal process which may not be specifically addressed in existing heat exchanger programs are noted below.

Selective leaching of gray cast iron (e.g. heads for heat exchangers), copper alloys with greater than 15% zinc (e.g. Muntz metal tubesheets or Admiralty brass tubes) or 8% aluminum (i.e. aluminum bronze tubes or tubesheets) are specifically identified in the license renewal GALL report (ref. 4), but are not addressed in most standard PM templates. NUREG-1801 revision 2 clarifies that dealloying inspections of copper alloys with greater than 15% zinc exclude inhibited brass. This clarification was not present in earlier revisions and may not have been applied to license renewal applications submitted prior to 2010, when revision 2 of NUREG-1801 was issued. Admiralty brass tubes installed in US nuclear plants are in almost all cases inhibited (alloy C443). The susceptibility to selective leaching is significantly reduced with inhibited brasses, although it may not be eliminated. Industry experience has noted some cases of dealloying of inhibited Admiralty brass tubes. The ability to detect and accurately characterize dealloying with ECT or similar NDE techniques is a topic for discussion between the BOP Heat Exchanger program owner and NDE group or service provider to determine the most effective means of addressing this potential risk. Methods for detection in NUREG-1801 for brass tubes involve visual detection of change in color from the “normal” yellow color to a reddish copper color. (See NRC Information Notices 84-71 and 94-59 for selective leaching related reports.)

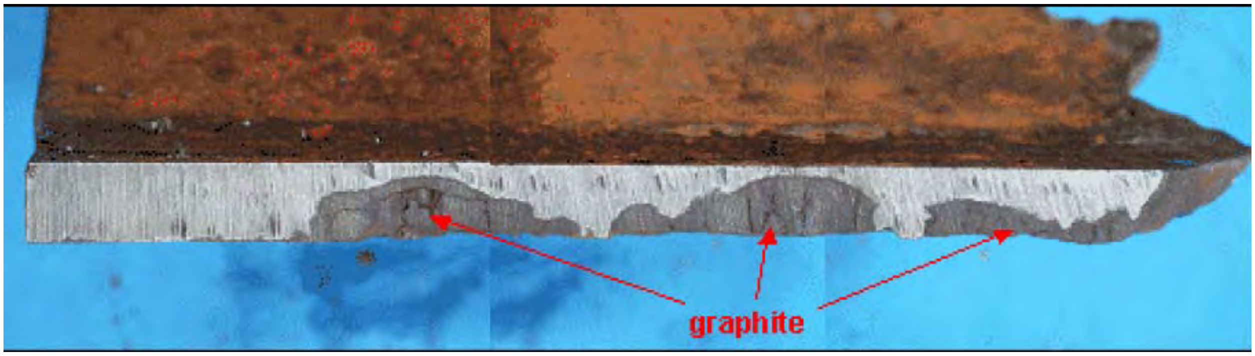


Figure 5-4
Graphitic corrosion of cast iron

5.8 Power Uprate Considerations

Power uprates have helped improve the economic efficiency of the nuclear fleet. Uprates are becoming larger in size, either individually or in aggregate. As of 2010, four stations had completed uprates of 20% above their original licensed power and another 11 have increased power by 15-20%. In addition to thermal power uprates, numerous stations have implemented turbine upgrades to improve efficiency and further increase output. These turbine upgrades also impact steam conditions supplied to the steam path heat exchangers.

Prior to implementing a power uprate, a detailed technical analysis evaluates the impact to plant components, including the main condenser, feedwater heaters, and moisture separator reheaters. This analysis may result in decisions to replace some of the steam path heat exchangers, particularly degraded feedwater heaters and main condenser tube bundles, as well as MSR internals. Post-uprate industry experience with steam path heat exchangers remaining in service includes several cases of unexpected increases in tube degradation and elevated failure rates. These experiences indicate improvements may be warranted to uprate impact evaluations as well as the post-uprate condition monitoring and inspections. Appendix C provides additional detail for heat exchanger considerations related to power uprates.

6
HEAT EXCHANGER RELATED INDUSTRY GROUPS AND MEETINGS

6.1 EPRI Heat Exchanger Performance Users Group (HXPUG)

The Heat Exchanger Performance Users Group (HXPUG) addresses both GL 89-13 heat exchanger thermal performance issues as well as structural integrity issues such as tube leaks. The group includes members responsible for GL 89-13 program actions and/or BOP Heat Exchanger program actions. Utility member participation may include:

- Annual HXPUG meeting
- Periodic webcasts
- Collaboration web page for questions/answers and information exchange.

HXPUG has developed a variety of EPRI reports and technical documents related to heat exchanger performance testing, inspection, maintenance, and programs.

6.2 EPRI Service Water Assistance Program (SWAP)

The Service Water Assistance Program (SWAP) provides service water engineers with multiple access points for obtaining technical guidance to address service water issues. Members gain access to:

- A technical report library containing more than 2,300 reports on 300 topics
- Industry surveys that capture fleet-wide service water experience
- Training courses on piping, corrosion, and heat exchanger testing

SWAP, which has been available to EPRI members since 1988, makes it possible for engineers to access the nuclear fleet’s broad knowledge base and apply it to service water issues. Built as an “information clearinghouse,” the collective utility experience available through SWAP represents a valuable resource for field-proven solutions and advice.

To facilitate technology transfer, SWAP members designate a SWAP Coordinator as the point of contact between EPRI SWAP and the plant. A SWAP Coordinator's Manual helps guide access to SWAP resources and services, and EPRI sponsors an annual meeting of SWAP Coordinators for sharing operating experience and discussing solutions to field problems.

6.3 EPRI Balance-of-Plant (BOP) Heat Exchanger NDE Symposium

The biennial EPRI Balance-of-Plant Heat Exchanger NDE Symposiums are a forum for discussion, presentation, and exhibits on this topic. The symposium presentations are available from EPRI (example: 11th EPRI BOP Heat Exchanger NDE Symposium, August 2010, see EPRI report 1021661). These conferences provide information and an interface opportunity for the BOP Heat Exchanger program owner as well as utility ECT qualified NDE personnel. Most of the BOP NDE vendors are in attendance, allowing personnel to be educated on the latest technologies involved in inspection, condition assessment, and repair of BOP heat exchangers.

The symposium focuses on nondestructive evaluation (NDE) technologies and lessons learned related to the inspection, condition assessment, and repair of balance-of-plant (BOP) heat exchanger components. Pre-symposium courses are often available, followed by paper presentations and a vendor fair displaying the latest products and services offered in support of inspection, condition assessment, and repair of various BOP heat exchanger components.

6.4 EPRI Condenser Technology Conferences

The EPRI Condenser Technology Conferences are held approximately every three years. These conferences provide excellent information for the condenser system engineer as well as the BOP Heat Exchanger program owner. The condenser technology conference has become a forum for industry experts to periodically convene and address new developments and research needs for steam condensers in the power industry. Attendees have an opportunity to learn from condenser experts and gain from their experience. Recent proceeding publications are available from EPRI— see proceedings from 2008 (EPRI report 1015736), 2005 (EPRI report 1010322) and 2002 (1007309), with earlier conferences also available.

Participants include vendors, consultants, utility personnel, and EPRI experts. The conferences may be preceded by a one-day seminar on condenser design, performance, and operation, which provides an introduction to condenser technology for engineers new to condensers.

A large body of information exists on damage in condenser tubes, tubesheets and waterboxes. Although technical understanding of damage mechanisms is generally good, past efforts often have not emphasized the practical, action-oriented steps needed to effectively deal with the various forms of damage. These conferences are organized to help utility users identify, resolve, and prevent condenser tube and sub-component failures.

6.5 EPRI Feedwater Heater Technology Conferences

The EPRI Feedwater Heater Technology Conferences are held approximately every three years (past conferences in 2010, 2007, 2004, etc.). Conference presentations are available from EPRI. These conferences are similar to the Condenser Technology Conferences noted above and provide excellent information and interface opportunity for system engineers responsible for feedwater heaters as well as the BOP Heat Exchanger program owner. Participants include utility managers, engineers, manufacturers, engineering consultants, and researchers involved in improving feedwater heater reliability and performance, plant life extension, and plant operation and maintenance. The objectives of the conferences include:

- Review state-of-the-art feedwater heater technology.
- Provide a forum to exchange knowledge and experience.
- Identify major problems.
- Establish priorities for additional research and development in this technology.

7 REFERENCES

7.1 Regulatory Guidance

1. NRC Generic Letter 89-13, Service Water System Problems Affecting Safety Related Equipment, July 18, 1989
2. NRC Generic Letter 89-13, Supplement 1, April 4, 1990. (ADAMS # ML031140185)
3. NRC Inspection Procedure 71111.07, Heat Sink Performance, 7-6-2010 (ADAMS # ML100820347).
4. NUREG-1801, Generic Aging Lessons Learned (GALL) Report, Revision 2

7.2 Industry Standards and Guidance

5. Institute of Nuclear Power Operations (INPO), Engineering Program Guide, EPG-04, “Service Water Reliability”
6. Institute of Nuclear Power Operations (INPO), Engineering Program Guide, EPG-14, “Balance-of-Plant Heat Exchanger Program”
7. ASME Boiler and Pressure Vessel Code, (Section III – Rules for Construction of Nuclear Power Plant Components; Section VIII – Pressure Vessels)
8. ASME PTC 12.1 – 2000 Closed Feedwater Heaters
9. ASME PTC 12.2 – 2010 Steam Surface Condensers
10. ASME PTC 12.4 – 1992 Moisture Separator Reheaters (MSRs)
11. ASME PTC 12.5 – 2000 Single Phase Heat Exchangers
12. ASME PTC 19.1 – 2005 Test Uncertainty
13. ASME PTC 23 – 2003 Atmospheric Water Cooling Equipment
14. ASME PTC 30 – 1991 Air Cooled Heat Exchangers (ACHE)
15. ASME OM-S/G-2009, Operation and Maintenance of Nuclear Power Plants, Part 21, Inservice Performance Testing of Heat Exchangers in Light-Water Reactor Power Plants
16. Standards of the Tubular Exchanger Manufacturers Association, Tubular Exchanger Manufacturers Association, Inc., Tarrytown, New York.
17. Standards for Closed Feedwater Heaters, Heat Exchange Institute, Cleveland, Ohio.
18. Standard for Power Plant Heat Exchangers, Heat Exchange Institute, Cleveland, Ohio.
19. Standards for Steam Surface Condensers, Heat Exchanger Institute, Cleveland, Ohio.

7.3 EPRI Documents

20. *Heat Exchanger Maintenance Guide*. EPRI, Palo Alto, CA: 2009. 1018089.

21. Materials Handbook for Nuclear Plant Pressure Boundary Applications (2006). December 2006. 1014481.

22. *Balance of Plant Heat Exchanger Condition Assessment and Inspection Guide*. EPRI, Palo Alto, CA: 1999. TR-108009.

23. *Equipment Condition Monitoring Templates, Addendum to the Preventive Maintenance Basis (TR-106857 Volumes 1-38)*. EPRI, Palo Alto, CA: 2000. 1000621.

24. *Guideline for Condition Assessment and Inspection of Fossil Plant Heat Exchangers*. EPRI, Palo Alto, CA: 2001. 1006305 .

25. *Plant Support Engineering: Heat Exchanger Tube Plugging Calculator*. EPRI, Palo Alto, CA: 2009. 1019322.

26. *Guidance for Replacing Heat Exchangers at Nuclear Power Plants with Plate and Frame Heat Exchangers*. EPRI, Palo Alto, CA: 2006. 1013470.

7.3.1 Thermal Performance/GL 89-13

27. *Heat Exchanger Performance Monitoring Guidelines*. EPRI, Palo Alto, CA: 1991. NP-7552.

28. *Service Water Heat Exchanger Testing Guidelines*. EPRI, Palo Alto, CA: 1998. TR-107397.

29. *Supplemental Guidance for Testing and Monitoring Service Water Heat Exchangers*. EPRI, Palo Alto, CA: 2003. 1003320.

30. *Heat Exchanger Thermal Performance Margins Guideline*. EPRI, Palo Alto, CA: 2005. 1012129.

31. *Alternative to Thermal Performance Testing and/or Tube Side Inspections of Air-to-Water Heat Exchangers*. EPRI, Palo Alto, CA: 2002. 1007248.

32. *The P-NTU$_I$ Method*. EPRI, Palo Alto, CA: 2010. 1021065.

33. *Heat Exchanger Single Tube Test Device*. EPRI, Palo Alto, CA: 2004. 1009839.

34. *Temperature Stability Criteria for Heat Exchanger Testing*. EPRI, Palo Alto, CA: 2007. 1014882.

7.3.2 Chemistry/Cleaning

35. *Service Water System Chemical Addition Guide*. EPRI, Palo Alto, CA: 1996. TR-106229.

36. *Closed Cooling Water Chemistry Guideline*, Rev. 1. EPRI, Palo Alto, CA: 2004. 1007820.

37. *Biocidal Treatment for Control of Service Water System Microfouling*. EPRI, Palo Alto, CA: 1993. TR-102823.

38. *Detection and Control of Microbiologically Influenced Corrosion*. EPRI, Palo Alto, CA: 1990. NP-6815-D.

39. *Service Water System Corrosion and Deposition Sourcebook*. EPRI, Palo Alto, CA: 1993. TR-103403.

40. *Water Treatment Strategies, Microorganism Control*. EPRI, Palo Alto, CA: 2004. 1009598.

41. *Recommended Cleaning Practices for Service Water Systems*. EPRI, Palo Alto, CA: 1997. TR-108923.

42. *Role of Manganese Dioxide Deposition in MIC*. EPRI, Palo Alto, CA: 2004. 1009597.

7.3.3 Moisture Separator Reheaters

43. *Moisture Separator Reheater Source Book*. EPRI, Palo Alto, CA: 1997. TR-106345.

44. *Procurement and Operation Considerations for Moisture Separator Reheaters*. EPRI, Palo Alto, CA: 1984. NP-3692.

7.3.4 Feedwater Heaters

45. *Feedwater Heater Tube Failure Manual*. EPRI, Palo Alto, CA: 2009. 1015826.

46. *Guidance for Replacing Feedwater Heaters at Nuclear Power Plants*. EPRI, Palo Alto, CA: 2007. 1014826.

47. *Life Cycle Management Planning Sourcebook, Volume 10: Feedwater Heaters*. EPRI, Palo Alto, CA: 2003. 1009073.

48. *Life Cycle Management for Feedwater Heater and MSR Controls at Hope Creek Station*. EPRI, Palo Alto, CA: 2003. 1009152.

49. *Level Control Guide for Feedwater Heaters, MSRs and Other Equipment*. EPRI, Palo Alto, CA: 2002. 1003472.

50. *Feedwater Heater Maintenance Guide*. EPRI, Palo Alto, CA: 2002. 1003470.

51. *Enhanced Reliability of Replacement Feedwater Heaters*. EPRI, Palo Alto, CA: 1994. TR-103940.

52. *High Reliability Feedwater Heater Study*. EPRI, Palo Alto, CA: 1988. CS-5856.

53. *Nuclear Plant Feedwater Heater Handbook Vol. 1*. EPRI, Palo Alto, CA: 1985. Project 2230-2.

54. *A Pictorial History of Tube Failures in Closed Feedwater Heaters*. EPRI, Palo Alto, CA: 1983. RP-1928-1.

55. *Failure Cause Analysis, Feedwater Heaters*. EPRI, Palo Alto, CA: 1981. CS-1776.

56. *2010 Feedwater Heater Technology Conference Proceedings*. EPRI, Palo Alto, CA: 2010. 1021491.

57. *2007 Feedwater Heater Conference Proceedings*. EPRI, Palo Alto, CA: 2007. 1014165.

58. *2004 Feedwater Heater Technology Symposium*. EPRI, Palo Alto, CA: 2004. 1004121.

59. *2001 Feedwater Heater Technology Seminar and Symposium*. EPRI, Palo Alto, CA: 2001. 1004022.

60. *1998 Feedwater Heater Technology Symposium*. EPRI, Palo Alto, CA: 1998. TR-111046.

61. *1992 Feedwater Heater Technology Symposium*. EPRI, Palo Alto, CA: 1993. TR-102923.

7.3.5 Main Condensers

62. *Update Report on Condenser Air In-Leakage Monitoring*. EPRI, Palo Alto, CA: 2009. 1015663.

