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Comprehensive Tube Plugging Guidelines

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Comprehensive Tube Plugging Guidelines

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ABSTRACT

This report provides a compilation of tube plugging-related information and guidance for nuclear plant heat exchangers other than steam generators. This report can be used by site engineers as a resource when making tube plugging decisions and supporting maintenance actions.

The Electric Power Research Institute (EPRI) issued an updated tube plugging calculator and associated guidance for nondestructive evaluation results in 2013 in report 3002000544, *Heat Exchanger Tube Plugging Calculator.* Various other EPRI reports and documents have provided examples of tube plugging criteria or thresholds based on the original plugging calculator (1019322) as well as values used in the industry. This report provides a comprehensive review of the available guidance for tube plugging thresholds, as well as information on actions related to tube plugging.

This report will be helpful to nuclear utility engineers and maintenance personnel involved with heat exchanger tube plugging decisions and/or the performance of tube plugging-related maintenance.

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Comprehensive Tube Plugging Guidelines

PRIMARY AUDIENCE: Utility engineers responsible for making tube plugging decisions for heat exchangers, with the exception of steam generators.

SECONDARY AUDIENCE: Utility heat exchanger engineers responsible for supporting maintenance actions for balance-of-plant heat exchangers.

KEY RESEARCH QUESTION

Multiple documents and organizations provide guidance for tube plugging for heat exchanger engineers. The purpose of this report is to capture the guidance relevant to balance-of-plant (BOP) heat exchangers and capture the relevant experience and guidance that can be applied to heat exchangers. This report is intended to address conflicting guidance and gaps, by providing a comprehensive reference for plugging tubes in specific heat exchangers while capturing the pros and cons of the various methods for plugging tubes.

RESEARCH OVERVIEW

The research in this report commenced with a compilation of Electric Power Research Institute (EPRI) and other industry guidance related to BOP heat exchanger tube plugging, including guidance on tube plugging: margin, criteria, limits, and additional actions, such as stabilization, piercing, and insurance plugging. Research also included guidance on plug selection and the use and configuration control of tube plugging maps. Additional research was obtained through industry surveys and industry operating experience reviews. After the compilation of guidance, gaps and inconsistencies were captured and addressed. The report was developed, consolidating the industry references and citing pros and cons for specific types of tube plugs as applicable to specific conditions. Guidance for plugging margins and limits were captured, as well as the appropriate logic for additional actions, such as piercing, stabilization, and insurance plugging. The report was then sent to an industry technical advisory group for review and comment.

KEY FINDINGS

- A variety of guidance is available and can be used for tube plugging decisions, such as rule-of-thumb 40% through wall, the original EPRI tube plugging guidance provided in report 1019322 (*Plant Support Engineering: Heat Exchanger Tube Plugging Calculator*), the updated EPRI tube plugging calculator (3002000544), insurance plugging, and guidance provided from nondestructive evaluation (NDE) reports.
- Section 2.2 of the report covers four questions to answer when deciding to perform insurance plugging.
- Section 2.4 of the report covers the tube plugging decisions with a bias toward reliability, while avoiding future tube leaks.
    - The degree of conservatism applied can vary between different heat exchangers based on the severity of the consequences of failure.

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- Multiple types of tube plugs exist, and each has considerations for use and limitations. Industry experience over the years has provided data to capture the pros and cons of the variety of plug types, captured in Section 3 of his report, and Table 6-1 captures more specific industry experience.
- Selecting the appropriately sized tube plug involves many considerations to ensure that the plug functions as intended. Section 3.3 presents considerations such as tube inner diameter (ID) in tubesheet, tube ID erosion, ID coatings, and deformation. Selecting the appropriately sized plug should involve measurement to avoid an undersized tube plug based on the nominal dimensions of the tube.
- Consideration for stabilizing tubes is presented in Section 4. This section includes considerations for material type, length, cleanliness, and insertion. Stabilization of a straight-length tube differs in options from a U-bend tube.

WHY THIS MATTERS

This report provides comprehensive guidance for utility engineers who are tasked with maintaining optimum heat exchanger reliability while managing tube bundle degradation. This report provides plugging and stabilization guidance for a broad range of BOP heat exchangers, including industry experience and considerations for selecting a tube plug with the appropriate characteristics and required performance for a given heat exchanger.

HOW TO APPLY RESULTS

Engineers interested in learning the basis for tube plugging requirements should focus on Section 2 of the report. For selection of tube plugs, engineers should focus on Section 3, which includes sizing considerations, as well as pros and cons for specific types of plugs. Engineers faced with the potential necessity to stabilize or pierce tubes should focus on Section 4 of the report.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- Users of this report might be interested in the EPRI Heat Exchanger Performance Users Group (HXPUG). The objective of HXPUG is to improve the reliability, availability, and operational capability of heat exchangers. This group addresses all heat exchangers with the exception of steam generators and boilers. This users group also provides a forum for discussion, development, and communication of information on operation, maintenance, analysis, and performance testing of heat exchangers.

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ACRONYMS AND ABBREVIATIONS

ALARA	as low as reasonably achievable
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
BOP	balance-of-plant
CAP	corrective action program
CFR	Code of Federal Regulations
ECT	eddy current testing
EPRI	Electric Power Research Institute
°F	degrees Fahrenheit
FME	foreign material exclusion
FWH	feedwater heater
ID	inside diameter
ISI	in-service inspection
IST	in-service testing
MIC	microbiologically influenced corrosion
NDE	nondestructive examination
NRC	Nuclear Regulatory Commission
NSSS	nuclear steam supply system
OD	outside diameter
O&M	operations and maintenance
PM	preventive maintenance
psi	pounds per square inch
PWR	pressurized water reactor
TEMA	Tubular Exchanger Manufacturers Association

DEFINITIONS

eddy current testing. Although this is a specific type of commonly used tube nondestructive evaluation (NDE), it is frequently used to generically refer to tube inspections that can include other types of NDE.

overdesign (or **excess tube surface area**). The amount of additional heat-transfer capability beyond what is needed to achieve the design operating point conditions on the data sheet (including the tube plugging limit in the specification).

partition or divider plate. The plate that separates the tube flow passes in the channel or head of the heat exchanger. The partition plate designs vary and include partitions integral to the cover/head with a gasket seal to the tubesheet, plates with gaskets at a bolted full channel cover, or plates internal to the channel with bolted removable covers or even welded plates that require cutting/rewelding for access.

plugging criteria. The threshold, usually expressed in terms of reported through-wall depth, at which a tube is required to be taken out of service by plugging. The plugging criteria are applied to the reported results of tube NDE inspection (for example, eddy current testing).

tube plugging limit. The maximum number of tubes that can be removed from service for a heat exchanger to continue to meet its most limiting design requirement.

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1
INTRODUCTION

1.1 Background

This report provides a compilation of tube plugging related information and guidance for nuclear plant heat exchangers other than steam generators. This report can be used by site engineers as a resource when making tube plugging decisions and supporting maintenance actions. The objective of this project was to create a document that can be used as the comprehensive reference material when making tube plugging decisions for Balance-of-Plant (BOP) heat exchangers.

EPRI issued an updated tube plugging calculator and associated guidance for NDE results in 2013 via report 3002000544, *Heat Exchanger Tube Plugging Calculator*. Various other EPRI reports and documents have provided examples of tube plugging criteria or thresholds based on the original plugging calculator (1019322) as well as values used in the industry. This report provides a comprehensive review of the available guidance for tube plugging thresholds as well as information on actions related to tube plugging.

1.2 Scope

Nuclear power plants strive to maximize the reliability of important heat exchangers through the efficient use of operations, maintenance, and engineering resources. Maintenance of essential heat exchangers considers a balance between minimizing tube leaks and maximizing service life. While inspection practices may vary between heat exchangers as well as from station to station, the underlying objectives remain similar. Nuclear plants entail a greater emphasis on heat exchanger reliability than typical fossil generation stations due to the economic necessity to maintain high capacity factors and to ensure that safety related heat removal functions are maintained. The report scope is not intended to address PWR steam generators.

This report is focused on tube plugging, including the inputs to preventive plugging decisions, such as:

- Tube Eddy Current Testing (ECT) results and Plugging Criteria
- Tube Leak Response Plugging without ECT data
- Tube Bundle Barrier/Protective Plugging
- Plugging Margin
- Insurance Plugging
- Plug Selection
- Tube Stabilization
- Tube Piercing
- Plugging Preparation and Verification Actions

There are additional EPRI reports addressing related factors supporting heat exchanger reliability and service life, such as; maintaining proper fluid chemistry during operation and lay-up periods, preventive maintenance templates, guidelines for heat exchanger programs, and selecting the optimum tube nondestructive evaluation (NDE) method for the materials and service, and life cycle management considerations.

2
TUBE PLUGGING CRITERIA

The guidance in this section pertains to heat exchangers (other than steam generators) with tube leak consequences that justify preventive maintenance (PM) to improve reliability. Heat exchangers with low failure consequences are expected to have tubes plugged in response to a leak via corrective maintenance.

The purpose of establishing tube plugging criteria for the NDE results of higher leak consequence heat exchangers is summarized well by the following:

> *"The purpose of tube repair limits, in conjunction with the other programmatic elements…, is to provide reasonable assurance that tubes accepted for continued service….will exhibit adequate tube structural and leakage integrity,….with appropriate allowance for NDE indication size measurement error or variability and for defect growth prior to the next scheduled inspection." (NRC DG-1074)*

While the above guidance was issued for steam generators, the basic premise of establishing confidence in the reliability of tubes remaining in service is applicable to all heat exchangers receiving preventive maintenance and NDE inspections. The flaw measurement or sizing uncertainty along with the flaw growth influences the confidence in tube reliability and therefore the plugging criteria.

Established acceptance criteria for safety related heat exchanger tube NDE inspection results are typically necessary to satisfy regulatory requirements, an example being 10CFR50 Appendix B, Criterion V.

> *"Activities affecting quality shall be prescribed by documented instructions, procedures, or drawings, of a type appropriate to the circumstances and shall be accomplished in accordance with these instructions, procedures, or drawings. Instructions, procedures, or drawings* ***shall include appropriate quantitative or qualitative acceptance criteria*** *for determining that important activities have been satisfactorily accomplished."*

The acceptance criteria may involve a "process" versus a traditional formula driven or fixed numeric value. For example, the license renewal application for two nuclear stations in the United States (ref. 27) involved a process as described below. The licensee described the use of a four-step process to determine if eddy current test results were acceptable. These steps consisted of the following criteria:

1. Plugging recommendations are provided by the NDE vendor in a preliminary inspection report.
2. Utility review of the NDE vendor plugging recommendations considers the rate of degradation, wall loss, and inspection frequency.
3. Depending on tube material, damage type (possibly verified with tube pull samples), and past operating experience with the type of tube flaw, a wall loss plugging threshold is determined.

4. If the loss of material is due to pitting, which is not likely to fail heat exchanger tubing due to stress based on the reinforcement of nominal tube thickness around the pits, the primary factor considered for tube plugging is the pitting rate as determined by comparison to past test results.

The regulatory acceptance of this more flexible process involving a mix of NDE vendor and utility personnel evaluation of test results, rates of change, experience, materials, and flaw types indicate that the "acceptance criteria" applied by utilities to heat exchangers, other than steam generators, may include some engineering judgment, provided the methodology is defined and includes appropriate technical considerations.

EPRI report 1022980, *Guidance for an Effective Heat Exchanger Program*, states the following (in Section 5.2.1.3):

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

The guidance in EPRI report 1022980 also addresses plugging decisions for tubes near a tube leak when tube NDE data is not available and preventive tube plugging as a protective barrier against potential failure of the internal parts in a heat exchanger which could affect tube reliability.