63. *Air In-Leakage and Intrusion Prevention Guidelines*. EPRI, Palo Alto, CA: 2008. 1014125.

64. *Condenser Air Removal Equipment Maintenance Guide*. EPRI, Palo Alto, CA: 2007. 1015058.

65. *Expansion Joint Maintenance Guide*. EPRI, Palo Alto, CA: 2003. 1008035.

66. *Life Cycle Management Planning Sourcebook, Volume 3: Main Condenser*. EPRI, Palo Alto, CA: 2003. 1003651.

67. *Condenser Performance Monitoring Practices*. EPRI, Palo Alto, CA: 2002. 1007309.

68. *Condenser Application and Maintenance Guide*. EPRI, Palo Alto, CA: 2001. 1003088.

69. *Condenser In-Leakage Guideline*. EPRI, Palo Alto, CA: 2000. 112819.

70. *Condenser Configuration and Performance Evaluation Using CFD*. EPRI, Palo Alto, CA: 1998. TR-109725.

71. *On-Line Condenser Fouling Monitor Development*. EPRI, Palo Alto, CA: 1998. TR-109232.

72. *In-Situ Coating of Condenser Tubes as an Alternative to Retubing*. EPRI, Palo Alto, CA: 1997. TR-107068.

73. *HEWCA v2.0 Heat Exchanger Workstation – Condenser Application*. EPRI, Palo Alto, CA: 2008. 1016475.

74. *ABCs of Condenser Technology*. EPRI, Palo Alto, CA: 1994. TR-104512.

75. *Condenser Microfouling Control Handbook*. EPRI, Palo Alto, CA: 1993. TR-102507.

76. *Symposium on State-of-the-Art Condenser Technology*. EPRI, Palo Alto, CA: 1983. CS-3344.

77. *Condenser Technology Conference Proceedings*. EPRI, Palo Alto, CA: 2008. 1015736.

78. *Condenser Technology Conference*. EPRI, Palo Alto, CA: 2005. 1010322.

79. *Condenser Technology Seminar and Conference*. EPRI, Palo Alto, CA: 2002. 1004116.

80. *Condenser Technology Conference*. EPRI, Palo Alto, CA: 1996. TR-106781.

81. *Condenser Technology Conference Proceedings*. EPRI, Palo Alto, CA: 1991. GS-7349.

7.3.6 NDE and Repair

82. *Electromagnetic NDE Guide for Balance of Plant Heat Exchangers, Revision 3*. EPRI, Palo Alto, CA: 2009. 1019124.

83. *Guided Wave Ultrasonic Technology Applications for BOP Heat Exchanger Tubes and TSP Degradation*. EPRI, Palo Alto, CA: 2008. 1016672.

84. *Enhanced Ferromagnetic Inspection Techniques for High Performance Thin Wall Stainless Steel and Carbon Steel Tubing*. EPRI, Palo Alto, CA: 2005. 1011624.

85. *NDE for Carbon Steel Heat Exchanger Tube Support Plates and Tube Fretting*. EPRI, Palo Alto, CA: 2005. 1011252.

86. *Eddy Current Evaluation of ID Pit Sizing*. November 2004. 1009589.

87. *Repair Technology for Degraded Pressure Vessel and Heat Exchanger Shells*. EPRI, Palo Alto, CA: 2002. 1003286.

88. *Engineers Guide 1: Electromagnetic NDE Guide for Utility Engineers*. EPRI, Palo Alto, CA: 1999.
TM-114284.

89. *Eddy Current Testing of Service Water Heat Exchangers for Engineers Guideline*. EPRI, Palo Alto, CA: 1999. TR-110392.

90. *Heat Exchanger Tube Support Plate Characterization Using Eddy Current Examination*. EPRI, Palo Alto, CA: 2008. 1016677.

91. *11th EPRI BOP Heat Exchanger NDE Symposium*. EPRI, Palo Alto, CA: 2010, 1021661.

92. *10th EPRI BOP Heat Exchanger NDE Symposium*. EPRI, Palo Alto, CA: 2008, 1018055.

93. *9th EPRI BOP Heat Exchanger NDE Symposium*. EPRI, Palo Alto, CA: 2006, 1014336.

94. *8th EPRI BOP Heat Exchanger NDE Symposium*. EPRI, Palo Alto, CA: 2004, 1011122.

95. *7th EPRI BOP Heat Exchanger NDE Symposium*. EPRI, Palo Alto, CA: 2002, 1006692.

96. *6th EPRI BOP Heat Exchanger NDE Symposium*. EPRI, Palo Alto, CA: 2000. 1000579.

97. *4th EPRI BOP Heat Exchanger NDE Symposium*. EPRI, Palo Alto, CA: 1997. PC-108010.

7.4 General References

98. *Nalco Guide to Cooling Water Systems Failure Analysis*. Harvey M. Herro and Robert D. Port. McGraw-Hill Inc., copyright 1993.

A

LISTING OF KEY INFORMATION

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. Identifies tasks which potentially consume significant resources or create scheduling problems.

Page Number	Key Point
3-6	It is important to ensure changes to BOP Heat Exchanger program PM actions which impact the scope or frequency of tube NDE inspections are communicated to the individual responsible for the program's NDE budgeting and contracts.
3-7	BOP Heat Exchanger program PM actions and their frequencies are best established based on the known material condition of the heat exchanger without preference to maintaining generic PM template intervals.
3-12	Structured guidance for performing heat exchanger remaining life projection is beneficial to avoid late identification of major repair or replacement needs relative to the site's long range planning cycle. Administrative limits, such as exceeding 50% of the tube plugging limit, can be used to trigger remaining life evaluations.
5-2	Heat exchanger PM actions, scope, and frequencies adjustments from those in generic templates are expected based upon inspection and test results.

A.2 Key Technical Points

Key Technical Point

Targets information that will lead to improved equipment reliability and/or program performance.

Page Number	Key Point
2-3	Closed loop cooling systems which reject heat to the SW system rely upon chemistry controls and monitoring as the principal basis for exclusion from the GL 89-13 program. Documentation of the effectiveness of those measures and their consistency with industry guidance provided in EPRI Report 1007820 is a beneficial practice for ensuring the UHS function.
2-7	Documenting the technical basis for reasonable assurance of adequate heat transfer for heat exchangers not thermal performance tested is beneficial for GL 89-13 programs not directly validating thermal performance capability of all SW heat exchangers.
3-2	A structured process is beneficial for determining the scope of heat exchangers to be included in the BOP Heat Exchanger program with clear identification of heat exchangers included and any critical/important heat exchangers excluded from the scope.
3-3	A presentation to plant management on critical heat exchangers which do not have actions established for maintaining reliability is beneficial to ensure their awareness and concurrence with the lack of action.
4-4	A key design aspect of some air-to-water heat exchangers is tube access for NDE and visual inspection. Designs with header pipes and u-bend fittings are not accessible for maintenance actions.
4-6	Plate heat exchangers have smaller flow passageways than shell-and-tube heat exchangers, which may increase their macrofouling or blockage risk pending the adequacy of filtration. This increased macrofouling risk is their principle design limitation for open cooling water system service.
4-10	Maintaining tube fluid velocity >3 ft/sec (0.9 m/s) is recommended to avoid sedimentation, although variations in suspended solid size and concentration both influence the velocity needed to maintain materials in suspension. Sedimentation may be a seasonal occurrence due to cooling water flow reductions during periods of low water temperatures.
4-12	Maintaining tube velocities of 6-7 ft/sec (1.9-2.1 m/s) or higher has been found to significantly reduce microfouling in open cooling water systems compared to lower velocities, although velocities in this range may be detrimental to long-term service life for copper and brass tubes.

Page Number	Key Point
4-17	Specialized ECT probes may be needed to detect tube circumferential cracking. Cracking has a higher progression uncertainty, may cause larger initial leaks due to sheared tubes and leakage may progress rapidly if adjacent tubes are also cracked.
4-18	Tube ID erosion commonly occurs in copper based tube materials in open cooling water systems and is strongly influenced by water velocity. Localized metal loss, similar to pitting, is readily detected by ECT, but general wall loss is often not detected without ID measurements. General wall loss, if present, may vary significantly within the tube bundle as well as within individual tubes. It is often most severe within the first several inches of the tube but may extend full length.
4-35	It is beneficial for the GL 89-13 program owner and SW system engineer to be aware of chemistry control lapses and out-of-specification conditions. The SW system relies upon chemistry monitoring and controls as a first line of defense for several potential fouling issues.
4-40	Ejection of multiple elastomeric tube plugs following a loss of circulating water has occurred on several occasions. Consider condenser tube plug verification as a response action to a loss of circulating water, if using elastomeric plugs.
4-40	Significant vibration induced tube damage related to excessive shell-side flow may result from ineffective implementation of controls to protect vendor specified maximum flow values.
5-7	The most commonly used NDE technique for heat exchanger tubes is ECT. It is relatively fast, repeatable, and accurate in sizing defects, but it also relies on skilled analyst for subjective interpretation. Detection of some types and locations of defects can be difficult or require specialized equipment.
5-26	The consequences of tube plug leakage should be factored into tube plug selection, as well as the level of detail provided in plug installation guidance, training, and verification actions.

A.3 Key Human Performance Points

Key Human Performance Point

Denotes information associated with complex, critical, and difficult to perform tasks and content appropriate in a planning/work package to minimize human performance problems (i.e. improve the efficiency and effectiveness of the task).

Page Number	Key Point
2-7 & 3-4	Clear and specific identification of assigned roles and responsibilities for program driven actions as well as supporting or interfacing roles of other programs is an important factor in their effective implementation. It is beneficial for each program action to have an identified responsible individual (by position). This is not intended to limit the ability to distribute or delegate work within the organization, but to remove uncertainty regarding ownership of program actions.
2-8	Periodic structured meetings between various individuals performing key roles related to GL 89-13 actions, such as the GL 89-13 program owner, SW system engineer, SW chemist(s), etc., are beneficial to program performance by establishing an integrated understanding of the monitoring, testing, inspection, and treatment results for the system and components.
2-10 & 3-6	An integrated database or spreadsheet for program heat exchangers containing the schedule for cycles and refueling outages in which GL 89-13 tests or inspections and ECT tube inspections by the BOP Heat Exchanger program are to be conducted is a beneficial practice supporting budgeting, NDE service contracts, maintenance planning, test equipment calibration scheduling, and related actions.
4-39	Fluid at the tube-side operating pressure may be trapped behind a tube plug. Injuries have resulted from tapered plug ejections while attempting to remove one-piece tapered plugs. Precautions may be warranted in documents directing work which could dislodge tubes (intentionally or inadvertently) notifying the workers of the potential for fluid to be trapped behind the tubes and the need to capture or restrain the plug.
4-41	Incorrectly installed reversing heads on small four-pass heat exchangers have caused a reduction in active tubes and thermal capacity. Establishing multiple barriers to ensure correct head orientation for susceptible heat exchangers is a beneficial action to avoid future occurrences.
5-9	When selecting an ECT inspection scope of <100%, tubes most likely to be degraded are chosen combined with random sampling. A common approach is to test periphery tubes, around plugged tubes, and other randomly selected tubes, with scope expansion as needed to bound significant degradation.

B
AN INTEGRATED APPROACH TO GL 89-13 HEAT EXCHANGER VISUAL INSPECTIONS

The visual inspection guidance provided in EPRI Technical Report 1003320, Supplemental Guidance for Testing and Monitoring Service Water Heat Exchangers is discussed in this section in context of integrating the various GL 89-13 program actions and design features into the visual inspection process.

GL 89-13 requires a test program to verify heat transfer of Service Water (SW) heat exchangers performing a safety-related heat removal function. Since thermal performance testing is not practical for many SW heat exchangers, an alternative acceptable action of regular maintenance (i.e. visual inspection and cleaning) is allowed. Most utilities have credited visual inspection and cleaning for a portion of their SW heat exchangers, while some have credited it exclusively.

Visual inspections are intended to verify the heat exchanger has not degraded such that performance of its intended safety function is challenged. This verification, while primarily qualitative, can be an informed evaluation based upon comparisons with the inspection, testing and monitoring results from other heat exchangers in the system, as well as consideration of applicable design features. As a result, the heat exchanger acceptability can be determined based not only on the visual inspection, but also on the results of programmatic actions taken in the SW system.

B.1 Thermal Degradation and Visual Inspection

Visual inspections most effectively provide confirmation of heat exchanger thermal performance capability when macrofouling (i.e. tube blockage) is the principal type of fouling.

B.1.1 Macrofouling

Visual inspection is capable of quantitatively determining tube blockage from macrofouling. For SW heat exchangers where required minimum flow has been confirmed and macrofouling is the only significant source of fouling, a quantitative assessment of thermal capability can be made.

Design calculations establishing SW system heat exchanger performance requirements typically include a tube plugging allowance of 5-10%. The difference between this value and the actual number of tubes permanently plugged represents the allowable macrofouling tube blockage limit.

Macrofouling may only result in partial rather than full tube blockage, in which case determining the appropriate equivalent quantity of fully obstructed tubes may be less obvious. The use of reasonably conservative engineering judgment and analysis can be applied in those cases to determine thermal capability.

Where macrofouling has reasonable potential to exceed the available tube blockage margin (or historical inspections have exceeded the tube blockage margin), the combination of visual inspections with the dp monitoring method may be used in between scheduled visual inspections. This may be particularly useful if increased visual inspection frequency would require potentially unnecessary out-of-service time, since the dp monitoring may provide confirmation of acceptable flow and dp conditions and thereby reduce out-of-service time for safety related components.

B.1.2 Microfouling

The principal weakness with reliance on visual inspection as a thermal performance monitoring tool is associated with its lack of a quantitative assessment of microfouling, since visual inspection does not determine heat transfer or a fouling factor. Ensuring microfouling has not exceeded the fouling factor credited in the design limiting analysis relies heavily on other programmatic actions and design features. Principal among these are water quality (i.e. non scale forming) and chemical treatment (to avoid biological microfouling, scale inhibition, and/or precipitates). Design features such as higher tube velocities may also reduce microfouling potential. High sand or sediment loading in some SW systems may also reduce microfouling potential due to its abrasive action, although this may shorten the life of softer metal tubes.

SW systems with credible potential for microfouling to exceed the allowable fouling factor typically would not rely solely upon visual inspection, since it is most effective at addressing macrofouling. Thermal performance testing at least one set of heat exchangers in the system (even if historical tests) may allow reasonable correlations for as-found conditions of thermal tested (i.e. known fouling factor) heat exchangers and as-found conditions of other heat exchangers. Thermal tests may also support correlations between on-line scaling or fouling monitors in the system and the measured thermal performance. Thermal performance tests may have been used to establish the acceptability of cleaning methods and their frequencies. Additional discussion on programmatic actions and design features which support visual inspection suitability are provided below.

B.2 Programmatic Actions and Design Features Related to GL 89-13 Visual Inspections

Visual Inspections of GL 89-13 heat exchangers rely on a variety of inputs and considerations beyond the as-found observation of the heat exchanger to determine acceptable thermal performance. These inputs may include the following design features and programmatic actions:

1. **Water Quality** – SW system water quality, including seasonal variations and cycle concentration potential for recirculating systems, should be well known by the chemistry department. The potential for microfouling due to mineral scaling is important with respect to the chemical treatments applied to SW as well as the acceptability of visual inspection as an alternative to heat transfer testing, since visual inspection is most applicable to systems where macrofouling is the only significant threat to exceeding design fouling factors. If SW has significant mineral scaling potential, then visual inspection is generally only acceptable if combined with additional tube scale monitoring and/or tests (i.e. heat transfer testing of at least one set of SW heat exchangers).

2. **Chemistry Treatment/Monitoring** – The ability to chemically treat the SW system with biocides and scale inhibitors (if applicable) is key to minimizing the threat of significant microfouling due to biological, scaling, and precipitation issues in the SW system. Chemical treatment is often important to reduce macrofouling potential from biological sources (i.e. bi-valves, algae, etc.) and possibly corrosion nodules from carbon steel pipes in intermittent service systems. If chemical controls can be shown to result in microfouling being minimized or bounded by the design fouling factor, then the principal remaining challenges to thermal performance relate to macrofouling and to a lesser extent bypass flow (if multi-pass design), both of which can be readily detected via visual inspections.