2.1 Plugging Criteria Guidance

The tube NDE and plugging actions for the heat exchangers addressed by this report are not required by the ASME Section XI ISI/IST Programs. The ASME Code in Section V provides the bases for development of heat exchanger tube NDE calibration standards used during the inspections, but this does not include acceptance criteria for tube plugging. Requirements for allowable minimum wall thickness for tube inspections of safety related heat exchangers, other than steam generators, are not provided in regulatory documents. Tube plugging criteria for these heat exchangers are typically established based upon one or more of the following:

- Site/utility experience
- NDE vendor experience/recommendations
- Industry guidance documents such as EPRI reports
- Minimum acceptable wall thickness for component design per equations in codes and standards

Tube plugging decisions generally seek to maximize reliability by avoiding tube leaks. However, leak consequences may influence the degree of conservatism applied to the plugging decision, with high leak consequence heat exchangers warranting more conservative plugging than lower leak consequence heat exchangers. Additional considerations influencing tube plugging decisions include:

- **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 NDE follow-up verification actions (that is, reacquire data, alternate probe type, reanalysis, etc.) prior to making the final plugging decision
- **Replacement Cost**. The balance between heat exchanger reliability and service life can be significantly affected by the conservatism of the tube plugging criteria. Generation and/or safety risks may be increased on the one hand, while overly conservative plugging criteria may result in premature replacement.

2.1.1 EPRI Tube Plugging Guidance

The revised EPRI report 3002000544, *Tube Plugging Calculator*, provides an updated compilation of guidance on thresholds for plugging flaws detected by tube NDE.

Several previous EPRI reports included tube plugging information and values based upon the original tube plugging calculator. EPRI documents and reports have also included plugging guidance not based upon the original plugging calculator, such as:

- "Conservatively, tube wall degradation of 40% indicates a need for plugging. …this limit can be raised with justification …from trending or experience with the exchanger or others operating in similar capacity. The actual criterion must be based on the mechanical ratings of the pressure vessel and its life expectancy and the individual plant plugging criteria must be based on defect growth, measurement errors, and the damage mechanism." (TR-106741)
- "…if any cracking is determined, the tube must be…plugged." (TR-106741)
- "The established percent of wall loss plugging criteria is not generally damage or location-specific and, therefore, is applicable to all flaw types regardless of flaw locations." (TR-110392)
- "A common practice is to evaluate the eddy current analysis results first and then decide on the final plugging criteria." (TR-110392)
- "…steam generator tube plugging limits of 40% wall loss were based on a model of remaining tube integrity for wastage-type degradation. Plugging criteria includes factors for increase in the flaw size between the inspections (10%) and for measurement errors (10%) associated with the eddy current examination. Many in the industry view plugging criteria to be overly conservative." (TR-110392)
- "There is no Code allowable minimum remaining wall requirement for SW heat exchanger tubing and, as such, plugging criteria varies from component to component. In general, the plugging criteria vary from 40-90 percent wall loss." (TR-110392)
- "If the margin is low or nonexistent, the plugging criteria might be raised to maintain the margin and allow continued operation." (TR-110392)

EPRI report 1022980 in Section 5.2.1.4 noted several of the reasons changes were made to the original EPRI tube plugging calculator, which include:

- Damage progression rate, which is an important consideration, 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 (that is, 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 (that is, wear/corrosion/loose part).
- Under-weights risk contribution of high energy service compared to cooling water systems.
- Overly conservative plugging threshold for pitting in cooling water service (that is, 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.)

EPRI report 1022980 in Appendix E includes a discussion of tube NDE results, including the following:

- 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.
- Crack indications are often plugged due to uncertainty in predicting progression.
- Tube plugging is not warranted for dents in feedwater heaters unless accompanied by another more significant problem or symptom (that is, 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.
- 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 inspection may provide sufficient assessment of erosion to avoid plugging.

2.1.2 ASME Required Tube Wall Thickness

As previously noted, the ASME Code does not mandate the BOP heat exchanger program eddy current inspections, nor does it specify tube plugging thresholds. The use of minimum wall thickness equations for the design of heat exchanger tubes, piping, and/or pressure vessels from the Codes and Standards are therefore generally not viewed as a mandatory basis for determining tube plugging thresholds for flaw depth. However, in the absence of clearly defined sources of

acceptance criteria, various Code based equations are often used to generate tube plugging acceptance criteria. Frequently used equations include those in ASME Section VIII, Subsection A, Part UG-27 for pressure vessel shells under internal pressure, and Part UG-28 for external pressure. Equations used to determine acceptable flaw depths for moderate energy piping, such as in Code Case N-597, have also been used.

The presentation, "A Recapitulation of Recommended Wall Loss Criteria for Determining When to Plug Non-Leaking Feedwater Heater Tubes", in EPRI report 1004022 includes additional insights regarding tube plugging thresholds by industry technical experts.

The maximum allowable heat exchanger tube flaw depth has been very conservatively determined at some utilities based upon:

- Code equations for the design of pressure vessels and piping
- Code allowable stress limits and the associated factors of safety (4.0 pre-1999 and 3.5 post-1999)
- Heat exchanger design pressures versus the maximum operating shell and tube pressures

This methodology when applied to all flaw types and heat exchangers may result in more conservative plugging requirements than used for PWR steam generator tubes, the failure of which have much greater consequences (orders of magnitude greater than most heat exchangers). Applying plugging criteria to smaller non-structural flaws may result in premature replacement or the need for similar margin recovery actions for heat exchangers in the scope of this report. The following section addresses the use of NDE signal voltage as a means to differentiate between structural and non-structural flaws.

2.1.3 NDE Voltage Correlation to Structural Failure

Heat exchanger tubes are structurally over designed, meaning they have significantly greater wall thickness than necessary to meet the stress limits for Code analysis. Flaws that do not involve a significant axial and/or circumferential extent (that is, small volume) have built-in reinforcement to strengthen the remaining wall around the flaw. Tube damage below a given area or volumetric size does not introduce the risk of tube rupture, regardless of the damage depth. Non-structural flaws even when through-wall do not result in risk of tube burst or rupture, only leakage in proportion to the hole size, fluids, and differential pressure. These small flaws are similar to corrosion pitting leaks in cooling water system piping.

EPRI report 1022980 (App. E) notes this describing pitting damage:

> *"Pitting damage is very rarely structural in nature…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."*

The presentation, *Enhanced Tube Plugging Criteria for Safety Related Heat Exchangers*, at the 2009 EPRI Heat Exchanger Performance Users Group (HXPUG) annual meeting [8] provides additional detail related to the reinforcement available to pitting flaws in heat exchanger tubing.

Table 2-1 shows the changes in voltage for different size flaws in an eddy current calibration standard. This relationship between signal voltage and flaw volume can be used to determine if a flaw indication is of structural significance. Some flaw types with somewhat well-known shapes and characteristics, such as the pitting example above, may be categorized as not posing a structural risk, while others may use a minimum voltage threshold, below which indications are considered non-structural.

Table 2-1
Calibration Standard ID Flaw Size and Volts

Flaws	600 Khz – Differential		300 Khz – Differential		200 Khz – Differential		100 Khz – Differential	
	Volts	Phase	Volts	Phase	Volts	Phase	Volts	Phase
0.052” diameter TWH	4.19	41	4.22	42	4.28	41	4.28	41
3/32” diameter TWH	15.47	33	14.14	34	13.67	33	13.02	36
3/32” diameter B/Thru	11.58	30	10.46	33	10.13	33	9.73	36
3/32” 80% ID Pit	10.13	26	8.91	30	8.58	31	8.21	35
3/32” 60% ID Pit	7.77	20	6.48	27	6.16	29	5.86	34
3/32” 40% ID Pit	5.79	15	4.47	21	4.12	25	3.88	33
3/32” 20% ID Pit	2.55	9	1.86	16	1.67	21	1.52	30
0.052” diameter TWH	5.04	38	4.96	40	4.99	39	4.91	40
1/8” diameter TWH	35.07	26	29.94	27	27.84	27	25.35	32
1/8” diameter B/Thru	25.95	27	22.58	29	21.31	29	19.71	33
1/8” 80% ID Pit	23.78	25	20.66	28	19.57	29	18.28	33
1/8” 60% ID Pit	17.53	18	14.37	24	13.47	27	12.59	33
1/8” 40% ID Pit	11.63	13	9.03	20	8.32	24	7.71	31
1/8” 20% ID Pit	4.67	9	3.39	16	3.03	20	2.77	30

Additional EPRI reports and other references noting the absence of structural risk associated with small volume indications include:

- "…case of overcalls for small-volume indications. Thus, this will require setting an amplitude threshold and analyze only those signals exceeding the given threshold…..OD signals exceeding 1.0 volt in peak-to-peak amplitude shall be reported as OD flaw with percent wall losses."
- "…only those flaw-like signals exceeding given amplitude threshold should be evaluated and quantified. Any flaw-like signals exceeding the plugging criteria but falling below the amplitude threshold shall be monitored, and not plugged." (EPRI 1004022)

Manufacturing Defects

Non-service related tube indications resulting from original fabrication, handling, assembly and installation are often generically referred to as "manufacturing defects".
As noted in Appendix E, Section E.6 of EPRI report 1022980:

- "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…For these reasons, manufacturing related indications generally do not warrant plugging, regardless of percentage through-wall.
- 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.

Accordingly, manufacturing indications represent another example of an NDE defect that may apply voltage screening to support the classification type and/or avoid plugging.

2.1.4 Assessing Tube Plugging Recommendations from NDE Vendors

If contracted by a utility do so, NDE vendors provide plugging recommendations to the utility in the inspection reports. Best practices are to request that the vendor include, at a minimum, tubes with inspection results exceeding the plugging criteria used at the site and to document the plugging criteria used for the plugging recommendations.

Additional tubes for plugging may be recommended by the NDE vendor for conditions which are not addressed in the plugging criteria or are more conservative than the criteria based upon the analyst's reliability concerns. For example, it is difficult for plugging criteria to adequately address combinations of flaw types and conditions and their rate of change which may be evident to the analyst.

2.1.5 Tube Plugging Criteria 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, and so on), operational changes, tube plugging margins, and so on.

Allowing deviations from tube plugging criteria may be desired, and can be addressed by establishing controls for the deviation process. Program documents can be used to describe the controls used for plugging criteria deviations, which could include:

- Conservative deviations are at the discretion of the responsible engineer.
- Less conservative plugging decisions for non safety-related heat exchangers are allowed at the program owner's discretion and noted in the tube plugging report, work package document, or related engineering document.
- Less conservative plugging decisions for safety related heat exchangers require concurrence from Design Engineering and documentation via appropriate engineering change processes.

It is considered 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.

Changes to the tube plugging criteria may be needed for specific heat exchangers to address margin issues, as noted in EPRI report 108009. The basis for such changes to program acceptance criteria should be in an appropriate engineering document.

Similarly, EPRI report TR-110392 states

> *"... At the conclusion of the examination…. decisions should be made to either plug those tubes exceeding the established criteria or to change the criteria based on the population of defective tubes. In general, if the excess heat exchanger tube margin is available, those defective tubes exceeding the established criteria will be plugged."*

The EPRI Tube Plugging Calculator and guidebook (3002000544) include the following:

> *"This document does **NOT** meet the requirements of 10CFR50 Appendix B, 10CFR Part 21, ANSI N45.2-1977…"*

Accordingly, the utility users are required to perform a technical evaluation or acceptance review of the report guidance under the utility's quality program prior to use as acceptance criteria for safety related heat exchangers.

2.2 Insurance Plugging

The practice of plugging additional tubes around a leaking tube is often referred to as "insurance" plugging. There are numerous references to insurance plugging in EPRI reports, some of which caution against use of the practice. The cautions against the use of insurance plugging are primarily associated with failure to perform follow-up NDE to determine if tubes could have been returned to service versus the practice itself.

When the heat exchanger is opened to address a tube leak, it is ideal to obtain ECT, unless the leak is identified as a plug leak or tube-to-tubesheet joint leak. The tube ECT data will assist in determining the cause of the leak(s) and provide information on the condition of surrounding tubes.