   Chemical treatment generally results in a system-wide impact, but normally operating systems with isolated safety-related heat exchangers may have very different conditions in the isolated versus operating parts of the system (differences can be magnified if treatment is intermittent vs. continuous).

   Chemistry monitoring considerations:

   – Targeted chemical concentrations are verified on each train, including checks downstream of heat exchangers in addition to the supply headers.

   – Effectiveness monitoring such as bio-boxes and/or scale/fouling probes can provide added confirmation of treatment adequacy.

   – Normally isolated parts of system can be periodically checked with samples.

   – Performance indicators and tiered action levels can be used to escalate priority and response actions for out-of-specification or out-of-service conditions for the SW chemical treatment system.

   Chemistry monitoring provides the principal line of defense for heat exchanger thermal performance in most open cooling systems. Therefore, it is beneficial for the GL 89-13 program engineer to be well informed regarding chemistry monitoring. Periodic meetings between chemistry and engineers involved with the SW system are beneficial.

3. **System Flow Balance Testing** – Fouling is only part of the thermal performance equation, with required minimum flow another necessary component. A flow balance test is typically performed periodically on open loop SW systems, unless instrumentation and alignments provide flow data during the cycle. Adjustments to measured flows consider instrument accuracy, allowed pump degradation, changes in intake water level, more restrictive flow alignments, added loads, and similar potential losses for the most limiting design basis accident response condition to ensure minimum flow requirements continue to be met. Periodic system flow balance tests confirm minimum required flows to each SW heat exchanger, and confirm adequate margin exists to address flow degradation sources. This test may also detect significant macro-fouling issues.

4. **Thermal Performance Testing** – Periodically or previously conducted thermal performance test results provide an indication of fouling factors to expect in the system and an indication of the effectiveness of system-wide controls and actions. The quality of the correlation of test results to other SW heat exchangers can be affected by different flow and operating conditions as noted in the next section.

5. **Thermal Performance Monitoring** – where the capability exists, thermal monitoring data, such as approach temperatures for heat exchangers having stable tube and shell side flows, provides an indication of effectiveness of system-wide controls and actions. The correlation to other SW heat exchanger conditions is influenced by similarity of service conditions as noted in the next section.

6. **Visual Inspection of Thermal Performance Tested and Monitored Heat Exchangers** (when opened for ECT or other PM actions) – Thermal performance tested SW heat exchangers do not require visual inspection for GL 89-13 compliance, but it is beneficial to perform when they are opened for cleaning or ECT. The as-found condition in a heat exchanger with quantitative thermal performance data provides a visual correlation opportunity for as-found conditions in other heat exchangers. Similarly, visual inspection of a thermal performance monitored heat exchanger provides a comparison point for as-found conditions to correlate to other heat exchangers in the SW system.

7. **DP Monitoring** – DP monitoring may be performed on selected heat exchangers for evidence of macrofouling, particularly if a history of macrofouling problems exists.

8. **External Macrofouling Control** – External debris sources are commonly minimized by intake traveling screens and pump discharge strainers. Site experience from previous inspections/monitoring provides confirmation of effectiveness.

9. **Intra-System Macrofouling Control** – Debris from system internal sources can be addressed by chemical treatment (corrosion reduction and biological control) and system design (i.e. coated or corrosion resistant pipe), and/or have been shown by site experience from previous inspections and monitoring to be a manageable threat (i.e. tube blockage limits not exceeded due to intra-system materials).

10. **Tube Velocities, Sediment and Flushes** – Tube velocities above 6 ft/sec are known to reduce microfouling potential. Systems with moderate to high levels of coarse suspended solids (i.e. sand) will have reduced microfouling potential at slightly lower velocities, but are also subject to ID erosion in softer metals and sedimentation risks as velocities decrease. Periodic high velocity tube-side flushes of standby or low velocity in-service SW heat

exchangers may reduce sedimentation buildup as well as microfouling. Such flushes should not be performed exclusively in advance of visual inspections (preconditioning), but as part of a routine or periodic action. Shell side flushes, if SW is on the shell, should always observe the maximum flow limits established by the manufacturer to avoid damaging tube vibrations, if applicable.

It is appropriate to place a SW heat exchanger in service briefly prior to a scheduled visual inspection if it has been in standby or has had a temperature control valve with throttled flow (manually throttled valves should remain in their throttled position consistent with post-accident alignments). These flushes are intended to simulate flows similar to post-accident limiting conditions, since this is more representative of the heat exchanger than what may be found after extended lay-up or with low flows due to valve leakby or control valve throttling in winter months.

11. **Risk Informed Actions and Staggered Scheduling** – Identification of higher fouling susceptibility and low thermal margin (flow, tube plugging, or fouling margin) heat exchangers can be used to target heat exchangers warranting more frequent inspections and/or scope expansion for issues identified in other SW heat exchangers. Scheduling visual inspections to levelize the number of heat exchangers inspected each cycle or outage, to the extent practical, may allow earlier detection and correction of problems than grouped inspections (e.g. 12 heat exchangers on 3R inspection interval preferred as 4 per outage versus 0 in first outage followed by 6 in the next two outages, since the second approach results in a 2 cycle information gap).

B.3 Limitations on Applicability of Other Heat Exchanger Data

Data from thermal tested heat exchangers combined with chemistry monitoring data provide reasonable indications of overall SW system heat exchanger health. There are often exceptions or reasons good performance in one part of a SW system failed to indicate problems in another part, and vice versa. Potential sources of variation include:

- Normal flow versus normally isolated flow. Macrofouling potential is likely to be greater for the heat exchanger with normal flow. Biological microfouling problems may be higher in normally isolated heat exchangers, particularly if valve leakby is occurring.
- Normally isolated heat exchanger conditions may vary due to differences in isolation valve leakage. Low flows generally promote higher fouling potential.
- Isolated heat exchangers may have significantly different intervals of being placed in service.
- Tube velocities influence fouling potential, with >6 fps minimizing fouling and <3 fps detrimental. The normal operating tube velocity should be considered, not design or data sheet values. Temperature or flow control valves on the SW side may resulting in tube fouling and require seasonal cleaning due to sedimentation from low velocities.

- Macrofouling potential can be influenced by the SW system piping design. Pipe branches or tees on the bottom of supply headers are often avoided since they can result in preferential debris transport to the supplied heat exchanger. Heat exchangers supplied with straight flow through tees may also see higher debris loading than those supplied from branching tees. Poor heat exchanger channel design can cause variations in tube velocities allowing sedimentation.
- Differences in heat exchanger thermal margins may exist with different allowable fouling factors, tube plugging limits, or flow margins.
- Chemical treatment variations may exist between SW divisions or trains, due to system design, malfunctions, blockage, temporary changes, and other variables. Ideally, chemistry would detect this difference and take necessary actions.
- Tube sizes and materials can influence fouling susceptibility. Small tube sizes relative to other SW system heat exchangers are sometimes overlooked as contributors to macrofouling problems. Copper alloy tube materials are more resistant to biological fouling due to copper toxicity to microorganisms and thus, may experience less microfouling than a stainless steel tube in similar service. This variation may be counteracted in some cases by velocity limitations imposed on copper alloy tubes to avoid erosion problems, while stainless tubes can operate with much higher velocities, which reduce biological microfouling potential.
- An uncoated carbon steel tubesheet may cause occlusion of tube openings due to corrosion nodules and increase susceptibility to or cause macrofouling.

B.4 One-Time Actions for Integrated Visual Inspections

1. Inspection History Database – Supports comparisons with past conditions, provides storage location for future results.
2. Thermal Margin Comparisons – Compiling the fouling factor, available macrofouling tube blockage % and # of tubes, and flow margin for SW heat exchangers allows low margin components to be identified for more frequent inspections and/or action limits.
3. Fouling Susceptibility – Historical data will often pinpoint heat exchangers with higher fouling susceptibility. Comparison of heat exchanger data for tube sizes, operating tube velocities, uncoated carbon steel tubesheets, shell-side cooling water in small coiled tube heat exchangers (i.e. seal water), normally isolated, SW temperature control valve and susceptible piping configurations may all reveal heat exchangers more susceptible to fouling.
4. Difficult Access – identification of heat exchanger inspections involving high dose or scaffold support may warrant consideration of longer inspection intervals.
5. Inspection/Test Matrix – thermal tests, visual inspection, and ECT. Stagger actions to minimize # times each heat exchanger is opened and levelize # per cycle as practical.
6. Action Limits – scope expansion triggers can be established for low margin or high fouling susceptibility heat exchangers if not opened each cycle.

B.5 Pre Visual Inspection Reviews

Prior to performing GL 89-13 heat exchanger visual inspections, familiarity with the following should benefit the inspector:

- **Previous visual inspection results** (photos and report): familiarity with inspection history of the component and any recent changes in fouling related trends for the system.
- Tube plug map and plugging limit for any changes that would reduce available tube blockage (macrofouling) margin.
- Thermal Tests and Thermal Monitoring – trends of SW system thermal data.
- Flow tests – results from last test, low margins, adverse trends.
- DP monitoring trends (if applicable to this heat exchanger).

B.6 Precautions for Less Frequent Inspection and Cleaning

Adjusting inspection frequencies is a potential outcome of improved understanding of SW system thermal performance. While it may be determined that acceptable thermal performance margins can be maintained with less frequent inspection and cleaning for some heat exchangers, additional considerations are provided below.

- Increased tube pitting – tube cleaning may not be needed as frequently to maintain acceptable thermal performance, but the removal of deposits and films may significantly reduce pitting initiation sites. This is particularly true for plants with MIC issues (i.e. intermittent biocide treatment) or manganese deposition (risk to 300-series stainless tubes). Check with chemistry on deposit and foulant types and tube material susceptibility to additional pitting problems prior to extending cleaning frequencies.
- More aggressive cleaning methods may be required due to the longer intervals between tube cleaning. This may increase manpower, costs, duration, and cleaning waste generated per cleaning evolution.
- Fouling may be non-linear and progression rates can vary from cycle to cycle due to differences in open cooling water system environmental conditions.

A well documented basis for changes to safety-related heat exchanger maintenance practices is beneficial. An implementation plan to gradually phase in changes with validation of expected results is also a beneficial practice for more significant changes.

B.7 Maximum Inspection Intervals

The maximum interval between thermal performance tests (and by inference visual inspections, if used instead of thermal tests) noted in GL 89-13 is 5 yrs, although other intervals may have been included in a licensee's 89-13 response commitments. Longer visual inspection intervals may be justifiable at some stations via use of an integrated approach with triggers or action limits established for scope expansion. The justification of longer intervals than 5 years between tests or inspections would need to address the site's commitment change process, as appropriate.

C
POWER UPRATE CONSIDERATIONS

This section provides considerations to improve heat exchanger evaluations related to power uprates. The considerations are targeted at plants planning a power uprate, but include actions which may be beneficial at plants having previously performed a power uprate or at plants experiencing steam path heat exchanger reliability problems caused by flow and vibration issues.

C.1 Condition Assessment

An accurate assessment of the existing condition of heat exchangers which will have increased post-uprate shell flow is vital. The evaluated heat exchangers will include those in the major steam-path (i.e. MSRs, feedwater heaters, and condensers), and may include additional components. Uprate modifications could result in increased flows in other systems, requiring heat exchanger impact evaluations. The greater the magnitude of flow change, the greater the potential for adverse impacts due to vibration or erosion. Steam quality changes may also occur with the power uprate. Turbine efficiency upgrades typically accompany major uprates, and may result in changes to the shell-side conditions in the steam path heat exchangers.

Careful consideration is warranted for heat exchangers with degradation/failure history, since the damage mechanism may be exacerbated by the increased flows. Vibration and erosion damage often only occur above a threshold value, with little or no damage resulting below the threshold but rapid increases in damage rates may occur as the threshold is exceeded. Seemingly small increases to the driving mechanism near the vibration damage threshold can result in large increases to the tube degradation rates. Careful attention is needed for vibration related tube damage previously observed in evaluated heat exchangers.

The heat exchanger evaluation considerations include:

1. Support Plate/Baffle Plate Damage – Metal loss at the ligaments separating tubes in the carbon steel baffle and support plates may be present in steam path heat exchangers due to tube vibration (as well as flashing or steam bubble collapse in drain coolers). This damage is most prevalent in feedwater heater drain coolers and the tube bundle periphery near the shell inlets. The plate wear results in looser tubes, which allows greater movement and tube-to-tube impacts. When the wear progresses through the ligaments, star shaped plate fragments are released as debris which may cause tube fretting damage, drain and level control valve interference, and related problems. Damage can progress to the extent the interior portion of the plate becomes separated from the edges of the plate where connecting rods establish plate spacing.

Feedwater heater drain cooler end plate ligament wastage may also be present. This damage is driven by steam erosion associated with steam bubble collapse in the annulus space around the tubes as well as tube vibration. Newer feedwater heater designs use thicker end plates and may specify tighter tolerances on end plate holes. End plate damage allows increased steam leakage into the drain cooler, with the steam bubble collapse often occurring next to in-service tubes resulting in added tube vibration.

Substantial improvements in detecting and sizing the extent of support, baffle, and end plate damage with ECT data have been made in recent years. However, weak or absent plate signatures may not be identified consistently or at all in the ECT data report. These indications, when reported, are sometimes ignored by the utility since they do not represent tube damage. Determining the extent of plate wear may require reanalysis of previous ECT data and/or acquisition of new data with alternative probes, expanded scope, etc. The references include EPRI Technical Reports, EPRI BOP NDE conferences and FWH Technology conferences, which have included papers regarding detection and sizing of FWH plate degradation.

2. <u>Tube Damage</u> – The types and causes of tube damage, as well as the number of affected tubes in-service and plugged are all of interest for the uprate evaluation. Tube damage that is vibration related is of particular interest due to expected increased vibration from higher shell flows.

3. <u>Internals Damage (FWH)</u> – The condition of FWH internals may not be known due to the absence of shell-side inspection data. Opportunities for even limited shell-side videoprobe inspections, such as when shell relief valves are removed for maintenance, can be beneficial to document the condition of accessible items. Evidence of support plate damage can be obtained from ECT data, as noted above. Drain Cooler Approach (DCA) temperatures notably above design may indicate shroud damage, end plate damage, and/or inadequate operating level. Tube failure history that is potentially related to impingement plate failure, drain cooler shroud damage, or baffle/support plate damage can be used to justify follow-up shell-side inspections, including those requiring shell cuts for access, unless the need to replace the FWH has already been established.

4. <u>DCA/TTD</u> – Feedwater heaters warrant review of their DCA and TTD against design values, including the stability of the readings (at 100% power). As noted above, a DCA above design may indicate damage to the drain cooler shroud or inadequate operating level. Instability in this value may indicate level control instrument tuning issues or operation at a level too close to the drain cooler entrance.

5. <u>Shell/Nozzle Erosion</u>- The extent and rate of wall loss of FWH shell and nozzle material is typically addressed by the FAC program or PM driven inspections. The potential for changes in the damage rates can be factored into the power uprate evaluation regarding the need for repairs, modification, or replacement.

C.1.1 Uprate Evaluation Conclusions

The power uprate heat exchanger evaluation generally results in one of three actions:

- Replacement: Normally limited to heat exchangers with significant existing degradation. The cause(s) of past degradation can often be addressed by the replacement design.
- Repair/Modification: This may include tube expansion in end plates to address ligament wastage, tube sleeving to recover previously plugged tubes and/or address degraded in-service tubes, tube staking, drain cooler shroud repair, impingement plate repair, shell/nozzle erosion repair, or similar actions. Note several papers describe these type repairs in past EPRI BOP NDE conferences or FWH Technology conferences. Repairs may also target the cause(s) of previous damage.
- No Action – Heat Exchanger Acceptable As-Is: This may be contingent upon actions to validate overload operation limits, operating level for two-zone FWHs, and to reset heat exchanger PMs and increase monitoring.

C.2 Feedwater Heater Operating Level

The FWH operating levels may not be at optimum values prior to an uprate. Operating level tests are beneficial to ensure the normal level is adequate. The level tests are conducted with the unit at steady-state full power. Operating level tests may be prudent prior to an uprate for FWHs with drain cooler tube damage history, bottom row(s) of tubes plugged, or with high or unstable DCA values. Performing level tests prior to an uprate may reveal the need to raise the level control instrumentation and/or revise setpoints for high level alarms and dump valve controllers to accommodate the new level. Identification of these additional changes prior to the uprate allows them to be addressed by the uprate project and ensure an acceptable level adjustment range is available when the post-uprate level test is conducted.