Schedule and cost constraints, as well as the availability of NDE equipment and qualified personnel, may not support obtaining and analyzing tube ECT data prior to the need to return the heat exchanger to service. Tube leak response in the absence of NDE requires deciding if only the leaking tube(s) will be plugged or if additional tubes will be plugged.

Insurance plugging decisions are based upon a risk assessment of the potential for additional leaks prior to the next planned inspection of the heat exchanger. The risk assessment considers the probability of additional tube leaks in the vicinity of the leaking tube based on the tube material, service, and the most likely cause of the tube leak. The consequences of additional leaks, plugging margin and the ability to install removable plugs to allow follow-up NDE are additional considerations. The determination of the risk verses benefit balance for insurance plugging seeks to answer the following questions:

1. What is the probable cause of the tube leak?
2. What is the potential for nearby tubes to be degraded?
3. How significant are the consequences of a tube leak?
4. How much plugging margin is available until the next inspection?

Insurance plugging in feedwater heaters is described in the *Feedwater Heater Maintenance Guide* (EPRI report 1003470) as follows:

> *"Time constraints can influence how a leaking tube is repaired. For example, a tube leak may be plugged with a temporary tube plug and insurance plugging performed on the tubes around the leaking tube when outage time is at a premium. At the next planned outage, the temporary tube plugs can be removed, and testing can be performed on the leaking tube and adjacent tubes to determine the actual condition. Only the defective tubes would then be plugged with a permanent plug, and the insurance plugged tubes would be returned to service."*

EPRI report CS-1776, *Feedwater Heater Failure Cause Analysis*, states:

> *"A leak (in a FWH tube)…often leads to high velocity feedwater jets and rapid erosion of other tubes adjacent to the leaking tube. At the time of plugging the failed tube(s), maintenance personnel rarely have information on the condition of the surrounding tubes and may decide to plug them as insurance against their failure soon after returning the FWH to service."*

The description of insurance plugging in EPRI report TR-112819, *Condenser In-Leakage Guideline*, is as follows:

> *"However, even when the leaking tube has been positively identified, "insurance plugging" can be considered good maintenance practice. Since in many cases, the exact mechanism that caused the tube to fail is uncertain, selected surrounding tubes may be plugged as insurance against additional leaks developing before the next outage. Those tubes with "insurance plugs" can then be subjected to careful eddy current testing during the next outage so that as many tubes as possible may be returned to service."*

What is the probable cause of the tube leak?

Engineering judgment is used to determine the most likely cause of a tube leak when ECT data is not available. The cause of the leak relates to the potential for nearby tubes to be degraded. In general, ID initiated tube failures are unlikely to warrant insurance plugging. OD initiated tube damage is more likely to justify insurance plugging.

For example, pitting type damage is the most common cause for ID initiated tube failures in raw water service. Pitting damage tends to be randomly distributed. Therefore, plugging nearby tubes is not likely to reduce the potential for additional ID pitting leaks. In addition to ID initiated tube leaks, insurance plugging is not needed for leaking plugs or tube-to-tubesheet joints.

OD initiated tube damage often affects multiple tubes in the same vicinity. For example, flow-induced vibration damage at baffle or support plates, water droplet impingement erosion of main condenser tubes, and damage from FME or failed internal parts, all typically affect multiple tubes. Accordingly, tubes degraded by the same cause may be in the immediate vicinity of the leaking tube(s) and may be near failure. In this case, plugging tubes around the leaking tube(s) or with similar exposure to the damage mechanism (that is, edge of the bundle), is likely to improve reliability.

Determining the probable cause for a tube leak requires careful review of the relevant data such as:

- Past NDE data for the failed tube and the heat exchanger
- Leak location (both in the tube bundle and axial location)
- Damage mechanisms relevant to the heat exchanger design, tube material, and service conditions.

What is the potential for nearby tubes to be degraded?

The probability of additional tubes near a leaking tube(s) to be degraded is primarily determined by the cause of the initial leak. In the absence of tube NDE data, it is difficult to determine if nearby tubes are near failure themselves or remain relatively unaffected.

In high energy service heat exchangers, adjacent tubes may also be damaged as a direct result of the leak itself. Feedwater heaters are an example of high-energy service where surrounding tubes are often degraded as a result of sustained operation with a tube leak. Tubes may be damaged by the high velocity jet impingement from the ruptured tube, related vibration fretting wear in the adjacent support or baffle plates due to the impingement, and possible impact damage if the leaking tube sheared or is no longer intact.

Large flow rates from a tube leak may be due to a sheared tube. Ideally such a tube would be stabilized to reduce the risk of damage to surrounding tubes from impact by the broken tube (see Section 4.1). If unable to install a tube stabilizer through a sheared tube, then insurance plugging the surrounding tubes is often performed to address the potential for damage from the severed adjacent tube.

Selecting tubes for insurance plugging should address the most likely cause of failure. For high energy heat exchangers and/or unstabilized sheared tubes, insurance plugging typically includes a ring of tubes around the leaking tube(s) to address damage from the leak or the sheared tube, as applicable. This plugging ring may not be adequate to address the tubes affected by the cause of the initial leak, which may require insurance plugging to extend out multiple tubes on the periphery of the bundle.

The presentation “Optimized Feedwater Heater Testing, Inspection and Condition Assessment”, by Thomas Muldoon and Raymond Reardon (ref. 11), described the potential for nearby tubes to be damaged following a feedwater heater tube leak as follows:

“When a tube fails in a high-pressure heater, the feedwater exiting from the rupture impinges upon the surrounding tubes. This can cause serious erosion and additional failures, which is one reason why tubes sometimes fail in patches. In the past, it was common to preventatively plug all tubes (usually six) adjacent to a failure, to ensure that any tubes damaged by the erosion were also plugged.”

How significant are the consequences of a tube leak?

If insurance plugging is based upon an impromptu risk assessment, then clearly the consequences of a tube leak in the heat exchanger is an important consideration. Tube leak consequences vary significantly and may include nuclear safety, environmental impacts (for example, release of lubricating oils or contaminated fluids to public waterways), power generation impacts, long-term degradation of important plant components (that is, PWR steam generators affected by feedwater chemistry excursions from a large condenser tube leak), and in all cases there is disruption to organizations supporting plant operation and maintenance, including work control schedules. Tube leak consequences may also include regulatory violations and/or adverse public opinion. For other heat exchangers, tube leak consequences may be limited to swapping to a standby spare heat exchanger.

How much plugging margin is available?

When the tube plugging margin is small, it may be necessary to limit the use of insurance plugging. Although insurance plugging is not frequently applied to safety related heat exchangers, plugging margin must be maintained for design basis compliance. Performing follow-up tube NDE to potentially return insurance plugged tubes to service is a means of maximizing service life by maintaining plugging margin.

The use of easily removable plugs for insurance plugging results in less effort for plug removal during the next scheduled opening of the heat exchanger to perform the follow-up NDE. Permanent plugs can be installed after NDE data determines which tubes require plugging and which can be returned to service. Section 3.1.5 of the report addresses temporary plugs.

2.2.1 Insurance Plugging Alternatives

When uncertainty exists regarding integrity of nearby non-leaking tubes, actions that have been used instead of insurance plugging have included the use of hydrostatic testing of individual tubes. EPRI report CS-1776, Failure Cause Analysis- Feedwater Heaters, notes, "A hydrostatic test at 1.5 times the rated pressure" for individual tubes has been used to avoid insurance plugging.

The EPRI Condenser In-Leakage Guideline, TR-112819, also states,

> *"…pressure testing by pneumatic or hydrostatic means can be used to proof test a tube. ….using this method to test one or two rows of tubes surrounding a suspect or leaking tube will not only confirm the leak, but will also identify any additional leaking tubes, and may even eliminate the need to install insurance plugs."*

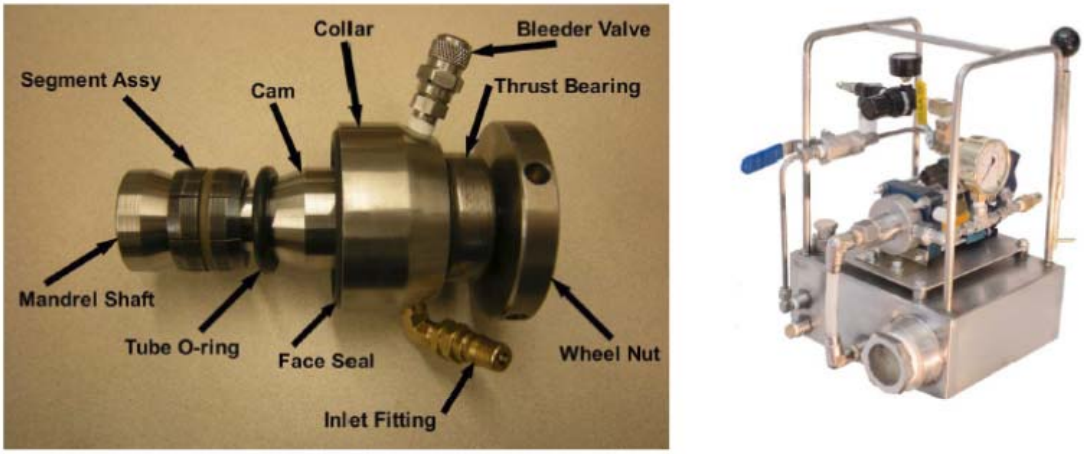


Figure 2-1
Tube Hydrotest Device

2.3 Preventive Tube Plugging and Barrier Plugging

While tube plugging in response to tube damage detected by ECT prior to a tube leak could be considered preventive plugging, the term in this section refers to plugging tubes potentially susceptible to failure of an internal part. This plugging may be performed before tube damage indications exceed the plugging criteria or may be prior to the appearance of tube damage. Preventive tube plugging may be in response to site and/or industry experience with tube failures in similar heat exchangers and service conditions. Visual inspection of shell internals may have revealed degraded internals, such as impingement plate supports being near failure, prior to tube damage having occurred.

Regardless of the source of detection or warning, heat exchanger internals degradation may result in rapid tube damage. Accordingly, tube failure may occur in a much shorter interval than the existing tube NDE frequency. The tube NDE PM task frequency is based upon detecting/ correcting tube damage from "normal" causes with slower damage progression rates.

Options to address reliability risks resulting from these anticipated degradation mechanisms and their potential for rapid tube degradation rates are often limited to:

- Repair/restoration/upgrade of the internals
- More frequent tube NDE to detect tube damage prior to failure
- Pre-emptively plugging the most likely affected tubes

The most cost-effective option to manage risk when failure consequences are high and plugging margin is available may be to plug the susceptible tubes in advance of tube damage developing.

The term "barrier plugging" is sometimes used interchangeably with pre-emptive or preventive tube plugging or it may describe the installation of a stabilized layer of tubes installed to protect tubes deeper in the tube bundle from being damaged, often from high energy two-phase flow impingement. Examples of preventive and barrier plugging are described in the following sections.

2.3.1 Condenser Debris Barrier

Several stations have plugged (and stabilized in many cases) the top tube rows and selected high point edge tubes of their main condensers to provide a debris impact barrier. Larger pieces of internally generated condenser debris within the condenser such as expansion joint shield plates, insulation lagging from condenser neck feedwater heaters, and basket tips have resulted in sudden failure of impacted tubes on the outer edges of the tube bundle. These periphery condenser tubes may also have been prone to water droplet impingement erosion. Tube plug barriers have also been applied on the outer side walls of tube bundles exposed to water droplet impingement from bypass or dump valve connections. The high energy discharges into the condenser normally include spargers to diffuse and direct flow away from the tube bundle, but various issues ranging from inadequate design to reaction off of adjacent structures have resulted in tube erosion during period of sustained bypass or dump valve operation.

Alternative actions to plugging for protecting condenser tubes from high velocity water droplet impingement have included:

- Shields attached to the tubes in the impingement target areas.
- Angled floor grating has been installed in some condensers to provide a physical impingement and impact barriers.
- Modular replacement condenser tube bundles often including an outer row of solid bar stock encircling the upper portion of the tube bundle as an impingement and impact barrier.

2.3.2 Impingement Plate Barrier

Impingement plates in feedwater heaters below high velocity shell inlet nozzles, such as extraction steam and cascading drains, protect the tubes below the nozzles from damaging tube vibration as well as water droplet impingement damage. As feedwater heaters age the tie rods used to support the impingement plates may erode to the point of failure and attachment welds may crack and fail. This internals degradation may result in the impingement plate shifting out of position, allowing high energy flow into the tube bundle. In some cases, the impingement plate has become dislodged completely, resulting in direct two-phase high-velocity impingement into the tube bundle below the associated nozzle.

The symptoms include a localized pattern of similar damage near a shell inlet nozzle experiencing a sudden increase in degradation rates. These symptoms warrant preventive plugging and tube stabilization since the rapid tube damage rates associated with a failed impingement plate may result in tube leaks developing between inspection intervals.

If the affected tubes are simply plugged but not stabilized, the high energy flow will continue to degrade the tube. Circumferential shearing of the tube at the nearest support plate may occur, which then exposes additional tubes to direct impingement and rapid degradation. This progression path has allowed tube damage below failed impingement plates to extend multiple rows into the tube bundle.

Plugging and stabilizing tubes below a degraded or failed impingement plate has been shown to be a cost effective alternative to restoring the impingement plate. Plate repair requires large openings to be cut into the shell for access. Plugging and stabilizing the tubes (two rows due to the tube off-set pattern) directly below the plate creates the equivalent of a rod impingement barrier, which is an accepted and effective design.

Stainless steel bar stock provides the most durable long-term protection against high velocity two-phase impingement. Wire rope has been used in some cases due to the access limitations resulting from hemispherical heads and manway openings. When wire rope is used instead of bar stock, heavier gauge wire is more durable (but is less flexible), and it should be stainless steel. Ensure it is grease or lubricant free with a thorough cleanliness inspection prior to use. Lubricants commonly used in the manufacture of wire rope (and for shipping/storage of carbon steel wire rope) are non-compatible with condensate/feedwater system chemistry.

PWR polisher fouling and resin replacement has occurred due to petroleum based lubricants from wire rope stabilizers. The high energy impingement and high vibrations associated with stabilizers serving as a rod impingement barrier support use of full length stabilizers to achieve the greatest long-term durability versus partial length stabilizers anchored at the tubesheet. This is particularly true for segmented bar stock stabilizers since the pieces may detach, allowing them to shift out of position and become debris in the shell.



Figure 2-2
Feedwater Heater Impingement Plate

2.4 Reliability vs. Service Life

Tube plugging decisions should maintain a bias toward reliability and not lose sight of the purpose of the tube NDE and preventive tube plugging, which is to avoid future tube leaks. However, this reliability bias cannot ignore the heat exchanger's heat removal requirements.

When the consequences of a tube leak relative to lost generation, nuclear safety, or corrective maintenance costs do not justify leak avoidance actions such as eddy current testing tubes, then the heat exchangers are classified as "run-to-failure" or "run-to-maintenance".

In most cases the tube degradation rates do not result in the sudden need to plug large quantities of tubes unexpectedly such that the available tube plugging margin is exceeded. Tube plugging margin typically is tracked for many years, allowing measures to maintain or restore thermal margin via retubing, sleeving, or heat exchanger replacement to be planned well in advance. Thus, the benefits of improved service reliability outweigh the reduced service life resulting from preventive tube plugging.

The degree of conservatism applied to tube plugging thresholds may vary between heat exchangers, based on differences in consquences of failure and other considerations, such as:

- High leak consequences warranting conservative plugging.
- Infrequently inspected heat exchangers requiring flaw growth rate extrapolation over long time periods, which increases the uncertainty in the projected flaw depth at the next inspection.
- Some tube materials (for example, ferritic stainless) or configurations (for example, integral finned) result in lower quality NDE results and may have a greater degree of uncertainty in flaw sizing and characterization.
- New flaw types or non-typical indications may have a higher uncertainty in reported size pending tube removal and analysis and/or inspection with alternative probes.

Options to maintain tube reliability in heat exchangers with low plugging margins may involve evaluations or maintenance to reduce the need to plug tubes, return tubes to service, increase plugging limits, or similar action. Examples include:

- Follow-up NDE – reacquire data, alternate probe type, reanalysis
- Reduce inspection interval (that is, flaw growth is projected over shorter time span)
- Tube pulls for metallurgical analysis to confirm flaw size and type
- Hydrostatic pressure testing individual tubes
- Tube sleeving to bound the flaw location
- Partial retubing sufficient to maintain plugging margin
- Plug removal, reinspection/testing to return tubes to service (that is, insurance plugs)
- Reanalysis to increase plugging limits
- Limited operability analysis (for example, operable with cooling water below a threshold that does not support summer operation to allow response actions to be prepared)
- Internal tube coating

3
TUBE PLUGS

The selection of a suitable heat exchanger tube plug is a relatively simple task, but it should reduce risk when this can be cost effectively achieved.

Risk = Probability x Consequences

Since actions generally cannot be taken to reduce plug leak consequences, reducing risk should focus on reducing the probability of plug leaks. The robustness of the plug design should be commensurate with the consequences of plug leakage. Similarly, the installation guidance, training, and verification activities should also reflect the consequences of leakage, as well as the type of plug selected.

Examples of actions to reduce the probability of tube plug failure include:

1. Robust plug designs – include margin for transients and off-normal conditions
2. Plug installation instruction detail commensurate with plug type
3. Plug installation training for maintenance craft
4. Verification of correct plugs, locations, and properly installed
5. Pre-plugging inspections for issues that may affect plug size or sealing, for example, rough inner diameter (ID), coated tubesheet, welded tubesheet joint, tube ends projecting from tubesheet
6. Elastomeric plugs have periodic actions to retighten or replace

The plug selected should include a factor of safety for the plug's differential pressure rating versus the heat exchanger design pressure that reflects the plug leak or failure consequences. The term "factor of safety" does not typically describe small percentages (that is, 10-50%) of over design but multiples of over design.

Excess design margin for plug retention should consider the following:

- Upset or off-normal conditions such as unit trips, loss-of-offsite power, waterhammer, and other thermal/hydraulic transients
- Plug seating surface variations (that is, ovality, surface roughness, hole size at limit of acceptable range, and so on)
- Difficult installation conditions (confined space, interferences/obstructions, contamination level, elevated temperatures, limited dexterity and freedom of movement due to personnel protetive equipment, and so on)

- Personnel safety
- Aging/degradation (pressure/temperature cycles, differential thermal expansion of metals, corrosion, impact from debris or during future maintenance, creep, stress concentration, and so on)

The factors of safety used in codes and standards applicable to heat exchanger design typically do not fall below 2 even for low pressure/temperature applications, and designs subject to the ASME Code include a 3.5x or 4x factor of safety for pressure boundary material strength. Since the both the tubes and tubesheets are pressure boundary components, this provides a reasonable target to consider when selecting design pressure margin for plugs. The selection of a "low pressure" plug design, with a dp pressure rating of 1000 psid, results in a low factor of safety if used in a low pressure feedwater heater with a 700 psig design pressure (that is, 1.43 SF), compared to using it in a cooling water system heat exchanger with a design pressure of 150 psig (that is, 6.7x SF). The use of a much higher design pressure rated plug in the low pressure feedwater heater application would significantly reduce the potential for plug leakage and possibly sudden failure over the service life of the component.

The design pressure rating for some plugs such as hammered in tapered plugs is unknown. While it is possible to achieve a relatively high plug dp capability with a tapered plug, a significant range is likely to exist due to variations in the force applied by different individuals when installing the plug, particularly when the potential for damage exists associated with the application of "excessive" force. Variations in other parameters such as the condition of the tube edge at the plug contact surface, the taper angle of the plug, and so on, must be controlled to avoid additional effect on the differential pressure (dp) capability. This uncertainty in the plug leakage and plug retention capability may limit the suitability of this plug type to service applications with very low plug leakage or failure consequences.

The dp capability of some plug types may decrease with time, such as due to elastomer sealing plugs experiencing creep relaxation or age hardening of materials. Measures may need to be put in place to address the potential loss of performance of this plug type for higher leak consequence applications.

EPRI report 1022980, Guidance for an Effective Heat Exchanger Program, provides the following tube 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 (that is, 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 service in a non-leaking tube, has industry plug ejection experience been addressed?

The following criteria for the selection of tube plugs are noted in EPRI report 1018089 (Section 7.1.3.1), *Heat Exchanger Maintenance Guide*:

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

EPRI report 1003088, *Condenser Application and Maintenance Guide*, includes the following "Key O&M Cost Point":

> *"In situations where previously installed plugs are missing, leaking, or have caused collateral damage to the tube and tubesheet, the actual plug cost should not be a major factor. The expense associated with controlling persistent water in-leakage as a result of tube and plug leaks can be many times the cost of even the most expensive plug."*

3.1 Plug Types

There are a variety of plug types, and within each type additional design variations exist. In many cases, plug selection is based upon what has been previously used versus an objective review and evaluation of the optimum plug for a specific heat exchanger. In some cases, the suitability of the plug for the heat exchanger has not been adequately considered. This section provides an overview of the principle plug types with some characteristics of each plug type noted.

3.1.1 Tapered Plugs

Hammer-in or friction-fit plugs are widely used. There are two basic types, a simple tapered plug and a two-piece ring-and-pin or pin-and-collar plug, as shown in Figure 3-1. Hammer-in tapered plugs can be fabricated from many different materials.

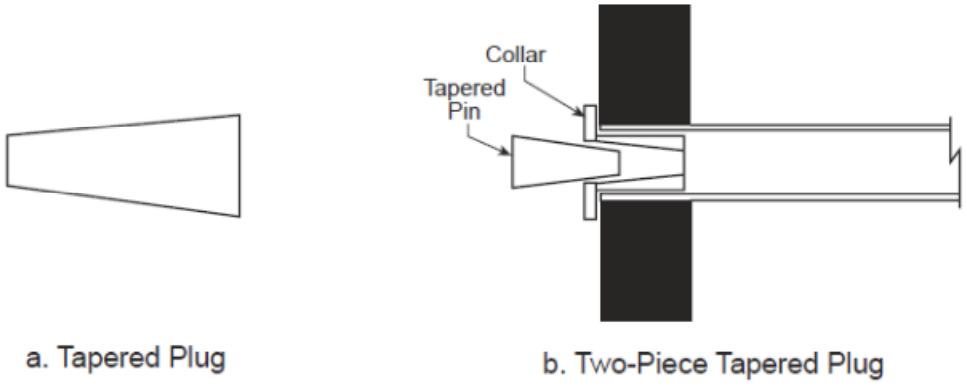


Figure 3-1
Tapered and Two-Piece Ring-and-Pin Tube Plugs

Tapered Plugs

Tapered plugs have the simplest design and are one of the mostly widely installed plugs. The plug has a gradual taper producing an interference fit and seal near the tubesheet.

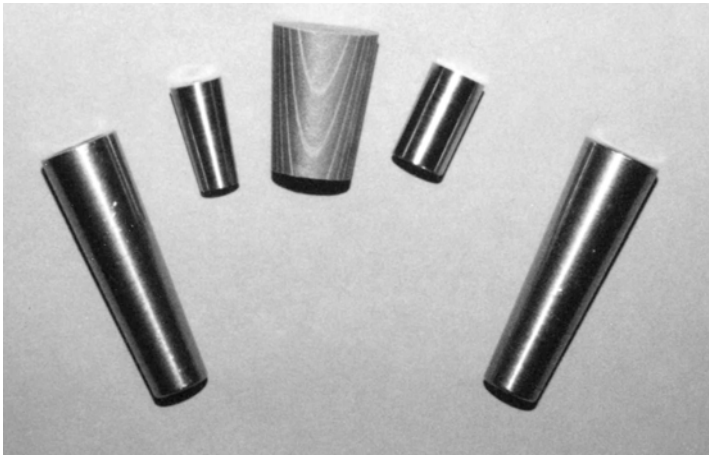


Figure 3-2
Assorted Hammer-In Taper Plugs

Characteristics of the tapered plugs include:

- Ease and speed of installation.
- Inexpensive.
- No special tools or training.
- No service auxiliaries required (compressed air, power, and so on).
- May be quickly manufactured on-site in large quantities.
- Can be installed with low clearance (need room for hammer swing).
- Minimal contact point at the tube end increases risk of leakage during tube-side thermal transients.