Following a power uprate, consider FWH level tests for:

- A single train of each stage of feedwater heaters.
- FWHs on other trains if they have a history of drain cooler tube degradation.
- FWHs on other trains if the tested train reveals the need to raise normal level.
- FWHs on other trains with high DCA, either sustained or intermittent.

FWH normal operating level is generally maintained away from alarm or hi-level switch settings, as well as the top end of the level controller displacer tube adjustment range, as applicable.

C.3 Overload Operating Limits

Operating limits for shell-side flows may not have been updated to reflect known tube or shell degraded conditions. Review of the overload limits with the original equipment manufacturer (OEM) or a heat exchanger vendor with modeling software capable of establishing new overload limits is beneficial for heat exchangers with increased shell-side flow. It is important for this reanalysis to be in context of the current condition of the tube bundle, including the number of tubes plugged, number of degraded in-service tubes, types of tube degradation, and known status of support/baffle plates and other shell internals. Otherwise, the overload analysis may be performed for the heat exchanger assuming new or as-built condition.

If overload limits for a heat exchanger are increased, the evaluation may need to address level control valve flow capacity and stability, impingement plates, the impact of the increased flow on condenser spargers and tubes, as applicable.

C.4 Preventive Maintenance Intervals

Resetting PM intervals for ECT and shell-side FAC inspections may be warranted for heat exchangers with increased flow. Inspections staggered over different outages provide the opportunity to evaluate the impact over multiple cycles. Heat exchangers with a past history of shell-side tube damage may be scheduled for follow-up ECT sooner. PM intervals can be set to appropriate intervals following the initial post-uprate inspections.

Most heat exchangers outside of the steam-path will not experience increased damage associated with an uprate since they will not have higher flow. Therefore, resetting heat exchanger PMs is only necessary for those with higher shell-side flow. Cooling water flow is infrequently increased in conjunction with an uprate, but if performed, may warrant attention to monitoring for erosion issues in copper alloy tubes in the system.

C.5 Other Actions

The responsible heat exchanger engineer may want to consider the following additional actions:

- Increased monitoring of heat exchangers with increased flows.
- Added attention during the initial post-uprate visual inspection of heat exchangers with increased flow.
- Increased attention to industry experience reports for heat exchanger uprate issues.
- Benchmark post-uprate heat exchanger actions/issues at other sites.

D
TUBE PULLING CONSIDERATIONS

This section includes issues for consideration prior to pulling a heat exchanger tube.

Removal of a heat exchanger tube for metallurgical analysis can yield valuable information. Tube removal does create potential issues or impacts to be considered by the responsible engineer prior to deciding to pull a tube. Most heat exchangers do not have readily removable tube bundles or shell-side access, resulting in tubes being removed from the channel or tube-side.

1. Perform ECT and any other NDE prior to pulling the tube.
2. If ECT is not available and the tube is being removed due to a leak, consider video probe inspection to determine the leak location and if the tube is intact or severely deformed.
3. U-tube bundle tube pulls require use of an internal tube cutting tool. The introduction of metal cutting fines into the shell-side fluid may require follow-up actions such as shell-side flushes. Tube cuts near a plate will minimize the unsupported tube length.
4. Welded tube-to-tubesheet joints require weld removal and may require a welded plug.
5. A plug size to fit the tubesheet drilled hole will be needed, or a replacement tube stub, tube rolling equipment, and associated guidance.
6. If a grooved tubesheet hole ID is present (check specifications and OEM) ensure the groove does not impair sealing of the selected tubesheet plug.
7. Tubesheet coating, if present, will need to be repaired following the tube pull.
8. If there is a manway opening instead of full channel access, the removed tube may need to be cut into sections. Be careful to mark/number the tube sections to maintain tube location and avoid cutting in the region of interest for metallurgical analysis.
9. If the tube is being removed from a feedwater heater drain cooler end plate, consider reinstallation (and anchoring) of a section of tube or round bar through the drain cooler end plate to avoid an opening which would allow steam entry into the drain cooler.
10. Pulled tubes create a linear flow path through the shell side allowing flow to bypass the intended cross-flow conditions established by the baffle plates. While the thermal performance penalty associated with bypass leakage through the empty baffle plate tube holes is limited, it may be difficult to model with accuracy. The thermal performance impact, even if limited, may need to be addressed for a safety related heat exchanger, or avoided by refilling the baffle plate holes. Reinstallation of a replacement tube (requires rerolling) or an equivalent OD round bar or stabilizing bar (anchored/captured in the tubesheets), are possible options to maintain the normal cross-flow developed by the baffle plates and avoid bypass flow through the pulled tube baffle holes.

E
RESPONSE ACTIONS FOR ECT TUBE DAMAGE INDICATIONS

This section discusses general response actions to the various tube damage indications which may be found in the heat exchanger ECT inspection report. The responsible engineer should recognize that generic guidance cannot address all combinations of damage, risk, and other relevant information for a specific application. The guidance in this section may not be appropriate or sufficient to address all heat exchangers.

E.1 Circumferential Cracking (CIR)

The detection of tube cracking is a serious issue. Circumferential cracks may remain undetected if traditional eddy current probes are used, since only the axial extent of the flaw is seen. Alternative probe types or probe combinations can be used to inspect for circumferential cracks.

E.1.1 Actions

- Crack indications are often plugged due to uncertainty in predicting progression.
- Since cracking is not an expected condition, pulling an affected tube for metallurgical examination is often needed to support cause determination.
- Cracking near the back of the tubesheet may be associated with tube rolling errors such as excessive rolling force having been applied or the roll extending past the tubesheet and over expanding the tube. Rolls extending past the tubesheet can be detected with a tube hole gauge, or other means such as a videoprobe or a 'go gauge' to determine the depth the tube ID returns to normal. Checking all tubes for roll depth exceeding the tubesheet thickness can be performed to establish the susceptible population, as warranted. Actions to address the issue include re-examination with a circumferential crack detecting probe, precautionary plugging, and/or sleeving.
- If cracking impacts a significant number of tubes, actions may be needed to justify maintaining cracked tubes in service, such as use of hydraulically expanded sleeves to bridge the cracked area. This may not be practical when the issue is first identified and the use of removable plugs may be important to support future tube recovery actions.
- Tubes with circumferential crack indications are infrequently left in service, and generally only if other tests are performed such as tube hydrostatic testing and follow-up ECT after hydrostatic testing to evaluate changes to cracking indications.

E.2 Deposit (DEP)

Typically deposit indications are not of concern in clean systems. In an open cooling water system the deposit could be covering defects (under deposit corrosion) and/or indicate the need for more effective tube cleaning prior to inspection. Significant tube ID fouling is often evident when the heat exchanger is opened and visual inspection is performed. The effects from dirty tubes during an ECT inspection may include resistance to the probe pusher, sludge or silt pushed out of the tube by the probe, reduced probe life, and reduced ECT data quality. Hard water (i.e. scale forming) may leave residual calcium deposits if cleaning was not effective. In closed loop systems, a deposit indication may be due to a minor film of a conductive material.

E.2.1 Actions

- Tube plugging is not warranted.
- Cleaning may be warranted, pending potential consequences of deposit remaining in tubes and/or if needed to achieve minimum ECT data quality.

E.3 Dent (DNT) or Multiple Dents (MDT)

Dents may result from manufacturing and handling and are often not active degradation. Exceptions can be dents due to loose parts or foreign material, high thermal stresses in straight tube bundles, or due to water hammer transients. Dents are of increased interest when away from support/baffle plates, on the bundle periphery near shell inlets, or near impingement plates, since dents at these locations could be due to debris or broken internals which may continue to impact tubes in the area. Dents are often grouped at support plates with numerous tubes affected.

E.3.1 Actions

- Tube plugging is not warranted for dents in feedwater heaters unless accompanied by another more significant problem or symptom (i.e. wear or loose part).
- Dents in brass tubes can be a stress riser, possibly resulting in crack initiation. Caution is warranted in this case for high leak consequence heat exchangers, particularly if high tube vibration service conditions are present.
- Large numbers of known dent indications at FWH support plates may warrant changes to reporting thresholds with the ECT service provider.

E.4 Erosion (ERO) – OD

Erosion can be difficult to detect and industry experience has shown it can be even more difficult to accurately size depth. Thus, caution is warranted for OD erosion plugging decisions.

E.4.1 Actions

- Tube plugging is a reasonable but cautious response for condenser tube erosion. Primarily due to uncertainty in reported depth and progression rate.
- Visual detection (via rough tube surface) in the condenser may be as effective as ECT in detecting erosion and is a useful follow-up action if erosion is reported. Visual inspections may provide sufficient assessment of erosion depth to avoid tube plugging.
- Erosion inspection of condenser tubes in the vicinity of the dump valve condenser inlet connection is an appropriate follow-up action to sustained condenser dump valve operation.

E.5 ID Indication (IDI) or Multiple ID (MID)

Most ID indications are due to pitting. ID pitting is the most common tube degradation mechanism in open cooling water systems. Pitting damage is very rarely structural in nature, meaning that the flaw must progress to 100% through-wall before there is risk of failure/leakage. Isolated pitting does not structurally weaken the tube due to strength provided by the shoulder effect of the surrounding nominal thickness tube metal. Tube plugging actions to address tube pitting can be limited to those necessary to avoid a 100% through-wall condition.

Tightly clustered or bridged pitting can degrade or in extreme cases eliminate the shouldering effect due to the reduction in surrounding sound metal. Cases of extremely high density pitting are not common and are generally associated with improper metal selection for the service conditions and/or significant loss of chemistry controls. Eddy current tests may only report the highest extent through wall pit indication in a tube with a defect code noting multiple pits (e.g. MID). It is beneficial for the engineer to understand the extent of pitting if MID is indicated, either via follow-up with the ECT analyst and/or video probe tube ID visual inspections.

Tube plugging thresholds for ID pitting in soft metal tubes such as brass, copper, or 90-10 Cu-Ni can be the least conservative of all defect types. The pits must progress through-wall to become an issue. If an ID pit standard is not used, then the pit sizing may already be conservatively high. Trending of pitting progression rates in heavily pitted tubes can be very difficult and may only yield general magnitudes or trends in spite of multiple inspections and careful analysis. If flaw progression comparison is pursued, it is beneficial to apply the most current technology with respect to pit sizing to earlier raw ECT data to determine previous pit sizing versus relying upon the results provided in an inspection report.

ID pitting in SS is normally only seen in open loop cooling systems. It presents greater uncertainty for progression rates. When conditions exist (e.g. MIC, manganese) to initiate pitting in low alloy stainless steels, it may progress at rapid rates. If leaks or through-wall indications have been reported which indicate active pitting, then caution is warranted for leaving any size pit in service in SS tubes, unless the application can tolerate small amounts of leakage. Pitting in SS is characterized by very small openings and the associated leak rates will be very slight.

In soft metal tubes, most commonly Admiralty brass or copper, and sometimes 90-10 Cu-Ni, the damage may be due to erosion (see Chapter 11 pictures in ref. 98).

E.5.1 Actions:

- Plug tubes based on the site's plugging threshold. If pluggable depth exists, consider if depth is corroborated by leakage history and if an ID pit standard was used for sizing.
- Multiple ID indications warrant follow-up with analyst or borescope to understand the approximate number of indications, their size range and axial extent.
- Multiple ID indications in soft tube materials in open cooling water service may be accompanied by general ID wall loss. ID measurements in the tubesheet and past it at both the inlet and outlet ends are warranted to check for general wall loss. ID general erosion affects pit sizing accuracy.
- In closed systems, an isolated ID indication may not be due to pitting. Reviewing the indication with the ECT analyst may be beneficial prior to a plugging decision.
- In closed systems if multiple ID indications are reported, consider follow-up with a video probe to confirm. If pitting is confirmed, then follow-up with chemistry regarding the chemical treatment and chemistry monitoring performed on the system.
- In open cooling water systems, follow-up with chemistry can be beneficial to ensure their awareness of pitting in the affected tube material and the general rate of change.
- If ID indications occur in stainless steel or pit resistant material, consider asking chemistry if samples from the tube interior are warranted (i.e. analysis for MIC or Mn).
- If pits in stainless steel tubes are to be left in-service, thorough tube cleaning to remove deposits, films, and biologics may assist with the pits becoming inactive.

E.6 Manufacturing Defects

It is generally not possible to definitively prove that some "defects" or indications have been present since original construction, and have successfully passed the hydrostatic pressure test. Baseline ECT data, if available, may support that the indications are historical and do not represent in-service (i.e. active) degradation. Review of previous inspection results may provide supporting confirmation the indication(s) have not been active since the earliest available ECT data was obtained.

Tube manufacturing or assembly defects can include incomplete fusion in seam welds, inclusions, nicks or buff marks from grinding, weld spatter, dents, scratches/gouges/abrasions from handling or assembly. Indications that occurred during manufacturing have been subjected to hydrostatic pressure tests. In the vast majority of cases these indications do not represent an on-going threat to tube integrity. The degradation mechanism is not active and the defect size is typically small in volume, meaning it is not structurally significant even if it has a high reported through-wall extent. For these reasons, manufacturing related indications generally do not warrant plugging, regardless of percentage through-wall. This conclusion may be problematic for sites with fixed plugging thresholds, as well as for safety related heat exchangers. In those cases, added justification such as individual tube hydro-testing may be required to justify leaving the tube in service. Given the added time and effort to support this activity, the indications may be plugged in spite of being acknowledged as not representing a credible threat to tube reliability. Where reasonable confidence exists that a defect indication is manufacturing related and latitude exists to avoid plugging it, then leaving manufacturing flaws in service can be justified.

Some ECT analysts may screen out these type of indications and not include them in the final ECT report. It is beneficial for these decisions by the ECT analyst to include concurrence by the responsible engineer. A different analyst performing the next data analysis may report all indications due to their steam generator inspection training. This can create the false impression of new flaws, since they were not previously reported. Review of historical raw ECT data, if available, can be performed to determine if the indication is new or has changed in size. The disposition of manufacturing defects involves some degree of engineering judgment, but it can be an informed decision combining the experience of the ECT analyst and the knowledge of the engineer for the heat exchanger being inspected, considering service conditions, tube material, and applicable degradation mechanisms.

E.6.1 Actions:

- Discussion with the NDE analyst prior to inspection can be beneficial in establishing expectations for disposition of indications such as manufacturing defects with respect to the final ECT report.
- Review previous ECT data (not just report), if available, to confirm indication presence.
- Suspect indications in open cooling water systems with pitting susceptible tube materials (copper alloys or low alloy stainless) warrant added caution when dispositioning flaw types. Pulling a tube for metallurgical analysis can improve understanding the indication.
- Comparison with other reported damage types and locations may be beneficial.
- Unexpected patterns for suspect indications may aid in their disposition.
- Hydrostatically testing the tube(s) may be justified.
- Tube plugging may be warranted with a removable plug style, allowing for additional data to be gathered or repairs in a future inspection to support return to service.

E.7 Missing End Plate (MEP) or Partial End Plate (PEP)

This condition is exclusive to feedwater heaters and represents a serious problem. The condition is similar to partial support plate (PSP) or missing support plate (MSP), but occurs at the thicker drain cooler end plate.

The drain cooler end plate is an internal pressure boundary for the drain cooler. As such, the consequences of a partial end plate can be more severe than a partial support or baffle plate, since the end plate opening allows steam to enter the drain cooler region. This can result in significantly increased tube vibration in the locations where the steam collapses when cooled by the tubes and/or by the sub-cooled condensate flow. If the drain cooler has been sufficiently breached such that it is no longer a separated lower pressure region, then the associated vibration problems will be greatly diminished.