- Unable to conform to minor tube defects or ovality, thus requiring surface preparation at the tube end if those conditions are present.
- The lack of control over the force applied to hammer in the plug can result in damage to the tube end, tube joints, and/or tubesheet.
- Tube hole enlargement may impact retube capability.
- Difficul to establish if plug is adequately seated.
- Installation into coated tubes or tubesheets requires coating removal and repair.
- Experience with ejected plugs in feedwater heaters during attempted removal due to pressure trapped behind unpierced tubes (see Sections 3.6 and 4.2).
- Tube ends projecting out of tubesheet need to be trimmed flush prior to use.
- FME impact could loosen plug since projecting out of tubesheet.

The taper angle of the plug generally ranges from 3 to 8 degrees, with shallower angles providing a wider sealing contact surface but a narrower range of hole size suitable for installation.

Guidance in ASME PCC-2-2011, *Repair of Pressure Equipment and Piping*, on the use of tapered plugs states (Article 3.12; Section 4.2):

> *"…only be used in services that meet all of the following conditions, unless an engineering evaluation is performed indicating the acceptability of these plugs in other services"*
>
> 1. *Shell-side operating pressure 200 psi or less*
> 2. *Shell-side operating temperature 400°F or less*
> 3. *Tube-to-tubesheet joints are…not welded*

The guidance in PCC-2 is non-mandatory. Tube plug selection should address the consequences of plug leakage. Tapered plugs are less likely to be deemed suitable for high leak consequence service even if the service temperature and pressure are lower than those noted in PCC-2.

Two Piece Ring-and-Pin Plug

Two-piece hammer-in plugs employ a tapered pin that fits into an outer sealing ring. Examples of this plug are shown in Figures 3-1 and 3-3.

Two-piece plugs are sized following the manufacturer's instructions. Installation is accomplished by using a hammer to drive the pin into the collar forcing it to expand outward and seal against the tube ID. The greater surface area of the ring distributes the installation forces over a larger area of the tube, thereby reducing collateral damage to the tube, tube joint, and tubesheet, when compared to a tapered plug. Two-piece hammer-in plugs are available in a number of metal alloy materials.

Characteristics of the two-piece plugs include:

- The ring distributes installation forces over a larger tube area than a tapered plug, thus reducing risk of damage to the tube, tube joint, and tubesheet.
- Greater contact area compared to a tapered plug results in greater sealing between the tube and plug.
- Easy to installation.
- Inexpensive.
- Can be installed with low clearance (need room for hammer swing).
- The smooth outer surface of the sealing ring is not able to conform to minor tube defects or ovality, thus requiring surface preparation at the tube end if those conditions are present.
- The lack of control over the force used to hammer in the tapered pin results in potential to damage the tube end, tube joints, and/or tubesheet, although less than that of a tapered plug.
- Installation into coated tubes or tubesheets requires coating removal and repair.
- Difficult to remove.
- Leak paths may develop between the pin and ring as well as the ring and tube.
- Smaller range of acceptable ID than a tapered plug.
- Tube ends projecting out of tubesheet need to be trimmed flush prior to use.
- FME impact could loosen plug since projecting out of tubesheet.

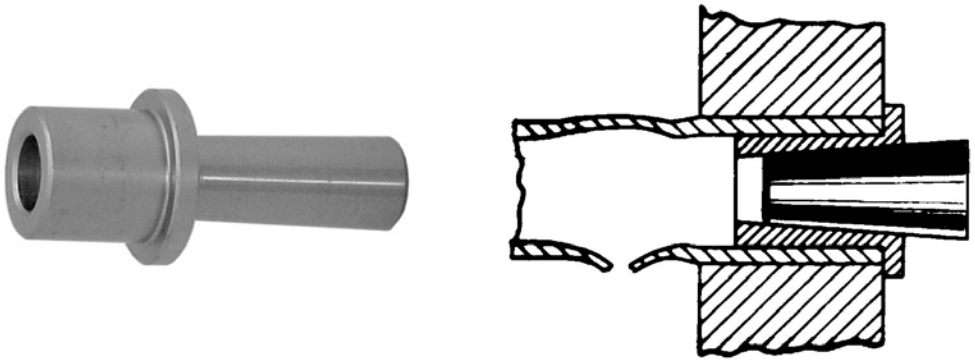


Figure 3-3
Ring-and-Pin Hammer-In Plug

3.1.2 Mechanically Expanded Plugs

Mechanically expanded plugs are widely used in the nuclear power industry. Expandable metallic plugs in this category use a mechanical means to expand a metallic member outward against the tube wall to provide gripping/retention capability. In some designs these expanded metal contact points provide the leakage sealing function as well, while in other designs an elastomeric material is relied upon to provide the leak sealing. The mechanical expansion may be either tension- or torque-controlled plugs or an expanded thimble design.

Pressure Ratings

The mechanically expanded plugs have a range of pressure and temperature ratings, with both "high pressure" and "low pressure" designs available. The high pressure plug ratings of 7000 psig are available with test data including pressure cycling of 0-8000 psi, thermal cycling, surrounding ligament stress tests, blowout tests (20,000 psi), and helium leak testing at 35 psi differential with 10^{-11} cc/sec sensitivity. These plugs provide high confidence of both dp capability and leakage integrity. The "low pressure" mechanical plugs are designed to provide a high confidence of dp and leakage capability for cooling water heat exchangers and condensers and may have pressure ratings of up to 1000 psig, providing a significant safety factor for these lower pressure but high leak consequence services.

Mechanical expanded plugs are allowed in Class 1 heat exchanger tubes per ASME Section XI IWA-4713. ASME Section XI does not specifically address rules for installation of mechanically expanded plugs into Class 2 or Class 3 heat exchanger tubes, but it can be readily inferred from other IWA sub-sections such as IWA-4712 that the Class 1 requirements may be used for Class 2 and Class 3 heat exchangers, but those requirements are not mandatory. The NSSS vendors have performed extensive testing to qualify mechanically expanded tube plugs for Class 1 heat exchanger tubes.

Characteristics of mechanically expanded tube plugs include:

- Installation at varying depths within the tubesheet is possible.
- Double plugs can be installed in thicker tubesheets.
- Installation in epoxy coated tubesheets does not require coating repair.
- Through-the-tube plugging tools available to plug far tube end (see Section 3.5.5).
- High pressure rating plugs are available.
- Multiple seal contact points reduce risk of leakage.
- Shell side pressure, if present, acts to seat the tension-controlled expanded plug more tightly versus expel the plug (see Figures 3-4 and 3-5).
- Vendors with Appendix B program are available for safety related service.
- Tension-controlled mechanically expanded plugs require training and detailed instructions for the installer.
- Support services (that is, compressed air) are required for tension-controlled expanded plugs than other manual methods.
- Tension-controlled mechanically expanded plugs (that is, Fig. 3-4) are not readily removable. Slide hammer removal of expanded ring may damage tube ID in the tubesheet. Removal of torque-expanded plugs can be very difficult (see Section 3.6).
- Sealing requires proper match of the tube hole and plug expansion range.
- False ID sizing has occurred with go/no-go step gauges.
- Tube ID preparation may be required to achieve adequate seal.

- FME sensitive systems require removal of break-away pin from tension-controlled expanded plugs (see Figures 3-4 and 3-5).
- Placement of the expansion rings is not recommended in unexpanded portions of the tube in the tubesheet.
- Placement of the expansion rings is not recommended over deeper ID grooves in the tubesheet, such as TEMA grooves (if applicable to the design).

Tension-Controlled or Break-Away Mechanical Plug

Tension-controlled plugs use a tensile member to control installation loads. A tapered pin is drawn under tension through a sealing ring. As the pin is pulled through the ring, the ring expands outward against the tube. Outward expansion is controlled by failure of the tensile member, eliminating damage to tube or tubesheet joints. At the correct installation load, the tensile member pops like a pop-rivet. External ridges or serrations along the circumference of the sealing ring compensate for a limited amount of tube wall defects and out-of-round conditions. Breakaway plugs are installed using a compact hydraulic ram or manual plug installation tool to provide the pulling force. This type of plug is initially smaller than the tube inside diameter and can be installed within the tubesheet where the tube has been expanded, other than over TEMA grooves in the tubesheet (if applicable).



Figure 3-4
Mechanical Break-Away Plug (Low Pressure)



Figure 3-5
Mechanical Break-Away Plug (High Pressure)

(Note the shallower taper angle of the interior pin and added quantity of seal rings in the high pressure plug.)



Figure 3-6
Assembled Installation Tool for Mechanical Break-Away Plug

Torque Expanded Mechanical Plug

The torque type plug uses torsion to expand a portion of the plug outward until it contacts the tube wall. External ridges or serrations along the circumference of the sealing ring compensate for minor tube wall defects. This plug type is initially smaller than the tube inside diameter and can be installed where the tube is expanded into the tubesheet other than over TEMA grooves (if applicable). The plug is installed using a manual plug installation tool, which does not require support services (that is, compressed air) or special tool set-up. Difficulty can be encountered achieving the necessary torque values if the anti-spin cam fails to stop plug rotation. Hole preparation and size matching are similar to the tension controlled expanded plugs.



Figure 3-7
Torque Expanded Plug

Roller Expanded Thimble Plug

The roll-in thimble plug is mechanically roller-expanded with a tube roller by hand or by using a torque-controlled rolling motor. These plugs allow a longer contact region between the tube and plug than the mechanically expanded plug designs. The roll expansion process requires an experienced installer, is slower than other mechanical plugs, and due to variations in the roll expansion process there is some risk of over-rolling and causing joint leaks or plug leaks in adjacent tubes. The process is not conducive to tight spaces or access constraints.

Hydraulic Expanded Plug

Hydraulically expanded thimble plugs are available. Being a relatively new technology with limited application in the power industry there is less service experience available for hydraulic expanded thimble plugs. The basic design provides a much longer contact region than the mechanically expanded plugs widely used in the industry. The hydraulic expansion process provides a more precise expansion process than roller expanded thimbles. The thimble expansion range is wider, at 0.040 inch, than most mechanical expanded plugs with the ability to conform to a non-concentric gap.

The potential to need a specialty vendor to perform hydraulic plug installation may result in a higher cost per installed plug than other plugging options.

Mechanically Expanded Gripping & Elastomer Sealing Plugs

This plug group is a hybrid or mix between the all metallic mechanically expanded plugs and the elastomeric plugs. Instead of relying upon the mechanically expanded metal rings to provide both pressure rention (that is, dp capability) as well as leak tightness, these plugs only utilize the expanded rings for dp capability and utilize separate elastomeric material for leak tightness. In contrast, the elastomer plug group relies on the elastomer interference fit for both dp capability and leak tightness. The use of the mechanically expanded gripping provides higher dp capability than elastomer plugs, with comparable values to those achieved in the all metallic mechanical plugs. The use of an elastomeric seal provides a more flexible and conformable plug seating capability than the all metallic mechanical plugs. These hybrid design plugs are available in both low pressure and high pressure designs, as shown in Figures 3-8 and 3-9. The service life of the plug's elastomer material in context of the remaining service life of the component should be addressed when these plugs are used as permanent versus temporary plugs. This could include PM actions to periodically replace the plug or elastomer portion of the plug, which could be synchronized with existing PM actions such as tube NDE.

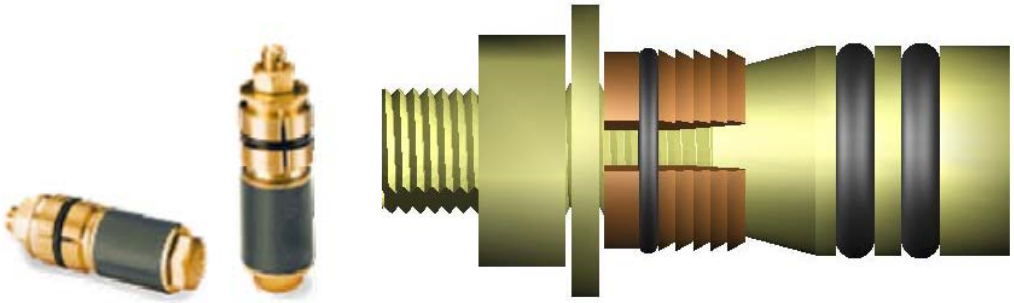


Figure 3-8
Examples of Low Pressure Mechanical Grip Elastomer Seal Plugs

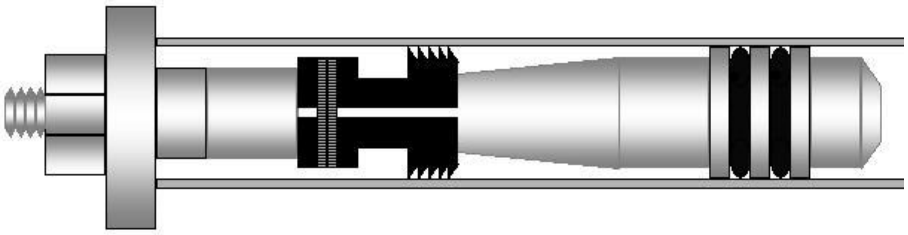


Figure 3-9
High Pressure Mechanical Grip Elastomer Plug

3.1.3 Welded Plugs

The use of welded plugs is typically limited to high-temperature and pressure heat exchangers, and some leakage critical services due to their added cost/schedule impacts. Examples include high pressure feedwater heaters and safety related Class 2 heat exchangers (residual heat removal, shutdown cooling, and decay heat cooling).

Welded plugs may be welded at the tubesheet face or explosively welded to the tube ID.

Welded hammer-in taper plugs consist of either a solid or thimble-shaped conical plug that is driven into the tube end or tubesheet hole. The hollow thimble-shaped welded plug is recommended in EPRI report NP-4057 due to its ability to withstand thermal expansion and contraction cycles without cracking and the reduced risk of “overwelding” which can result in excessive shrinkage and cracking.

The plug is seal welded to the tube and tubesheet cladding or tubesheet base material. Welded tube plugs must be compatible with the materials to which they are welded. Caution is needed when driving in the plug before welding to prevent cracking the tube and/or tubesheet. Pre-heat and post-weld stress relieving may be needed to prevent weld failure, warping of the tubesheet, and damage to the adjacent tube joints. When properly installed, these plugs support high working pressures and provide a high degree of seal integrity.

Characteristics of welded tube plugs include:

- Qualified welders for the process must be available.
- High level of cleanliness and dry surfaces are needed.
- Welding in a confined space (if applicable) may involve considerable safety planning and additional support/monitoring measures.
- Damage to adjacent tubes, tube-to-tubesheet joints, or tubesheet ligaments may result from improper welding, inadvertent arc strikes, excessive heat, or stress buildup from multiple clustered welded plugs. Thimble designs are less susceptible to cracking.
- Post-weld cleaning of heat exchanger internals may be required, depending upon the welding process and cleanliness requirements of the tube-side system.
- Welding difficulties due to cramped spaces and/or interferences (for example, partition plate), especially in vertical channel-down heaters.
- Welded tube plugs are difficult to remove.
- Use with coated tubes or tubesheets will require coating removal prior to plug welding and coating restoration after plug welding.
- Auxiliary services (power, compressed air, and so on) are needed.

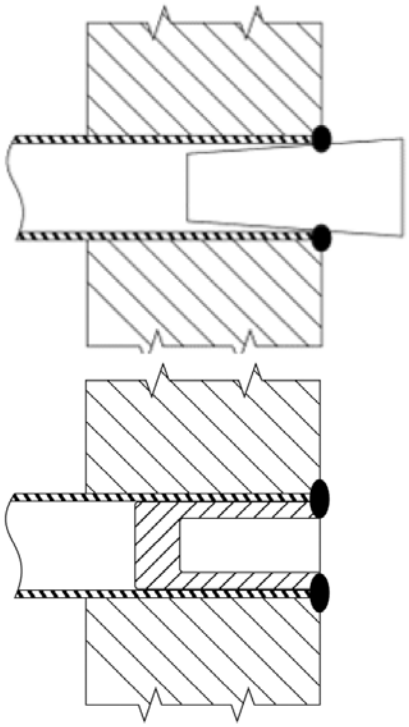


Figure 3-10
Welded Tapered and Thimble Plugs



Figure 3-11
Welded Tapered Plug

Explosive Welded Plugs

Unlike conventional high-temperature welding, explosive welding is a kinetic bonding process with weld lengths three to five times longer than conventional welds. Explosive welded plugs do not have a heat-affected zone and therefore do not require post-weld heat treatment. However, the charge size must be limited to eliminate deformation of the tubesheet ligament. Supporting adjacent tubes during the explosive welding process is a recommended precaution to avoid damage to the surrounding tubesheet ligaments and/or tubes. The force of the explosion expands the plug to fit snugly in the tube. The area of the kinetic weld corresponds to the tapered portion of the plug. The explosive forces accelerate the plug material, impacting and forming a strong metallurgical bond with the tube material. These plugs are typically used in fossil stations rather than nuclear stations.

Characteristics of explosively welded tube plugs are as follows:

- Ease of installation, even with limited access.
- Less support services are needed than for conventional welding.
- Can be performed more quickly than conventional welding, if multiple tubes are being plugging and planned in advance.
- Installation requires licensed, skilled personnel. This can require more time to arrange than is available during a forced outage.
- Plugs are difficult to drill out if removal becomes necessary.
- Very good cleanliness and a dry surface is required to achieve a leak-tight bond.
- Security issues must be addressed to allow the use of explosive devices by an outside vendor at a nuclear station.
- Tubesheet damage can occur without properly engineered explosive charges and the use of supports in adjacent tubes.
- Safety zones during explosive plugging may disrupt other work in the vicinity.
- Explosive residuals may need to be cleaned from the heat exchanger internals, depending cleanliness requirements and chemical compatibility reviews.

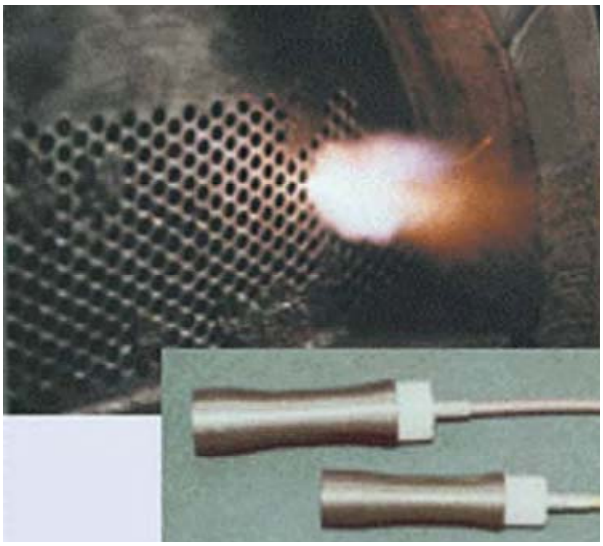


Figure 3-12
Explosively Welded Plugs

3.1.4 Elastomer Seal Plugs

Elastomer seal plugs, often generically referred to as “rubber” plugs, have been widely used in surface condensers and low pressure/temperature cooling water systems for many years. The differential pressure (dp) capability of the designs vary greatly. The plugs rely on elastomer material for both leak sealing and gripping strength (that is, dp capability). The plug design may include means to tighten it and increase the interference fit with the tube ID. Some of the plug designs rely upon uni-directional dp toward the condenser acting on an over-sized shoulder to maintain the plugs in place, and afford limited reverse dp retention capability.

A wide variety of plug designs and elastomer materials exist (see Figures 3-13 and 3-14).

Characteristics of elastomer seal plugs include:

- Ease of installation – quick, minimal tools, simple instructions
- Installation in difficult to access, low clearance locations
- Larger range of acceptable ID than many other plug types
- Can be very inexpensive for low dp capability plugs
- Easily removable without tube damage (follow-up tube inspection)
- Minimal surface preparation – conforms to tube surface irregularities better than metal plugs
- Reusable w/in service life range (specific designs, may require o-ring replacement)
- Minimal risk of ligament or coating damage
- Elastomer compressive load may relax over time, loosening the plugs
- Service life based on elastomer material, plug design, and service conditions

- Periodic inspection, retightening, and replacement are needed to maintain long-term reliability
- Shelf life and storage concerns
- Service temperature is limited by the elastomer material



Figure 3-13
Examples of Elastomer Plugs



Figure 3-14
Expandable Elastomer Plugs

There have been far more failures of elastomeric plugs than any other type of plug. These failures have included several instances where large quantities of plugs failed following condenser thermal/pressure transients (that is, loss of circulating water under full load). The wide spread occurrence of elastomer plug failures is of significance, but also warrants the following context:

- The quantity of condenser plugs (historically elastomer plugs) at most stations exceeds that of all other plugs combined, sometimes by a large degree.
- A wide range of design robustness existing with elastomer plugs.
- Various materials are used for the elastomer and other plug parts.
- Historically, only limited attention has been given to condenser plugs for size selection or basic installation instructions.
- Preventive maintenance has not historically been applied to elastomer plugs until recently.

Preventive Maintenance

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.

- Periodic retightening to address relaxation/creep of the elastomer
- Periodic replacement to address age-related deterioration

Temporary Use Actions

Elastomeric plugs are an example of plugs that may be allowed for temporary use, as discussed in Section 3.1.5. Work tracking or maintenance requests may be suitable actions to address future removal of temporary plugs in non-safety related heat exchangers. Actions tracked by the corrective action process may be needed to replace temporary plugs in safety related heat exchangers.

Loss of Circulating Water or Loss of Off-Site Power Response

If elastomer plugs are used in the condenser, recovery steps in the Loss of Circulating Water and Loss of Off-site Power procedures to open each waterbox and verify the plugs may be warranted, pending the robustness of the plug design(s) installed and the history of performing the above noted PM actions.

3.1.5 Temporary/Removable Plugs

Reasons for use of a temporary plug or different plug than normally installed for a heat exchanger could include:

- Forced outage time constraints
  - ALARA/dose considerations
  - Speed and ease of installation, prep work, support utilities
- Availability of plugs or support equipment
- Ease of removal for follow-up NDE (that is, insurance plugging)

A wide variety of technical, schedule, safety, and reliability/margin considerations may warrant the use of an “interim” or temporary plug, intended to be removed in a future scheduled maintenance window.

Tube plugging performed during forced power reductions or forced shutdowns may warrant the use of different plugs than those used for permanent plugging under normal scheduled maintenance conditions. Even during scheduled maintenance periods the use of temporary plugs may develop due to uncertainty with ECT results or discovery of a greater than expected quantity of pluggable indications. Plugging decisions often need to be made before additional information can be obtained from pulled tube metallurgical analysis, alternative NDE methods, or shell-side inspections. The causal information for tube leak or tube degradation may be incomplete. It is desirable to maximize reliability via plugging tubes as well as to maximize service life by avoiding unnecessary tube plugging. The use of temporary plugs which are more readily removable is an option that can be used to support both objectives, allowing questionable tubes to be removed from service until additional analysis or follow-up inspection data is available, at which point some tubes may be returned to service and others permanently plugged.