E.7.1 Actions:

- A partial end plate indication is not a basis for plugging tubes, but does warrant caution when selecting plugging thresholds for wear or similar pluggable indications in the vicinity. On-screen review of the tube data with the ECT analyst for changes from the previous inspections can be beneficial when making tube plugging decisions where significant internal degradation such as a partial or missing drain cooler end plate exists.
- ECT data analyst's awareness for reporting partial versus missing end plate signatures is beneficial due to implications on repair options.
- Review of operating data may provide confirmatory data such as a drain cooler approach (DCA) above design.
- Increased operating level and/or a heater level test may be warranted to determine the optimum operating level.
- Review if allowed overload (i.e. during bypass of FWH string or upstream FWHs) remains acceptable given the degraded internals. Typically overload would be greatly restricted or prevented if significant loss of tube support has occurred.
- Review possible actions to reduce causes of high shell-side velocities or tube excitation.
- Ligament wastage to the extent that no plate signature remains will result in loose part debris in the system. The ligament fragments can collect in drain valves, guide slots of isolation valves, or cages of control valves and result in erratic control or inability to isolate or close the valve. The material may pass through condenser spargers, if applicable. If drains are pumped forward, it may enter the condensate, heater drain, or feedwater systems, according to the pump output path and end up in bypass valves, tubesheets, tubes, etc. It is beneficial for the system engineer(s) of potentially affected systems to be aware of this condition.
- Evaluate inspection frequency if condition is new, progressing, or accompanied by related damage mechanisms.

E.8 Partial Support Plate (PSP)

Partial support plate indications occur when the support or baffle plates are detected, but the ECT signal response is weakened due to reduced metal proximity. High tube vibration and occasionally corrosion (i.e. open cooling water system on the shell-side of a heat exchanger with carbon steel baffle plates) may cause plate wastage and may progress until the ligament separating the tubes is worn or corroded through. Support plates of softer material than the tubes will wear at a faster rate than the tubes (e.g. carbon steel support plates in a feedwater heater with stainless steel tubes). See Figures E-1, E-2, and E-3 for examples of partial support plates.

The partially missing plate will not result in tube failure, but it does allow excessive tube movement and may be present with a combination of other associated damage types. This condition may be accompanied by wear calls at the location of the partial plate and at adjacent support plates, possibly tube-to-tube wear (TTW) on this and adjacent tubes, partial or missing support plates (PSP, MSP) for this tube and adjacent tubes, signal drift (ADI), etc. If no other damage types are reported, it may be prudent to request the ECT analyst to review the data to confirm the absence of any other damage or unusual indications or changes to the ECT signal in the vicinity of a partial or missing plate. Review of the axial location with shell-side design features such as shell inlet nozzles or the drain cooler entrance may provide useful information regarding potential causes for the degradation.

E.8.1 Actions

- See the actions in Section E.7 for Partial or Missing End Plates for related actions.

Figure E-1
Example of significant support plate ligament wear

Figure E-2
Missing and partial support plate

Figure E-3
Partial support or baffle plate due to severe ligament wear

E.9 Missing Support Plate (MSP)

Missing support plates are a concern since the support or baffle plate was not detected at the expected location and is a progression of partial support plate (PSP).

E.9.1 Actions

- See the actions for partial or missing end plates for related actions.

E.10 Non Quantifiable Indication (NQI)

A non quantifiable indication is not classified as a defect, generally due to not forming, rotating, or similarly "behaving" consistent with a normal defect. However, a definite shift in the ECT signal occurred, which the analyst is noting.

E.10.1 Actions:

- This is not a pluggable indication and normally only warrants follow-up with an analyst if it occurs in a suspicious location or a pattern emerges such as the same location in adjacent tubes. Comparison with historical data is normally the best reference point, since it may have been present previously, but not called/identified (i.e. culled as junk).

E.11 Obstruction (OBS)

Obstruction indications are generally associated with a bent tube end, which prevents ECT probe entry and tube inspection.

E.11.1 Actions

- Request maintenance use a tapered mandrel (preferred, no metal fines or debris generated) or a reamer to remove the tube end restriction under the existing work package. If required, submit a work request document to address all tubes with similarly damaged ends when the heat exchanger is next scheduled to be opened.
- Request the restricted tube be opened in the current outage if an adjacent tube has a pluggable or significant OD defect such that the condition of the obstructed tube is in question, or if random defects (i.e. ID pitting) are present at pluggable depths.

E.12 OD Indication (ODI) or Multiple OD Indications (MOD)

Outside diameter indications are often associated with one-time occurrences of tube impact during heat exchanger fabrication, installation, maintenance, or operation, in which case the damage mechanism is not active. An isolated OD indication is often justifiable to leave in service, even if the through-wall extent is relatively high, provided the volume (voltage) is low to moderate. Such a defect is similar in structural significance to a pit. Multiple clustered OD indications on periphery tubes may indicate a loose part or foreign material coming into contact with the tube. Even though a loose part indication (PLP) may not accompany the indication, it does not mean that material is not still present in proximity to the tube and could come into contact when shell side flow is reinitiated.

E.12.1 Actions

- Review shell side construction to determine the damage location relative to the shell inlet and other shell internal components (i.e. impingement plate) in the vicinity.
- For MOD calls, ask the analyst how many are present and their axial location(s). Comparing with past calls is more difficult, since the same flaw may not be called each inspection and the landmarks may vary accordingly. From a risk perspective, MOD on a periphery tube near the shell inlet is of greater significance than a deeper indication which is located in the interior of the bundle, due to differences in the potential for the damage to be active.
- Tube plugging is warranted if depth exceeds plugging criteria and damage is potentially active. For pluggable indications, determine if video probe into this region of the shell is possible/warranted.

The above are based upon the OD indications not being associated with open cooling system water pitting of the tubes, since it is generally not a good practice to have an open system on the shell side. If open cooling water is supplied to the shell, then treat similar to pitting.

E.13 Possible Loose Part (PLP)

Possible loose part indications may be restricted to loose parts without tube damage, or they may include those with wall loss, which should be evident through the presence or absence of defect depth and voltage. This often only indicates metal in close proximity or contact with the tube at a location other than the baffle/support plate landmarks. The axial location and shell-side features in this vicinity as well as adjacent plugged tubes (and reason for plugging, if known) may be of interest. The presence of other related damage mechanisms in this vicinity such as wear, MOD, PSP or MSP for plates on either side (including for other tubes at these plates since debris may have migrated down through the tube bundle) are also of interest. The decision to leave in-service or plug a PLP indication will need to consider the above with inspection frequency, history, leak consequences, and plugging margin. PLP's without associated tube damage and present in previous inspections are normally not plugged.

E.13.1 Actions

- Confirm with analyst intended meaning and absence of damage, if none reported.
- Check history to see if indication was present in previous inspection.
- If it is a new indication consider if the heat exchanger has had loose part indications previously and if they remained stable or caused further damage. Plug according to history, leak consequences, and interval until next inspection. Tubes can be unplugged in a future inspection, and if no significant damage is found, returned to service.

E.14 Permeability Variation (PVN)

A permeability variation indication is not classified as a defect, but is related to a shift in the ECT signal.

E.14.1 Actions

- PVN is not a pluggable indication, but warrants follow-up with an analyst if in a degraded heat exchanger at a suspect location or a pattern emerges such as the same location in adjacent tubes. Comparison with historical data is normally the best information to base plugging decisions for a suspect PVN indication, since it may have previously existed, but not been reported (i.e. culled from final ECT report).

E.15 Retest Bad Data (RBD)

A retest bad data indication is intended to be a temporary place keeper in a preliminary report until the tube is retested and analyzed. If in the final report, it indicates valid tube inspection data was not acquired.

E.15.1 Actions

- The tube would only be plugged if adjacent tubes required plugging and a possible common issue causes tube integrity to be suspect.

E.16 Restriction (RES)

Down-tube restrictions are most often caused by lodged foreign material (primarily in open cooling systems, or first time inspections of closed systems) or dents large enough to prevent an ECT probe from passing (typical probe ID fill-factor of 85%).

E.16.1 Actions

- Check with NDE analyst if the term refers to a tube access problem such as a bent tube lip, or a down-tube restriction, if not evident from the extent of survey reported.
- If it is debris related, the restriction may be dislodged by rodding the tube, such as by hitting the object from the opposite direction. Foreign material restriction removal is important to allow tube ECT to look for damage associated with the blockage. If the debris cannot be dislodged, consider plugging the tube, particularly for softer metal tubes (i.e. brass, copper, copper-nickel) due to localized erosion risk.
- If due to a large dent, inspection options include inspecting the tube from the opposite direction to the back of the restriction. A less preferred option is a smaller fill-factor probe, since data quality would be diminished.
- If the restriction prevents further inspection, consider video probe inspection.
- Note the axial location of the restriction with shell-side features in the area as well as dents or defects in this vicinity in adjacent tubes.
- If the obstruction is due to a dent near previous tube failures or pluggable damage, then caution is warranted when deciding if the tube should be left in service.

E.17 Retest Incomplete (RIC)

A retest incomplete indication is similar to the RBD indication and is not intended to be in the final report. If present, it indicates tube inspection was not completed.

E.18 Stress Corrosion Cracking (SCC)

The detection of tube cracking is a serious concern. Circumferential cracks can be missed completely by traditional eddy current probes since only the axial extent of the flaw is detected. Alternative probe types or probe combinations can be used to inspect for circumferential cracks.

Stress corrosion cracking can result in catastrophic metal failure promoted by the interaction of tensile stresses, time, and the environment. Cracking failures from high-cycle fatigue occur mostly at rigid attachments (i.e. tubesheets and plates) and stress risers. Fatigue failure of a tube near the tubesheet joint can be due to hardening of the tube material due to tube movement. The associated work hardening increases susceptibility to stress corrosion cracking. Residual stresses at the tubesheet roll transition may provide sufficient stress or combine with stresses from the fixed node point of the tube restraint under high vibratory excitation to support SCC initiation.

E.18.1 Actions

- See actions for Circumferential Cracking indication.

E.19 Tube-to-Tube Wear (TTW)

Tube-to-tube wear is not expected in a properly designed and operated heat exchanger. It indicates one or more of the following exist:

- Excessive cross-flow velocities or tube excitation.
- Tube spans are excessive per original design.
- Tube supports have changed such as ligament wear allowing greater tube movement.
- Tube supports have shifted due to failure of the cage restraints.
- Tube stiffness has changed due to thinning.

Related complications could include localized work-hardening or embrittlement of the tube, increasing susceptibility to cracking and rapid failure. The tube wear may not be the final cause of failure, but may combine with related dynamic degradation conditions such cracking. Plugging thresholds to avoid tube failure are more difficult to accurately establish when multiple related degradation actions are present and potentially interacting. This condition is normally accompanied by TTW wear calls on adjacent tubes and possibly by wear at support plates, partial or missing support plates (PSP, MSP), signal drift (ADI), or others.

E.19.1 Actions

- Check the axial location with associated shell-side design features such as a shell inlet nozzle or drain cooler entrance.
- If other accompanying damage indications are not reported in this or adjacent tubes, ask the analyst to review the data to confirm.
- Plug conservatively and/or consider more frequent inspections, until progression rate is known.
- Review if excess flow or overload operating conditions have occurred. Consider actions such as flow reduction to minimize recurrence.

E.20 Wear (WAR)

Wear at support or baffle plates may occur in some normally operating heat exchangers. Wear is a structurally significant damage mechanism due to larger volumes of tube material being lost and the shouldering effect from surrounding metal is diminished or not applicable. While a pit must reach 100% through-wall depth before a leak occurs, wear damage can result in structural failure of the tube wall.

Wear damage may not result in direct failure from an over-pressure rupture, but can combine with stress concentration to result in cracking as the final failure mechanism. Wear may cause stress concentration points and may be accompanied by larger tube vibration displacements due to increased gaps at plates. The looser tube is able to deflect further and wear rates will generally increase. Significant progression of support/baffle plate wear may combine with the high levels of vibration induced stresses to cause fatigue or stress cracking, rapidly weakening the tube to the point of failure. These combined or progressive damage mechanisms are termed dynamic interactions.

Small amounts (i.e. single digit to teen %) of wear occurring at baffle or support plates in a continuous duty heat exchanger with many years of service is not a condition of significant concern nor is it necessarily abnormal or unexpected, provided a slow progression has been occurring over many cycles. Due to the considerations noted above, a cautious approach is applied to wear, with the amount of caution increased in proportion to the rate of change of the wear damage.

Wear is not expected at locations other than baffle or support plates, since there should not be anything in contact with the tube at other locations. Tube-to-tube wear is a separate category. Wear other than at plates may be classified by the NDE analyst as ODI, since wear is associated with metal contact and on a bare section of tube the analyst is likely to size the damage consistent with an OD defect, which can significantly skew the indication. Wear away from the plates could be due to loose parts from within the heat exchanger such as a failed impingement plate or broken tube pieces, or the loose parts may be due to external material in the system. The wear may not be accompanied by a possible loose part (PLP) indication, but that does not ensure the debris is not present, only that it was not adjacent to the tube at the time of the inspection. Wear locations other than at support or baffle plates are of greater potential concern since the associated wear rate is less predictable than that at plates.

Tube wear at plates is normally accompanied by increased plate hole size, which further loosens the tube and can aggravate the vibration problem. Significant wear is most commonly seen in feedwater heater drain coolers, and while of concern due to the large volume of metal removed, may be relatively slow to progress in size (depending on frequency of occurrence of high vibration conditions in the drains cooler region).

Significant increases in wear are always of interest, even if the wear depth remains below the plugging limit, since it indicates a change in tube vibration conditions. Evaluation of the cause, actions to address the cause, and potential changes to inspection frequency and remaining life assessments may all be warranted. The location of the wear damage can be important in determining the cause of increased wear. Wear often occurs in multiple tubes at the same support or baffle plate due to the source of increased tube vibration affecting multiple tubes.

E.20.1 Actions

- Any wear away from a support or baffle plate warrants caution. Progression rate is a key variable in the plugging decision. Wear appearing since the last inspection at a location away from support or baffle plates is a candidate for plugging due to higher uncertainty for progression rate.
- Wear at support or baffle plates is often accompanied by a greater wear rate to the plate ligaments, causing weak plate signals indicated by PSP or MSP. If not reported, request the analyst confirm the strength of plate indications.
- If a high wear rate was not present previously, then check for operational causes, instrument or controller causes, and if those are ruled out then internal material condition changes are another possible cause.
- Elevated wear rates are a potential basis for more frequent ECT inspections.
- Wear damage may be misclassified as ODI due to the absence of metal in the vicinity of the damage. Shifted baffle plates can result in a set of wear indications a few inches away from the current plate location. Patterns of OD calls at a similar distances from a support or baffle plate on multiple tubes may indicate baffle plate shift. The analyst can check the plate landmark location relative to its expected or historical location (i.e. distance from tubesheet). Figure E-4 depicts a shifted plate which has left stranded wear indications away from the current plate location.

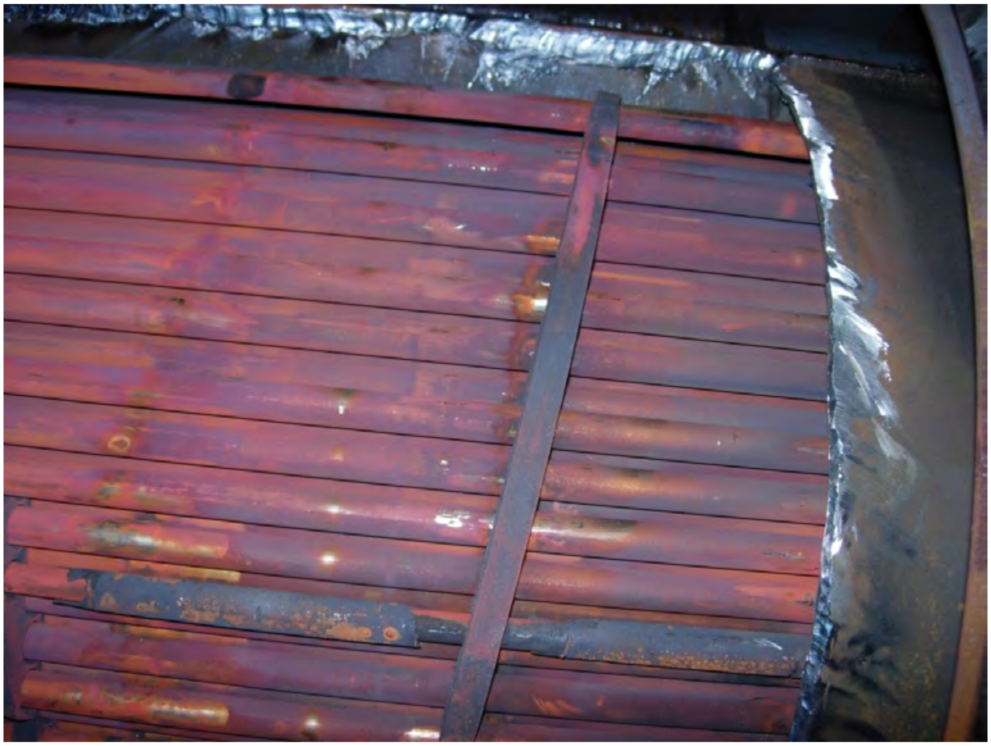


Figure E-4
Shifted baffle plate with stranded wear damage

E.20.2 Infrequent/Uncommon Indications

Infrequent and uncommon indications may be seen in tube bundles with significant degradation, such as the drain cooler region in a problem feedwater heater. They are best considered as a possible “tell-tale” indicator of changing tube conditions, generally thought to be related to excessive tube vibration.