Temporary plugging could also include the installation of elastomeric plugs in condensers or cooling water heat exchanger where mechanical plugs are used as the permanent plug, or the use of mechanical plugs in a heat exchanger where welded plugs are normally used. The additional time necessary to prepare for welding, to achieve the needed field conditions to support plug installation, differences in dose rates compared to scheduled outages, and similar variables may warrant the use of temporary plugs.

The temporary plug design should be suitable for the service conditions and expected installation duration. The installation of temporary plugs should include the initiation of follow-up actions to remove the plugs to support detailed failure investigation, potential tube recovery (insurance plugged tubes), and installation of permanent plug designs.

3.2 Plug Material

Plug material is typically specified to be consistent with the tube material when metal plugs are used. Considerations include the potential for corrosion (crevice, galvanic, and MIC if open cooling water service), dealloying, cracking, weld compatibility with the tubesheet (if welded plugs) and for elevated temperature service the thermal expansion differences between the plug and tubesheet if the potential for rapid temperature transients exists.

Elastomeric plug material typically does not result in galvanic corrosion concerns. Therefore, selection of suitable elastomer material is based upon the fluid chemistries and pressure/temperature ratings of both the tube and shell sides of the heat exchanger.

3.3 Plug Size

Tube plugs have an allowable ID size range to achieve effective long-term leak-tight sealing. The allowable size range varies with plug types.

3.3.1 Tube ID in Tubesheet

Tube plugs must be installed in a location within the allowed ID range to achieve and maintain leak-tight sealing. Estimating tube ID by subtracting twice the nominal tube wall thickness from the tube OD does not provide sufficient accuracy for size selection of many of the plug types since the variability of actual tube ID from the nominal estimated ID exceeds the allowed size range. Nominal tube ID determined in this manner underestimates the tube ID at the plug location. Causes for variations in tube ID in the tubesheet from the nominal value include:

1. Tube roll expansion in the tubesheet
   a. Tube expansion closes the gap between the tube OD and tubesheet hole ID.

      Tubesheet hole sizes are specified in TEMA Table RCB-7.21 as 0.008 inches larger than the tube OD for tubes in the ½ to 7/8 inch OD range for close-fit tolerances. Variation within +/- 0.002 inches must be met for 96% of the holes and +0.010 inches for a maximum of 4% of the holes. Thus, the tube OD may be expanded up to +0.018 inches for tubes in this size range before contacting the tubesheet.

   b. Tube wall reduction of 5-8% is commonly specified to achieve adequate sealing and/or joint strength.
2. Tube wall thickness may vary +/-10% for average wall tubes per the tube specification. (tubes specified as “minimum wall” have a +20%/-0% thickness tolerance).

One method to verify the tube ID is acceptable for the selected plug expansion range is via the use of a go/no-go gauge. The gauge, as shown in Figure 3-15, has a small end and large end corresponding to the minimum and maximum hole size or ID that can be effectively sealed by the size plug selected. The correct size opening for the plug is indicated by the ability to insert the small end of the gauge but not the large end. If neither end of the gauge can be inserted, then the plug is too large, or the hole is too small and may require reaming, or there may be a restriction at the tube opening. If both ends of the gauge can be inserted, then the plug is too small for the location. These type step gauges may be supplied by the plug vendor for mechanical plugs as part of a plugging kit. The gauge is used to verify the tube ID in the tubesheet is within the expansion range of the plug. If a go/no-go gauge is not available, the hole ID in the tubesheet can be quickly checked with a tube hole gauge, shown in Figure 3-16.

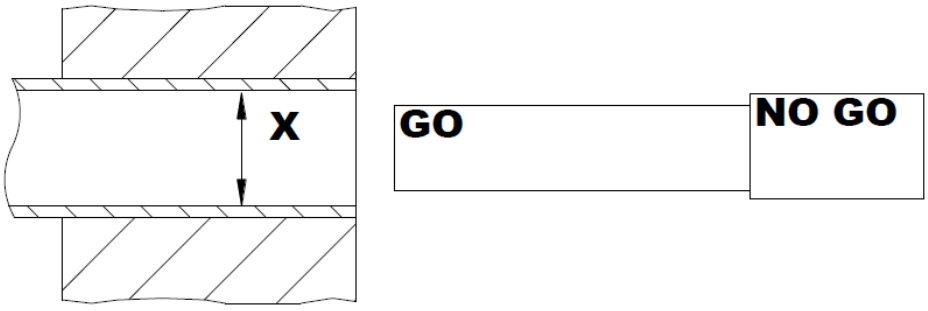


Figure 3-15
Mechanical Plug Sizing Gauge



Figure 3-16
Tube Hole Gauge

If the tube end is not trimmed flush with the tubesheet and projects out from the tubesheet, the ID measurements for tube size selection should be in the expanded region in the tubesheet, not at the tube end.

Tube ID Erosion

Tube ID erosion, as depicted in Figure 3-17, commonly occurs in copper based (that is, copper, brass, copper-nickel) tube materials in open cooling water systems. Tables 4-3 and 4-4 in EPRI report 1022980 provide velocity and ID erosion susceptibility comparisons for common tube materials.

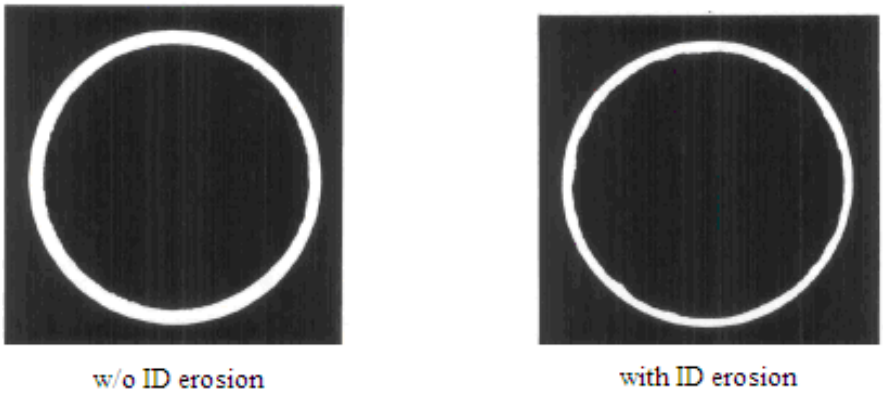


Figure 3-17
General Tube ID Erosion

Tube ID erosion is strongly influenced by water velocity and may vary significantly between different tubes in the heat exchanger, as well as along the length of individual tubes. It is often most severe within the first several inches of the tube from the tube end. Accordingly, when ID erosion is occurring it is of increased importance to check the ID of each tube end to be plugged. Tube end preparation is also typically required for this condition when mechanical expansion plugs are being used, which requires follow-up ID measurement after the tube cleaning and ID smoothing actions are performed.

3.4 Plug Installation

Plug installation difficulties and problems have been encountered for many years. EPRI reports CS-1776, *Feedwater Heater Failure Cause Analysis*, and NP-4057, *Feedwater Heater Handbook, Volume 3*, note a variety of difficulties associated with tube plugging in feedwater heaters in the 1970's and '80's:

- "…there has been so much difficulty in tube plugging that this solution has become a major source of feedwater heater problems."
- "Several utility maintenance personnel have advised that regardless of the type of repair (plug)…failure is likely if the procedure does not ensure proper…" (issues noted)
- "…extensive poor plug seating with subsequent leakage…"
- "Failure to properly prepare surfaces prior to welding"
- "…inadequate time allowance for the repair"
- "….poor access for machining and cleaning"
- "the inability to isolate the FWH adequately…", "…poor working conditions…"

While these examples are decades old, many of these same issues and problems persist today in feedwater heaters, with similar problems experienced in condensers and other heat exchangers. Problems are not limited to on-line plugging activities. To reduce the incidence of plug failures and plug leaks, the selection of a robust plug, as discussed in the previous section, is important. Selection of the right plug for the application must also be accompanied by providing proper instructions and training for plug installation, as well as verification actions for plug placement.

3.4.1 Plugging Instruction

The level of detail in instructions provided to maintenance personnel for tube plug installation should be commensurate to both the type plug being installed and the consequences of plug leakage. Different plug types have varying levels of preparation and installation actions and therefore more instructions are warranted for some type plugs. The same plug design may be used in heat exchangers with leakage consequences varying from severe to minor, with greater installation detail warranted for the higher consequence service.

The plugging instructions may be in a maintenance procedure, in work package instructions, or in vendor documents (plug vendor, heat exchanger vendor, or other).

Safety Related Heat Exchanger Tube Plugging Instructions

General regulatory requirements addressing the performance of actions that affect safety related equipment may be applicable to tube plugging. For example, 10CFR50 Appendix B, Criterion V states (bolding added):

> *"Activities affecting quality* ***shall be prescribed by documented instructions, procedures****, or drawings, of a type appropriate to the circumstances…."*

Work package instructions such as “Plug tubes as required” may not meet the intended meaning of “…instructions…appropriate to the circumstances…” The variables which could affect proper plug selection (that is, if various sizes could be used), preparation of the tube, plug placement within the tube, and seating or securing the plug may need to be sufficiently described to ensure the correct plug is properly installed.

3.4.2 Tube Plug Training

Training for tube plugging may include on-going or continuing training as well as just-in-time training conducted prior to a scheduled activity. Both provide useful opportunities to provide detailed explanations and demonstration of proper tube plugging actions. Lessons learned and industry experience may also be reviewed or covered in the training. Mock-up tubesheet sections may be used to assist with training exercises. Engineering involvement (that is, heat exchanger program owner, system engineer, or component engineer) with tube plugging maintenance training may prove beneficial.

3.4.3 Preparation for Plugging

Tube plugging field preparation actions are important to achieving leak-tight plugs. Problems noted in previous EPRI reports related to tube or plug preparation include:

- “Improper reaming has caused the loss of tubesheet overlay required for welding” “inadequate reaming to achieve…round holes before plugging.”
- “Incorrect weld rods have been used.”
- “Application of excessive weld material has resulted in shrinkage causing ligament damage.”
- “Lack of cleanliness and presence of moisture have resulted in poor welds.”
- “Excessive force in driving tapered solid plugs has caused ligament damage.”
- “Poor work atmosphere for personnel, resulting in low weld quality primarily due to small channels and/or leaking isolation valves.”
- “seal weld cracks in adjacent tube-to-tubeheet welds….attributed to the close proximity of tube welds and difficult welding conditions (poor access and limited space).”

As discussed in Section 3.3, measurements to ensure the proper size plug is being installed are important for most heat exchangers and plug types. The range of allowable hole size for the plug varies according to plug type, with elastomer plugs and tapered plugs typically providing wider ranges than mechanical expansion plugs, which may have a range of 0.020 inches.

Tube hole preparation with stiff wire brushes is recommended by some of the plug vendors prior to plugging to provide a smooth uniform ID. However, this action may not be desirable or allowed in FME sensitive systems to avoid the metal fines and/or wire bristles. The use of a “flapper wheel” or similar abrasive cleaning tools may be allowed in those systems for minor tube cleaning.

The tube ID should be inspected for cracks, pitting or defects in the area of plug seating/sealing contact. If aggressive tube cleaning or preparation has been performed for defect removal, then the tube ID should be rechecked to determine if enough material was removed to require a larger plug size.

Clearance for Plug Installation Tools

Tube plug preparation actions should consider a review of available clearance in front of the tubesheet for tools (or welder access) needed to install the selected/preferred plug type. Where the clearance or access is limited, alternative tooling or even plug types may be needed.

Limited access can occur in the tube row adjacent to the divider or partition plate, in the outermost tubes in the bundle for heat exchangers with hemispherical or ellipse heads, and other obstructions.

3.4.4 Plug Location Marking and Verification

The tubes to be plugged should be located and clearly identified. Both ends of the same tube should be clearly marked for plugging. Verification both ends of the same tube are marked correctly, such as passing a flexible probe through the tube or blowing air through one end of the tube, may be warranted.