E.21 Absolute Drift Indication (ADI)

An absolute drift indication does not have a calibration or reference standard, resulting in greater uncertainty with regard to characterization. While a change to the normal tube response to the applied eddy current can be detected, without a calibration reference it is more difficult to classify the detected indication. Patterns, such as multiple tubes affected in the same area or other tell-tale indicators, may provide evidence the indications warrant further investigation. Evaluate this type of indication in conjunction with other data for the affected tube(s) and region of the heat exchanger. Changes to ECT baseline drift have been found as the only precursor or change in tube condition detected prior to tube failures which occurred at the location of the changing drift signal in some degraded feedwater heaters.

E.21.1 Actions

- Follow-up with the ECT analyst to view the indications on-screen and obtain their input.
- Tube plugging is subjective for this indication, since it is not supported by a calibration standard and a high degree of uncertainty exists regarding its cause. It is best considered a possible “tell-tale” indicator of changing tube conditions in a degraded tube bundle. The best conclusions are reached based on comparison of changes from previous inspections, the proximity to tube failures, and accompanying damage types and their rate of change in this or nearby tubes. If isolated or without other supporting damage or degradation in nearby tubes, this indication only warrants monitoring.
- A pulled tube sent for metallurgical analysis may provide improved understanding.

E.22 Bulge (BLG) or Distorted Signal Indication (DSI)

Similar to the ADI description above, bulge or distorted signal indications may be applied to a distorted baffle plate signature where absolute baseline signal drift or other consistent abnormalities are noted. They have in some cases preceded tube failures and subsequently been used as a “tell-tale” indication. A possible explanation for the signal distortion is tube work hardening causing the baseline signal drift.

E.22.1 Actions

- See actions in section E.21.

Table E-1
ECT indication responses summary

Indication	Plug	Plug per Calculator	No Action	Other Action	Comments
CIR	X				
DEP			X		
DNT	*		X		Review location in FWH; for brass tubes with high leak consequence plugging may be used to avoid cracking risk.
ERO	X			X	Primarily condenser issue, visual follow-up beneficial.
IDI		X			
LPI		X			
Mfg. Defect			X		Confirmation of cause may be limited.
MEP/PEP MSP/PSP				X	See action list in Att. E.
NQI			X		
OBS				X	Open for future inspection
ODI		X			
PLP				X	Review history & suspected source for plugging determination
PVN			X		
RES	*			X	Remove if foreign material (plug if foreign material not removed)
SCC	X				
TTW		X		X	Not an expected condition, consider cause for action, related issues
WAR		X			
ADI	*			X	Large uncertainty, should only be in degraded heat exchanger in a susceptible area; plug if growing /changing.
BLG	*			X	(same as ADI)
DSI	*			X	(same as ADI)

F

GL 89-13 PROGRAM – PERIODIC CHEMISTRY MEETING AGENDA

This section provides a brief summary of the benefits from periodic meetings between chemistry and engineering personnel related to the SW/UHS system. Examples of discussion topics for the meeting agenda are included.

Periodic meetings with Chemistry and Engineering are beneficial to review the health and effectiveness of chemistry controls for the open-loop safety related cooling water systems performing an Ultimate Heat Sink (UHS) function. These systems are generically referred to as Service Water systems, although different terminology may be used at a given station. Discussions may also address other safety related closed cooling water systems (e.g. EDG Jacket Water) cooled by the SW system, or non safety-related open cooling water system parameters of interest to the SW system and GL 89-13 program.

Topics for discussion include SW system chemical treatment and monitoring equipment issues, changes to chemical treatment, observations during visual inspections of heat exchangers, piping, and pump bays, SW heat exchanger trends (fouling, flow and dp data), and industry OE. This section provides a generic outline for such a meeting.

Minimum Attendees:

- Service Water System Engineer
- Chemistry Owner for SW Chemistry
- Heat Exchanger/GL 89-13 Program Owner

Back-ups to these attendees may be used provided they are knowledgeable of SW system issues and have received information turnover from the primary representative.

Optional Attendees:

- Chemical vendor supporting SW treatment
- Heat Exchanger and/or Diesel Generator Component Engineers
- Diesel Generator System Engineer

The following pages provide a listing of potential topics of discussion. Not all of these issues may warrant discussion at each meeting and other topics may be covered as deemed appropriate.

F.1 Chemistry –Monitoring, Equipment, and Industry Information

- Service Water System chemistry trends of significance, include UHS water analysis, as well as closed systems cooled by SW.
- Chemistry generated adverse condition reports since the last meeting related to chemical treatment, equipment, or monitoring.
- Out-of-spec conditions for related chemistry parameters. Discuss/consider:
    - Why parameter went out-of-spec?
    - How cause can be avoided?
    - Is limit appropriately conservative?
    - Are responses commensurate with risk of condition being out-of-spec?
- Status of biological control in SW and closed-loop systems. Sample, test, monitoring, and inspection results regarding bacteria (particularly MIC related), slimes/algae, mussels/clams, other.
- Chemistry OE of note: benchmark, assessment, or industry meeting information related to SW, EDG-jacket water, or closed system chemical treatment or monitoring.
- Pending or proposed changes to chemicals, injection rates, times, locations, action limits, etc. Basis for change, intended results, possible other consequences due to dynamic interactions.
- Upcoming planned system outages for chemical treatment or monitoring equipment (major maintenance or modification driven, not instrument calibration).
- Visual inspection results by chemistry personnel for associated systems including piping, heat exchangers, pump bays, etc.
- Recommendations to provide greatest improvement in water quality, equipment reliability, monitoring capability, risk reduction, etc.

F.2 Engineering–Monitoring, Tests, Inspections, and Industry Information

- Trend results for SW heat exchanger thermal tests, as-found tube blockage (amounts and source materials), dp/temperature/flow monitoring. Margins available (thermal and tube blockage) for chemistry and other engineers awareness.
- Visual Inspection results for SW system heat exchangers, piping, and pump bays.
- Adverse condition reports related to SW heat exchanger trends.
- Failures of chemical treatment equipment. – discuss any of the following:
  - Time needed to recognize failure.
  - Impact of failure.
  - Available backup equipment.
  - Contingencies available.

  - Out-of-service time.
  - Frequency of failure.
  - Changes needed to PMs or equipment type.
- Pending or in-progress modifications to related chemistry equipment.
- Engineering OE reviews of note: benchmark, assessment, or industry meeting information related to SW heat exchangers or closed loop chemistry issues.
- Proposed changes to heat exchanger testing or inspections.
- SW heat exchanger eddy current testing results.
- Recommendations to achieve greatest improvement in SW heat exchanger health, margin, reliability, risk reduction, maintenance, etc.

F.3 Summary Review

- Meeting attendees to determine if follow-up actions are warranted based on the meeting discussion. Actions may include adjustments to system or program health indicators, initiation of adverse condition report, PM change, work request, action item, long range plan item, budget item, etc.
- Key discussion topics or issues may warrant summarizing in meeting minutes to place in system or program notebooks and/or forwarding to Supervisors in Chemistry, Engineering or other groups for awareness/communication.

G
BOP HX PROGRAM PRE-INSPECTION CHECKLIST FOR ECT

This section provides an example checklist which could be used by the BOP Heat Exchanger program owner for pre-inspection discussions with the lead NDE ECT analyst.

Engineer Review Prior to Discussion

Review the last ECT report, tube plugging records (and sister heat exchanger data) for the following:

Types of defects present and their locations (row and tube + axial) _____

Damage progression rates

Operational, chemistry, or system changes/events _____

Inspection scope from the last inspection _____

Tube leaks (recent and historical) and their causes _____

Nuisance indications (i.e. large # of small dents at FWH support plates) _____

Pre-Outage Discussion Topics with NDE Analyst

Inspection Scope (100% or partial; identify partial specifics) _____

Probe Type(s), their defect detection capabilities and limitations _____

Calibration Standard defects _____

Safety discussion for tapered plug OE in high pressure service (if applicable). _____

JIT brief with NDE analysts (if critical or problem heat exchanger) _____

Analyst review expectations – i.e. minimum 2 analysts reviewing data _____

Types of indications for analyst to review with engineer _____

Plugging list will be provided to NDE and Maintenance _____

Low thermal/plugging margin considerations _____

Excluded indications requiring engineer concurrence _____

Indication abbreviations used in results spreadsheet are explained in report _____

Partial or missing support, baffle, and end plates are all to be reported _____

Just-In-Time Training Review with NDE Analyst

Heat Exchanger #:_________ Date or Outage Last Inspected:_______

Items of Interest:

____

____

____

Heat Exchanger #:_________ Date or Outage Last Inspected:_______

Items of Interest:

____

____

____

____

H

GL 89-13 PROGRAM AND NRC INSPECTION PROCEDURE 71111.07 – UHS

This section highlights content in NRC inspection procedure 71111.07 which is NOT included in GL 89-13, and therefore may warrant additional consideration by GL 89-13 program owners. NRC inspection procedure 71111.07 is used for the triennial Ultimate Heat Sink assessment. The procedure is not a regulatory requirement, but it is used for the NRC's oversight of on-going actions related to GL 89-13 programs and it also includes content to address industry operating experience and significant events since GL 89-13 was issued.

1. End-bell checked for possible misorientation. Applicable to four-pass heat exchangers which may have return end-bells incorrectly installed and result in isolated tube passes.

   This issue was not included in the original GL 89-13 actions, but reflects industry experience since GL 89-13 was written. Multiple industry OE reports have been issued related to this condition (see Section 4.6.3). Through the OE response process, stations have had several opportunities to check for susceptible design and implement appropriate actions. Programmatic or on-going actions are not required, since the issue can be effectively addressed by appropriate work control instructions and verification steps for susceptible heat exchangers. Visual inspection checklists or guidance documents may also include inspection for this issue at sites with susceptible heat exchangers.

2. Heat exchanger tests and inspections are to be consistent with industry guidance. The inspection procedure only references EPRI NP-7552. However EPRI guidance for thermal performance testing is commonly understood to be provided in the more recent EPRI TR-107397, and for visual inspections in Section 3.3 of EPRI 1003320.

   Generic Letter 89-13 did not require testing, inspection or maintenance actions per EPRI or other guidance documents. However, it is beneficial for GL 89-13 program documents to include technical justification for notable differences from the guidance in the EPRI documents for the applicable testing, monitoring, or inspection applied.

3. Acceptance criteria are to be established and consistent with site design basis documents for tests and inspections.

   Establishing acceptance criteria is a one-time action versus an on-going process. Audits or self-assessments may be used to periodically verify acceptance criteria are established where appropriate, are quantitative, sufficiently detailed, and compliant with design basis requirements. Program benchmarking provides a potential tool for review of other utility acceptance criteria for best practices and improvements.

The use of quantitative acceptance criteria rather than qualitative terms is beneficial. An example is replacing "ensure corrosion is not excessive" (qualitative) in a visual inspection checklist, with a numerical corrosion limit for pitting such as, "ensure corrosion does not exceed the Tmin limit listed in Table 1 for this heat exchanger ".

4. The test or inspection frequency is to be based upon trends of results and sufficient to ensure degradation is detected prior to loss of required performance capabilities.

   GL 89-13 program results from tests and inspections are trended or compared to historical results to ensure acceptable margin is maintained. It is a good practice to document this review/comparison in the inspection or test report. Inspection forms or test guidance documents can require this step as part of performing the task.

   Heat exchangers with limited in-service hours between inspections/tests may need to further evaluate the fouling or degradation rate per in-service time, if the degradation is related to in-service time, when projecting acceptable intervals to protect a longer required mission time (often 30 days post-accident).

5. Tube plugs are verified in the correct tubes per controlled documents and the correct quantity per design analysis.

   This action is not mentioned in GL 89-13, but is related to ensuring heat transfer capability. It is expected that visual inspection guidance includes confirming the tube plug positions (both tube ends) and the number of plugged tubes being within the allowed quantity per the design analysis.

6. Operations procedure limits or plant controls (i.e. throttle or flow control valves) are established to prevent excessive shell-side flow from causing flow-induced vibration damage to heat exchanger tubes.

   Verification of proper shell-side flow control limits was not part of the one-time GL 89-13 response actions, but reflects industry experience. Multiple industry OE reports have been issued related to this condition (see Section 4.6.2). The issue is not limited to open-loop cooling water systems or related to heat transfer capacity problems.

7. Structural integrity is verified for tubes per ECT and for channels and tubesheets per visual inspection.

   Tube inspection by ECT or similar NDE methods may be per the BOP Heat Exchanger program. Visual inspection checklists or guidance documents with quantitative acceptance criteria for channel and tubesheet degradation limits are a beneficial practice. PM actions to periodically perform UT checks of channels and tubesheets (if carbon steel) would be an equally effective means of addressing their structural integrity.

8. Closed loop heat exchangers supporting the UHS function are provided chemical treatment consistent with industry standards and chemistry is controlled, tested, and evaluated.

   Closed loop systems may be exempted from the scope of the GL 89-13 program based on chemistry controls and monitoring consistent with industry standards contained in EPRI 1007820. As noted in Section 2.1.1, the GL 89-13 program is not responsible for closed loop cooling water system chemistry, although it is beneficial for program documents to reference the controls which ensure effective chemistry treatment and monitoring of those systems.

9. Cooling towers and spray ponds are periodically inspected for heat transfer capability and structural integrity.

   These components are relied upon for heat transfer functions as part of the UHS at some stations, and accordingly warrant periodic inspections for heat transfer capability and structural integrity. Similar to heat exchanger visual inspections, the use of detailed inspection guidance and quantitative acceptance criteria are good practices.

10. Fixed volume UHS systems (i.e. recirculating systems) are verified to have adequate chemistry monitoring to ensure adequate pH and calcium hardness are maintained to avoid scaling during design bases event response.

    This issue was not addressed in GL 89-13, however it is beneficial for sites with fixed volume (i.e. recirculating) UHS systems to have documentation evaluating chemistry control limits for pH and scaling potential with respect to post-accident conditions when evaporative losses may cause increased chemical concentrations.

I
GENERAL HEAT EXCHANGER VISUAL INSPECTION GUIDANCE

This section provides additional detail for general heat exchanger visual inspections.

The principal heat exchanger design addressed for visual inspection is shell-and-tube. Some shell-and-tube heat exchangers such as the main condensers and MSRs have sufficiently unique design that more detailed and specific guidance is appropriate, although some general aspects of the content will be applicable. Inspection guidance can be applied to air-to-water cooling coils (i.e. hydrogen coolers, isophase bus, room coolers and HVAC coils) if their design permits tubeside inspection via a bolted waterbox cover.

I.1 Principal Heat Exchanger Features of Interest

- Tubes
- Tube Plugs
- Tubesheet(s)
- Channel
- Cover or manway
- Partition plate, if multi-pass
- Shell

The features of interest and their degradation mechanisms are noted from the perspective of visual inspection, not from a design perspective or degradation which would require other inspection methods to detect (i.e. tube degradation requiring ECT).

I.1.1 Tubes

Tube integrity is addressed via NDE (normally eddy current testing for most materials), and is not the principal focus of visual inspections.

I.1.1.1 Degradation Mechanism

- A potential issue not easily detected by ECT is general ID erosion, which is common to copper alloy tubes in open cooling water systems.

I.1.1.2 What to Look For

- Debris, foreign material, sediments, shells, etc. in visible portions of tubes
- If open cooling water system – slimes or bio-fouling (contact chemistry if seen)
- If debris is lodged past the tubesheet in any tubes, have the tubes ECT checked for damage after the debris is removed
- If copper alloy tubes in an open cooling water system, check if PM task exists to perform ID measurements. If not, then:
    - Inspect visible portion of tube ID for evidence of roughness and erosion.
    - If noted, follow-up with tube ID wall loss sample measurements.

I.1.2 Tube Plugs

Tube plugs are normally not expected to fail, but PM relies upon visual inspection and after-the-fact on tube leak indication to check for leaks. Total number of plugged tubes as well as the correct locations should be checked, with the total number verified to be below the plugging limit (if defined). Inspect plug conditions for damage or degradation, particularly if elastomeric plugs are present (low pressure applications such as condensers).

I.1.2.1 Degradation Mechanism

- Aging and cracking of elastomeric plugs, loosening from thermal cycles, ejected or missing plugs, incorrect tube plugged.

I.1.2.2 What to Look For

- Correct quantity and location of tube plugs.
- If an FME sensitive system and plugs with break-away pull pins are used, then verify break-away tips are removed.
- Weeping, seeping, bubbling at tube seal. (see Caution below)
- For high plug leak consequence heat exchangers check:
    - If elastomeric plugs are used – note locations, appearance, and follow-up check that retightening and replacement actions have been initiated or established.
    - Verify plugs are set/tight
    - If hammered tapered plugs are used, note locations (not optimum plug).

CAUTION: Plugs may have trapped pressurized fluid behind them. Added caution should be used around tapered plugs or elastomeric plugs if checking tightness or if evidence of leakage from behind the plug is present.

Tapered plugs have ejected violently from feedwater heaters when being removed. Sufficient pressure could exist behind feedwater heater tube plugs (or plugs in other high pressure systems) to cause injury. Therefore, tapered plug removal from feedwater heater tubes warrants protective measures, unless the tube is known to be breached or the plug has known leakby.

Elastomeric plugs have ejected from condenser tubes when they were being removed and during plant operational transients. While sufficient pressure is not likely to be trapped to cause serious injury if normal personnel protective equipment is in use (i.e. safety glasses, hard hat, and gloves) due to the plug ejection itself, workers should not be positioned in the potential path of the plug. Risk of secondary injury exists from worker reflex reactions due to being startled. Workers checking plugs should be aware of potential for plug ejection. For additional information on plug ejection events see INPO[6] Operating Experience website.

I.1.3 Tubesheet(s)

Most tubesheets are carbon steel, but may be clad (if a welded tube-to-tubesheet joint is used), or made from copper alloy to match the tube materials (particularly in open cooling systems where corrosion potential is higher). Carbon steel tubesheets in open systems are often coated for corrosion protection.

I.1.3.1 Degradation Mechanism

- Tubesheet degradation is uncommon other than in open cooling water systems. Damage to tubesheet ligaments between tubes is occasionally caused by excessive force when driving tapered plugs and possibly by other plug designs.

I.1.3.2 What to Look For

- Corrosion buildup on tubesheet (carbon steel in open cooling system).
  - If present, then after cleaning check penetration depth at tube-to-tubesheet interface with a pit gauge, welder hi-lo gauge or similar.
- If tapered plugs are present, then examine tubesheet in vicinity for damage.

[6] Access to INPO reports and materials is restricted to organizations authorized by INPO. The information is confidential and for the sole use of the authorized organization.

I.1.4 Channel

The channel is located between the tubesheet and the cover or manway, and includes the supply/return nozzles. Some smaller heat exchangers or coils have a removable bolted cover with flanged pipe connections such that the entire end of the heat exchanger is removed past the tubesheet.

I.1.4.1 Degradation Mechanism

- Channel degradation is uncommon other than in open cooling water systems with uncoated carbon steel or cast iron (graphitic corrosion).

I.1.4.2 What to Look For

- Corrosion buildup on the channel. If tubercles are present, check under larger ones and at channel weld areas for corrosion depth. Follow-up with NDE to perform UT, if needed to quantify corrosion depth. If cast iron, surface may appear uniform, hardness checks may be required to detect dealloying.

I.1.5 Cover or Manway

Manways are used in applications where cleaning and/or retubing are not expected. They are often used on high pressure components to reduce leakage potential. Full diameter covers are common on most smaller and low pressure cooling water heat exchangers. Gasket designs and types may vary considerably including welded diaphragms in some feedwater heaters. Gasket leaks can occur in any bolted joint application. No specific PM activities apply other than visual inspection and good bolted joint practices.

I.1.5.1 Degradation Mechanism

- Cover degradation is uncommon other than in open cooling water systems with uncoated carbon steel.

I.1.5.2 What to Look For

- Awareness of the heat exchanger gasket leak history is beneficial. Inspect old gaskets for uneven compression set or missing sections. Inspect seating surface condition. For high energy systems or borated water service, ensure mechanics inspect fastener threads after cleaning, and check for hardened washers under nuts. Leakage critical applications may warrant review of torque values, gasket selection and related parameters.
- Corrosion buildup on the cover or end bell. If tubercles are present, check under larger ones and the gasket seating surfaces.
  - Corrosion damage to gasket seating surfaces in open cooling water is common due to large galvanic potential difference between graphite and carbon steel.

I.1.6 Divider or Partition Plate(s)

Dividers and partition plate inspections are applicable to multi-pass heat exchangers. Some partition plates include internal bolted (occasionally welded) covers independent of the access cover. A more common design is for the cover to provide the gasket seating surface with the edge of the partition plate. Smaller multi-pass units with removable heads often have integral partition ribs designed into the head that seal against the tubesheet. Gaskets may be independent of the channel cover gasket if an internal partition plate cover is used, or commonly a single gasket seals both exterior leakage as well as internal pass-to-pass leakage across the partition plate ribs.

I.1.6.1 Degradation Mechanism

- Degradation is not expected, but should be relatively evident, therefore, no specific PM actions exist other than visual inspection.
- *Partition plates are not ASME Code pressure boundary parts, thus, lower design standards and safety factors have historically been used, with some designs found to be marginal for plate thickness and weld size. TEMA standards have been upgraded regarding partition plates, but older units may have design weaknesses.*
- Installation errors on small four-pass heat exchangers with partition dividers in the head or endbell have occurred in several stations resulting in reduced thermal capacity.

I.1.6.2 What to Look For

- Bowed partition plates, cracked welds, proper orientation of heads (if of the integral partition rib design) for both as-found and as-left conditions (consider adding “match-mark” line), gasket condition (ask mechanics in advance to save gasket for inspection), and gasket surfaces. A more rigorous inspection may be warranted for safety related and/or high tube-side temperature change heat exchangers.
  - For internal bolted cover plate designs, ask mechanics if all nuts were intact and if they were as-found loose or tight.

I.1.7 Shell

Shell internals inspections and shell wall thickness inspections are discussed in Section 5.2.5. Accessible portions of the shell exterior are inspected for any obvious issues, although routine operator rounds or system engineering walkdowns normally detect leaks.

I.1.7.1 Degradation Mechanism

- Damage mechanisms are uncommon.

I.1.7.2 What to Look For

- Inspect insulation (if applicable).
- Evidence of external corrosion.
- Inspect pedestals for concrete damage and if applicable, expansion slots. Most horizontal shell-and-tube heat exchangers include provision for thermal growth via one support having a slotted base plate with the anchor bolt nut not tightened to allow movement. Verify the nut does not appear tightened and the slot is not full of rust or debris that could inhibit movement.

I.1.8 Other Heat Exchanger Parts or Features of Interest

- Coatings – While not a “part”, they may exist on tubesheets, channels, and covers and warrant inspection for damage or degradation.
- Anodes – check condition (include in PM steps to inspect/replace)
- Dissimilar metal welds – inspect for evidence of cracking (perform NDE if suspected)
- Asbestos gaskets – common in older heat exchangers, may be encountered in first-time inspections.

I.2 Thermal Degradation and Visual Inspection

Visual inspection is not sufficient to ensure required thermal performance, but it can detect degradation mechanisms and/or provide confirmation other controls and system design features are maintaining fouling within acceptable limits. The principal thermal degradation mechanisms detectable by visual inspection involve macrofouling (i.e. debris blocking tubes and/or sediment buildup in tubes) and bypass issues for multi-pass heat exchangers.

I.2.1 Macrofouling

As described in Section 4.2.1, macrofouling consists of large fairly obvious material, most often at the tubesheet but possibly lodged down the tubes or deposited in the tubes due to sedimentation. Includes foreign material, debris, corrosion nodules, dislodged coating, gaskets, component parts, biological material (shells, grass, fish, leaves, sticks, etc.), and solids that have come out of suspension. Many of these materials are exclusive to open cooling systems where macrofouling is more common. Macrofouling sufficient to noticeably reduce thermal performance is normally accompanied by other system effects such as reduced flow and increased pressure drop.

I.2.2 Microfouling

As described in Section 4.2.2, microfouling is primarily addressed by chemistry and should be limited to open cooling systems from biological agents such as slime or bacteria, from scaling mineral deposition, and rarely from chemical precipitates (i.e. recirculating systems such as cooling tower or spray pond). Microfouling can produce significant thermal effects without other indications of system problems since flow or pressure drop changes may be small.

I.2.3 Bypass flow

As described in Section 4.2.3, bypass flow in multi-pass heat exchangers can occur at divider/partition plate gaskets or at the dividers themselves due to corrosion, weld cracking, or plate failure. Where the dividers are integral to a removable head, improper positioning of the head during installation can block or bypass flow passages. Bypass flow from gasket leakage generally does not result in significant loss of thermal performance other than in high tube-side temperature change applications. Bypass flow is generally not detected by changes in monitored system parameters such as flow and dp.

I.2.4 Other

Additional causes for thermal issues such as inadequate venting (i.e. air binding), or improper reassembly of removable bundles are not likely to be detected by visual inspection.

I.2.5 Heat Exchanger Design Features and Visual Inspection

Review of heat exchanger design information, while potentially beneficial, is not necessary prior to most visual inspections. Familiarity with the basic heat exchanger design and service conditions is beneficial. Much of the general design details contained in the data sheet and outline drawing, such as materials of construction and # passes, are readily apparent during the inspection without prior review. Special circumstances such as very limited inspection time or high radiation levels may warrant the added preparation time spent reviewing the data sheet and outline drawing information, particularly if the inspector has not seen the component previously.

The data sheet and outline drawing are the two most commonly available sources of information. Design information of potential interest for visual inspection:

- Tube material, specifically if brass or copper are present (ID erosion checks).
- Tube design pressure (trapped energy potential behind tapered or elastomeric plugs, cover gasket leakage potential).
- For open cooling systems, carbon steel materials are of interest due to corrosion.
- Tube side temperature gradient inlet to outlet (high delta T increases cracking risks).
- Dissimilar metal welds such as tubesheet to channel (higher cracking potential).
- # passes (partition plate inspection issues).

I.2.6 System Design and Operation Impact on Visual Inspection

Design and/or operating conditions can significantly influence the potential for degradation and the types of degradation of interest. The individual performing the visual inspection is expected to be aware of the following, as they relate to the heat exchanger being inspected:

- Open Cooling Water Systems – open to the environment and may be from lakes, rivers, ponds, cooling towers, spray ponds, etc. Due to their interaction with the environment these systems have much greater susceptibility to a number of fouling, corrosion and degradation issues compared to closed loop systems. Open systems are classified as once-through or recirculating systems. Recirculating systems such as cooling towers or spray ponds, generally allow for better biological treatment but also concentrate minerals and materials in the makeup water source to a higher degree than once-through systems. Once-through systems may be significantly restricted on their ability to chemically treat the system for biological control due to local, state, and federal environmental laws.
- Standby or normally operating service is important information.
- Safety Related (active function) – Impacts condition report threshold for as-found conditions and increased scrutiny of potential thermal issues.
- Primary system water (borated) on tube side – high dose and contamination – more pre-planning and preparation is warranted to minimize dose, external gasket leakage can be significant issue due to impact on unidentified leakage, dose, and in the Auxiliary Building the control room dose calculations limit allowable leakage. Careful review of torque values, passes, retorque, and gaskets prior to work. Review if design includes Belleville washers under nuts. Inspection must balance speed (ALARA) against thoroughness to avoid leaks. Increase inspection attention to gaskets, gasket seating surfaces, and closure studs to avoid leaks.
- High tube-side temperature change – Principal examples are PWR letdown (300˚F or 167˚C delta T) and blowdown heat exchangers and shutdown/decay heat/RHR/ cooling and feedwater heaters. A high delta T condition significantly increases the potential for cracking problems at pass partition plates (if applicable). Thermal impact of partition gasket leakage is also higher.
- High tube-side operating pressure causes greater risk of manway or cover gasket leakage, and greater potential of stored energy in tubes if tapered plugs were used.

I.2.7 Heat Exchanger Leakage and Failure History

Awareness of past maintenance and operational problems such as tube leaks, external leaks, repairs, fouling, etc may be beneficial, particularly for heat exchangers with higher consequences (e.g. safety related, inaccessible at power, power reduction required, etc.)

I.2.8 Inspection Results – Immediate Actions

Visual inspection findings may require immediate response before returning the heat exchanger to service, or scope addition actions may be needed during the current outage.

1. Condition adverse to quality, as appropriate based on procedure guidance.
   - Extent of condition actions may be needed in the current outage.
   - Actions to address the source of the problem may be needed, if external:
   - Foreign material control problems.
   - Failed part from valves, pumps, strainers, etc.
   - Bypass or carryover issues with strainers or screens (open cooling water).
   - Failed coatings or liners from piping or pumps.
2. Corrective Maintenance:
   - Minor items are addressed by the current work package. (e.g. missing plugs, wrong tube plugged, tube cleaning, macrofouling removal, damaged studs).
   - Work requests are initiated for repairs, with outage scope addition criteria used to determine scheduling. (Examples: coating repair, corrosion repair, gasket seating surface damage, etc.)

I.2.9 Inspection Results – Follow-up Actions

Visual inspection findings may be beyond the scope of the current work package and may not warrant repair in the current outage. These type issues may be at a greater risk of not being captured or addressed for follow-up action. Examples include:

1. Corrective Maintenance:
   - Change plug type to address leaking, degraded, failed, or ejected plugs.
   - Addition of hardened washers or live-load washers to reduce gasket leaks.
   - Repair of upstream component coating to reduce macro-fouling.
2. Preventive Maintenance:
   - Add action such as tube ID measurements to trend brass tube erosion.
   - Change of upstream component PM to address damage or material condition (i.e. failed valve or pump part at tubesheet).

3. Engineering Change/Modification:
   - Changes to chemical treatment to reduce macro- or micro- biofouling.
   - Addition of protective coating to tubesheet or channel.
   - Changes to reduce gasket leakage (gasket type, torque, fasteners, etc.).
   - Improvements to traveling screens or strainers to reduce carryover/bypass.
4. Long Range Planning:
   - Uncommon for visual inspection to warrant LRP action; could include major repair or replacement due to corrosion damage.

J

HEAT EXCHANGER PROGRAM BENCHMARK SUMMARY

This section provides a summary of the three benchmarks/assessments conducted by EPRI HXPUG to gather information to support development of the "*Guidance for an Effective Heat Exchanger Program*" as well as two additional site assessments conducted during the same time period by other parties.

The benchmark/assessments involved:

- PWR (4) and BWR (1) sites with single unit (2) and multi-unit (3) stations.
- Evaluation of BOP HX programs (3) and GL 89-13 programs (4).
- Stations operated by fleet utilities and single nuclear site utilities.
- EPRI peers from other sites/utilities participated representing 4 additional fleet nuclear utilities and another single site nuclear utility.

The benchmark/assessment trips achieved three objectives:

1. Program Guidebook – The principal objective was to obtain program guide information related to good practices, strengths, topics needing additional guidance, and differences in organizational structure and practices for GL 89-13 and BOP heat exchanger programs.
2. Host Utility Assistance – The host utility received assessment support from other utilities and EPRI, which included review and comment on program documents, program health reports, and test/inspection results. Benchmarking also occurred with peer utilities providing documents and reference information to support program improvements.
3. Peer Participants – Benchmarking opportunities with the host and peer utilities provided opportunities to identify good practices and issues for follow-up in their programs.

The strengths, improvements, and observations made for the programs are noted for the GL 89-13 and BOP Heat Exchanger program sections.

J.1 Strengths/Good Practices – GL 89-13 and BOP Heat Exchanger Programs

J.1.1 Strong Ownership

1. Evidence of strong GL 89-13 and BOP Heat Exchanger program ownership at multiple sites:
   - Actively engaged in HXPUG meetings, webcasts, and industry surveys.
   - Good OE follow-up – vendor and peer contact, vibration analysis, and site communication.
   - Examples of good site issue follow-through combined with a questioning attitude.
   - Gaps in program performance have been identified and addressed.
   - Peer input actively sought from other sites and utilities to solve or understand HX issues.
2. Examples of good interaction between system engineers and the heat exchanger program owner on issues and future inspection planning.

J.1.2 Chemistry

1. The raw water committee is beneficial to engage engineering and chemistry personnel.
2. Chemical vendor service contracts have been effective to maintain biocide system reliability.

J.1.3 Qualification Process

1. Qualification tasks for the program owner and specific actions are beneficial to ensure the quality of inspections and test actions and allow additional individuals to support these actions.
2. Site heat exchanger pictures in the inspection qualification documents are a good practice.
3. A mentor guide is a useful tool for program turnover.

J.1.4 Inspection/Monitoring Methods

1. Use of thermography to detect tube blockage in air-to-water coolers allows more frequent and less resource intensive monitoring of thermal health compared to thermal tests. (GL 89-13)
2. Quality thermal performance tests were implemented, which provided high confidence regarding chemistry effectiveness and compliments the use of visual inspection and dp monitoring on other system heat exchangers. (GL 89-13)
3. Program owner identified need for a visual inspection checklist for BOP HXs and updates to GL 89-13 inspection checklist to address structural degradation. (BOP and GL 89-13)
4. Outage leak checks and smoke tests are used on feedwater heaters w/leak history. (BOP)
5. Visual verification of condenser ECT OD erosion indications improves tube reliability. (BOP)

J.1.5 Documents

1. Document with compiled tube plugging limits and reference calculations. (Good practice)
2. Visual inspection checklist and procedure consistent with EPRI guidance. (Good practice)
3. Acceptance criteria using quantified corrosion limits combined with measured and projected corrosion depth provides clear control of corrosion issues. (Strength)
4. Review of all GL 89-13 program work packages to ensure awareness. (Good practice)
5. Review of PM rankings to update program scope and exclusion basis. (Good practice)
6. Integrated analysis of thermal performance tests and other monitoring data to evaluate condition of containment air coolers. (Strength)
7. Electronic program notebook with links and attachments helps notebook remain current. Good use of references and plant heat exchanger information. (Good practice)

J.2 Program Improvements – GL 89-13 Programs

J.2.1 Qualification

1. Program owner qualification would be beneficial with existing 89-13 inspection qualification.
2. Qualification process for inspections exists, but needs to be improved. Current process includes extraneous information which should be removed.
3. Qualification tasks need to include significant site operating experience relevant to the task.

J.2.2 Procedure Upgrades Needed

1. Contradictory procedure information was noted for 89-13 commitments, work/inspection actions, and design inputs. Reducing the level of detail in some documents may be prudent.
2. Procedure contains outdated information and is inconsistent with limits in other documents.
3. Flow verification procedure has conflicting HX maximum flow with operations procedure. Also, design flow requirements do not match those in program basis document.
4. Procedure repeatedly references another procedure which was inactivated five years earlier, and references different chemistry control limits from those in the chemistry procedure.
5. Visual inspection rigor varies between procedures.
6. Procedures are not consistently incorporated into the program basis document.
7. Not all procedure steps are followed as written. Rewording is needed to differentiate between required and recommended actions.

J.2.3 Inspection/Monitoring/Testing Improvements

1. Improve inspection procedure and checklist to add corrosion to fouling inspections.
2. Changes to partial tube blockage acceptance criteria are needed.
3. Follow-up inspections are needed with down-tube blockage to verify tube integrity.
4. HX shell side DP monitoring is appropriate, but differences with EPRI guidance for DP monitoring should be explained as well as how it is used to monitor thermal performance.
5. Partial tube blockage criteria of zero impact if <100% blocked may be non-conservative.
6. Improve or add on-line flow and dp monitoring and/or as-found testing for the SW system flow balance to ensure minimum flows are available for GL 89-13 heat exchangers.
7. Inspection documentation is not timely, possibly due to excessive detail in labeling pictures.
8. Internal coating failures with localized corrosion damage were not evaluated by inspections.
9. New corporate visual checklist was developed without site inspector training or awareness.
10. An integrated schedule spreadsheet with ECT, visual, and thermal tests for all 89-13 heat exchangers would be beneficial.
11. A margin spreadsheet for GL 89-13 heat exchangers subject to macrofouling would be beneficial for plugging margins, inspection results and acceptable future inspection intervals.
12. Review threshold for condition adverse to quality reporting for heat exchanger inspections.

J.2.4 Reactive Processes – Living with Issues

1. Program (site) may be reactive versus proactive for some heat exchanger issues. Possible lack of urgency for root causes. Tube samples were obtained, but not sent for analysis.
2. Heat Exchanger on site Top 10 list for future replacement, but no interim action plan to ensure reliability and function is maintained until then.
3. Operability and action limits were not well defined for a long-standing degraded condition.
4. Yellow program was not required to frequently present a status to upper management.
5. Yellow program lacks detailed actions, budget, and schedule to resolve long-standing issues.

J.2.5 Chemistry

1. Periodic meetings between chemistry and engineering for SW/GL 89-13 are recommended.
2. Chemistry treatment and monitoring capability is strong for the normally operating non-safety cooling system, but significantly less robust for the standby safety-related SW system. Possible risk of undetected biological fouling if sustained operation of the system occurred.

J.2.6 Performance Indicators

1. Reliability of biocide system could be used as a leading indicator for the GL 89-13 program.

J.2.7 Margin Issues

1. Low plugging/blockage margin (i.e. 2% and 3%) w/o actions to improve margins in spite of engineering belief the low margin was very likely to challenge operability in the next 5 years.
2. Flow margins for SW heat exchangers were not known/monitored, although data was obtainable. Flow reviewed as "pass/fail" w/o tracking margin. Throttle valve position changes were tracked for one heat exchanger to indirectly indicate flow margin.
3. Fixed volume (recirculating) SW system had not evaluated chemistry scaling control limits for the increased chemical concentration and temperatures following a DBA.

J.2.8 Division of Responsibility (DOR)/Program Scope

1. DOR between the BOP Heat Exchanger program and GL 89-13 program is not established.
2. GL 89-13 program includes closed loop systems without a clear justification of need/benefit.
3. DOR not clearly defined for program inspection actions by engineering and maintenance.

J.2.9 Misc.

1. Site is a member of HXPUG but not at annual meetings. (They are joining webcasts.)
2. SW flow control valves upstream of HXs may be more susceptible to blockage or restriction.
3. Document review of safety-related HXs maximum shell flow and controls to protect.
4. Leakage is not checked for valves relied upon for system isolation in DBA alignment.
5. SW flow test with most limiting alignment is not performed periodically. Data corrections to address measurement uncertainty, pump degradation, tube plugging, minimum water levels, DG frequency, and similar considerations should be included.

J.3 Program Improvements – BOP Heat Exchanger Programs

J.3.1 Program Scope

1. Expand program scope beyond eddy current testing to include heat exchanger PM tasks.
2. Program scope should be better defined and basis for exclusions addressed.

J.3.2 Procedures

1. Program procedures do not reflect current program implementation practices.
2. Plugging limits for non safety related heat exchangers are not well structured or observed.
3. Procedure intent is unclear on several topics. Does not address frequently delegated tasks.

J.3.3 Communications

1. Delegated Work – Communication between the program owner and those performing delegated actions is ineffective, with individuals unaware of program procedural requirements. Results include inconsistent information provided to the site on heat exchanger health and delays in performing program actions.
2. Communication with system engineers is lacking, consider pre/post outage status meetings.
3. Communication/training for new heat exchanger inspection form.

J.3.4 Qualification/Training

1. Guidance documents, training, or qualification may be needed for delegated functions to ensure consistent quality due to limited procedure detail relative to non-program owners.

J.3.5 PM Basis Document

1. Program scope does not cover all critical heat exchangers, or identify responsible groups.
2. PM basis information has not been updated to match performed actions or the 20 year plan.
3. Heat exchangers in the program need a basis document for PM actions (or lack of action).
4. Owner needs to ensure work packages are generated to implement PM actions for program HXs (an integrated schedule spreadsheet would reveal gaps).
5. Previous assessment recommended ECT of heat exchangers has not been completed.
6. Lack of ECT baseline inspection in spite of numerous relevant OE reports.

J.3.6 Division of Responsibilities

1. Various parts of the BOP Heat Exchanger program are delegated to groups beyond those in the procedure. Work delegation is informal and does not address procedure responsibilities.
2. ECT Budgeting/Oversight – site NDE group previously addressed ECT budget, contract, and vendor oversight. Position eliminated without addressing ownership transfer.

J.3.7 Misc

1. Recent industry experience with RHR HX vibration damage not evaluated.

J.4 Comments/Observations – GL 89-13 Programs

1. Large flow margins may allow reallocation to improve margin for tube plugging limit.
2. Rotation of the standby BOP heat exchangers is a recommended practice.
3. Corrosion degradation needs more rigorous evaluation and review for long term implications and repair needs, which may require significant preplanning and outage resources.
4. The GL 89-13 program includes pipe inspection/monitoring, often done by another program.

5. SW Chemistry leads have <6 months experience, with limited turnover from retiring owner.
6. Latent issue – failed to evaluate HX impact of changing from standby to normal flow.
7. Lack of site communication for adverse impacts of biocide system being out-of-service.
8. Conservative change to partial tube blockage acceptance has greatly increased risk of exceeding available margin given historical results.
9. Additional actions to minimize FME entry into the UHS reservoir are recommended based on lack of SW pump strainers and low system FME tolerance (low blockage limit). Actions including caution signs and training for Operations and Maintenance to increase awareness.
10. Work instructions for dive inspections could be more specific for items to be inspected, measured, removed and provided to engineering, etc. Engineering could track or compare results with previous inspections for specific parameters.
11. Maintenance action limit for heat exchanger dp is recommended to be reviewed against the last five years of surveillance data to verify adequacy.
12. Macrofouling trend review for impact on future inspection interval could be added to inspection actions. Review could also consider the opposite division heat exchanger results.
13. Maintenance personnel performing heat exchanger visual inspections without engineering involvement is not considered the best practice and is not the industry norm.
14. Performing PWR Containment cooler thermal tests on-line may require review for GSI-191 compliance issues due to potential changes to sump debris sources.

J.5 Comments/Observations – BOP Heat Exchanger Programs

1. Review program heat exchangers for four-pass straight-tube designs and ensure maintenance PM packages include precautions to ensure proper end bell orientation during reinstallation.
2. Heat exchanger program electronic notebook could be placed in a more accessible location for system engineers or others.
3. Determine if routine feedwater heater tube cleaning is still required (not an industry norm).
4. ECT intervals/scope may be more frequent than needed based on past inspection results.
5. EPRI tube plugging calculator is used, but improved guidance is needed.
6. Investigate heat exchanger shell side flow limit versus operating practices and procedure guidance to determine if observed tube vibration damage can be avoided.
7. Generator H2 Cooler has pitting issues. Consider improved cleaning method or oversight due to ECT report noting scale remaining on tube ID, which reduces ECT quality and may contribute to pitting.

8. PM actions are weak to inadequate in some cases, related to poor guidance in EPRI templates:
   - "As-Required" for ECT interval effectively results in run-to-failure since no interval exists.
   - Lack of a reliability strategy for heat exchangers that do not permit NDE tube inspections.
   - Absence of shell UT inspections with open cooling water supplied to a carbon steel shell.
9. PM intervals have been left at original template value in spite of extent of or rate of HX degradation warranting more frequent inspection.
10. A long-term weakness for program health is associated with lack of engagement with industry users groups, conferences, and peers outside of the company.
11. Lack of long range planning (LRP) guidance can result in late identification of issues. Consider requiring life projection when a heat exchanger reaches a tube plugging action limit to determine if replacement or major repairs will be needed within the long range planning cycle. Remaining life updates could be performed when new ECT data is acquired. If projected replacement cost is >$1M, consider guidance to evaluate repair or margin recovery options to avoid or extend replacement.
12. Absence of a site PM basis database has caused the program owner to maintain their own basis document for deviations from EPRI PM templates.
13. HX program owner tracking and forecasting for maintenance hours and dose is not typical.
14. Replacement of elastomeric plugs in the condenser is a good practice based on industry experience.

J.6 Peer Participant Benchmark Take-Away Observations

1. Chemistry Periodic Meeting performance should be added to program health document.
2. Logic for NOT thermal performance testing PWR Containment coolers needs to be documented:
   - Transient materials in containment at power for thermal testing may impact GSI-191 analysis.
   - Improved basis for not testing containment coolers, or extending the inspection interval:
     - Analysis extrapolating fouling observed in the tests of other heat exchangers.
     - Thermography to detect macro-fouling and correlate to visual inspection (TR-107142).
3. ESF Loop testing and sequencing of EDG loads needs to be evaluated for SW system water hammer.
4. Copper-Nickel tubing, need requirement to check tube ID for general erosion, not detectable by ECT, especially with tube velocities >7 ft/sec.
5. UT inspection of shells for raw water heat exchangers when raw water is on the shell.

6. Investigate use of the DATS corrosion and fouling monitoring equipment
7. Follow-up on the potential for HDPE to be degraded by oxidizing biocides
8. Need improved visual inspection guidance for partial tube blockage with macrofouling:
9. Quantification and integration of partially blocked tubes into an overall macro-fouling count.
10. Analytical basis of guidance – Orifice analysis (matrix of DP versus orifice size), flow values vs. Reynolds # transition to laminar, at which point could discount the tube entirely.
11. Assess increased focus on chemical monitoring capability to provide an improved barrier to prevent undetected micro or macro fouling.
12. Consider incorporating GL 89-13 program notebook into electronic format.
13. SOER 09-01 Shutdown Safety is driving outage-related maintenance decisions that are more conservative than license basis, and limiting maintenance options (recommendation 9 impacts SW).

J.6.1 Program Procedures/Guidelines/Basis Documents

1. Should be clearly written.
2. Avoid overlapping or conflicting content.
3. Minimize number of procedures/guidelines/basis documents.
4. Clearly define roles and responsibilities of groups.

J.6.2 Training/Qualification of HX Engineers

1. Should have approved qual. card for heat exchanger program engineers.
2. Inspection guides/quals should include visual examples (i.e., photos) of HX degradation/clogging.
3. Knowledge transfer/turnover is key to continuing a successful program.

J.6.3 HX Program Work Practices

1. Regular communication (both informal and formal) between involved groups (i.e., Programs, Chemistry, Maintenance, HP, etc) is key to successful program.
2. Maintain and document HX margins/operability/action limits.
3. Evaluate additional actions to detect/verify tube leakage (i.e., acoustic monitoring, smoke tests) beyond ECTs whenever possible.
4. Perform visual verification of ECT flaw indications for tubes that are accessible.
5. Verify adequate post-accident flows especially on HXs that only “clean and inspect” to meet GL 89-13 requirements.
6. If site personnel/resources are unavailable, should use contract water treatment personnel to operate/maintain chemical treatment systems.

7. Ensure timely completion/update of program documents (i.e., inspection reports, ECT reports, tube plugging maps, calculations, etc.).
8. If program health degrades, ensure that plans are in place or in motion to restore.
9. Carefully evaluate off-normal operation/alignment for unintended consequences.
10. Evaluate HX related industry OE and document actions taken.
11. Ensure HX engineers access/use industry documents.
12. Document technical justification for heat transfer within partially blocked tubes as current industry guidance for partial blocked tubes may not satisfy the NRC.

J.6.4 HX Program Health

1. Site management should focus on actions/budget/schedule required to restore program health.
2. HX program health report should include industry standard indicators such as industry user group participation, periodic benchmarking and self-assessment, and biocide system reliability.
3. Complete and document actions taken in response to benchmark/self-assessment recommendations/findings.
4. Perform HX program benchmarks/self-assessments periodically (i.e., every 3–5 years).

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