Mechanical Plug Placement Depth

Expanded mechanical plugs must be installed in the expanded/rolled tube section within the tubesheet. Plug placement with sufficient depth such that the plug does not project beyond the tubesheet face avoids the risk of debris or loose parts impacting the plug. If the tubesheet is not thick enough or the roll length is insufficient, it may be necessary for part of the pin to project beyond the tubesheet since the plug must be expanded in the rolled portion of the tubesheet.

3.5 Special Plugging Cases

Various conditions encountered during heat exchanger maintenance may affect the tube plug selection, sizing, materials, installation preparation, or similar considerations. Several of these special cases are discussed in this section.

3.5.1 Plugging Tubesheet Holes

If the tube has been removed from the tubesheet a decision must be made on directly plugging the tubesheet hole or rolling a tube stub into the tubesheet prior to plugging. If plugging the tubesheet hole, the following considerations are noted:

1. **Hole size**. Different size plugs are likely to be needed due to the larger hole ID
2. **Grooves**. Tubesheet holes may have “TEMA” grooves in the ID, consisting of two 1/8-inch wide x 1/64-inch deep annular grooves added to give strength and tightness on the joint, integral leak-off grooves intended to reduce the risk of joint leakage reaching the condenser, or other configurations as detailed on design drawings. If present, these grooves may influence the plug type or placement, since they may interfere with sealing of mechanically expanded plugs.

3. **Material**. Tubesheets and tubes may be of different materials with cladding or coatings used on some tubesheets to avoid corrosion issues with the fluids and galvanic interaction with the tubes. In this case a plug should be selected capable of sealing at the tubesheet. If a welded tube-to-tubesheet joint existed prior to plug removal, then a welded plug may be the most appropriate plug, pending the reason/basis for the welded joint design.



Figure 3-18
Example of TEMA Grooves in Tubesheet Holes

3.5.2 Plugging ID Coated Tubes

Coating of heat exchanger tube ID with epoxy or other materials has been used to address inlet (and/or outlet) end tube erosion similar to the installation of tube sleeve inserts. The ID of a coated will be reduced. This must be accounted for via measurement or removal of the coating. When plugging is performed without coating removal, the potential for coating cracking due to forces applied by the plug is another consideration to be addressed for highly leak sensitive applications.

3.5.3 Plugging Insert Sleeves

The presence of tube inserts or sleeves at one or both tubesheets must be considered when selecting tube plugs for the heat exchanger. These inserts are often installed in response to erosion preferential to the tube inlet (and sometimes outlet) regions, typically in heat exchangers supplied by an open cooling water system. The insert materials are normally similar or compatible with the tube material to avoid creating a galvanic corrosion concern with the tube. Their expansion into the tube in the tubesheet region is often a very light roll expansion, and may not provide a leak-tight seal between the sleeve and tube. Thus, additional movement or yielding may occur when installing friction fit (that is, tapered) plugs or mechanically expanded plugs into a sleeve, and installation of an elastomer plug may leave a leak path between the sleeve OD and tube ID.

Ideally, these issues were considered as part of the evaluation authorizing installation of the sleeves, and updated guidance on the plug type, size, materials, and preparation actions were developed.

3.5.4 Tubesheet Welded Tubes

Welded tube-to-tubesheet joints may affect the plug selection and/or require additional preparation actions. It may be necessary to remove any of the weld bead protruding into the tube ID prior to measuring for the plug size selection or installing the plug.

When using mechanically expanded plugs, it is important to ensure the tube ID is measured in the tubesheet where the plug will be expanded and not measured at the tubesheet face. The weld at the tubesheet face may result in a smaller ID reading, or if using a plug sizing step gauge provided by the plug vendor in a plugging kit, the gauge size to clear the weld droop may result in selection of a plug too small for the tube ID in the tubesheet. The resulting undersized plug will be at risk of leakage or failure, if installed.

3.5.5 Through-the-Tube Plugging

Through-the-tube plugging refers to setting mechanical plugs in both ends (that is, both tubesheets) of the tube in a straight tube heat exchanger when access is only available from one side. An extension rod assembly can be used with some of the mechanical plug designs that allows the plug to be inserted through the full length of the tube to the opposite tubesheet, expanded and set. The direction of the center tapered pin will be reversed (that is, toward the tube interior vs toward the tubesheet face) in the plug installed at the far tubesheet. To ensure the far plug is expanded in the tubesheet, accurate dimensions of the tube length and tubesheet thickness will be needed. Field verification of these dimensions is strongly recommended prior to installing the first plug versus reliance on drawing dimensions. Careful measurement and marking of the pull-rod assembly extension piece will also be critical to ensure the plug is positioned in the correct location. Mock-up training may be useful to verify the ability to consistently achieve proper plug placement and expansion.

Tube ID verification in the far tubesheet is not possible with through-the-tube plugging, requiring reliance on measurements taken in the near tubesheet to determine the acceptability of the plug size. Tube hole preparation such as cleaning, wire brushing or other similar measures will also not be possible at the far tubesheet, limiting the suitability to applications not expected to experience tube end erosion or heavy ID pitting. These variables are likely to be well understood in advance based upon the tube material and service.

The OD of the plug must be able to pass through the tube, which prevents use of this method in integrally finned tubes, tubes with large dents, and possibly tubes which may have been expanded into the tubesheet with excessive force or if the tubesheet holes were oversized (such as due to multiple past retubing actions).

If the tube is not breached, then an individual tube test apparatus could be used to verify the far-end plugs are sealed prior to installing the near-end plugs.

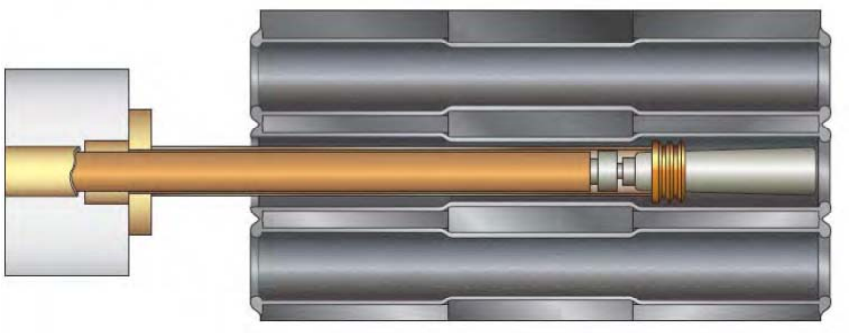


Figure 3-19
Diagram of Through-the-Tube Plugging

While there are several limitations to the use of through-the-tube plugging, and additional precautions, training, and document changes may be needed to support this action, it does provide an option for tube plugging when access is only reasonably available to one of the tubesheets.

3.5.6 Degraded Tubesheets

Tubesheets may be damaged or degraded for a variety of reasons such as galvanic corrosion, dealloying (for example, muntz metal tubesheets), crevice corrosion, pitting corrosion, cracking, disbanded or inadequately fused weld overlay cladding, defects in tube-to-tubesheet joint leaks in high pressure service such as feedwater heaters, or other mechanisms.

When a degraded/damaged tubesheet condition is found, it warrants careful consideration of its potential to adversely affect the tube plug sealing capability. Both hammered in tapered plugs and mechanically expanded plugs rely upon the backing of sound tubesheet material behind the plug to achieve an effective seal between the tube and plug.

3.5.7 Plugging Untrimmed Tubes

Tube ends may not be trimmed flush with the tubesheet face on one or both ends of heat exchangers as shown in Figure 3-20. Tapered plugs and two piece ring-and-pin plugs may not provide effective sealing unless tubes are trimmed flush with the tubesheet face.

Mechanical plugs can be installed behind the projecting tube end and expanded in the tubesheet region, the measurement of the proper mechanical plug size must be in the expanded portion of the tube in the tubesheet region and not be based upon a “go/no-go” gauge check in the tube end projecting past the tubesheet. A micrometer, tubehole gauge or similar means need to be used to obtain an ID measurement in the region where the plug will be placed. Trimming the tube flush with the tubesheet is another option to avoid tube plugging issues when projecting tube ends are encountered.

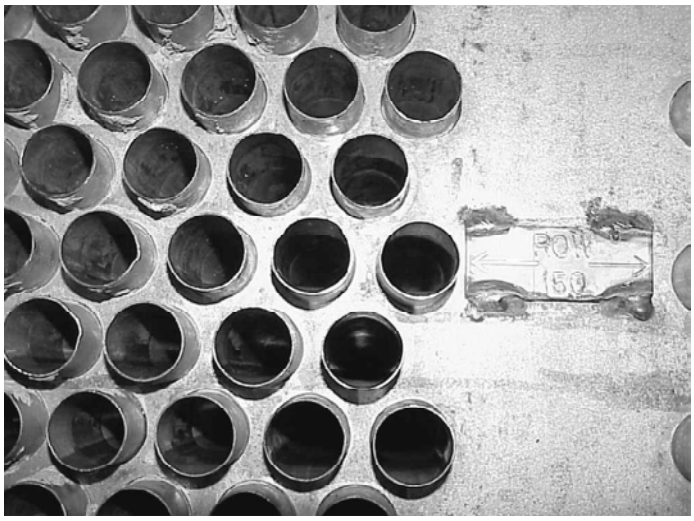


Figure 3-20
Untrimmed Tubes at Tubesheet

3.5.8 Robotic Plugging

Robotic arm installation of plugs has been performed by repair vendors when physical conditions and/or safety concerns with isolation valves may not permit access inside feedwater heaters for tube plugging. EPRI report 1004121, *2004 Feedwater Heater Technology Symposium*, described the use of robotic feedwater heater tube plugging.

"New robotic technologies are available to plug leaking tubes using remote controls. To gain access to both the inlet and outlet sides of the tubesheet, a robotic remote control method to cut or remove the pass partition plate had to be developed. The robotic arm is used to help locate the leaking tube, clean the tube, install an explosively welded plug, and restore the pass partition plate. A shell side air pressure test was used to identify the failed tubes."

Similar robotics were used for removal of tapered plugs from low pressure feedwater heaters at a nuclear station due to risks associated with pressure trapped behind the plugs.

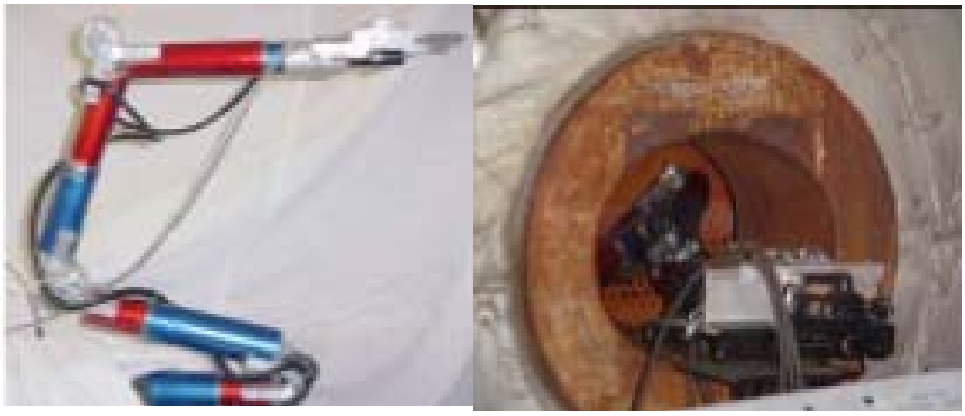


Figure 3-21
Robotic Plugging Apparatus

3.6 Plug Removal

The removal of existing tube plugs may be pursued for various reasons, such as:

- Insurance plugged tubes being unplugged for follow-up NDE.
- Tubes to be returned to service via sleeving, internal coating, and so on.
- Change/upgrade plug type.
- Change in plugging criteria, or availability of improved NDE, or reanalysis of NDE data has reclassified indications which no longer warrant plugging.
- Tube to be replaced (that is, retubing).
- Addition of stabilizers as a barrier for a specific damage type.

Key Human Performance Point

There are potential risks of trapped pressurized water in the tube during plug removal. Care should be taken during plug removal in accordance with the tube side operating pressure. Protection plates (see Figure 3-22), robotic plug removal, or other measures may be warranted.

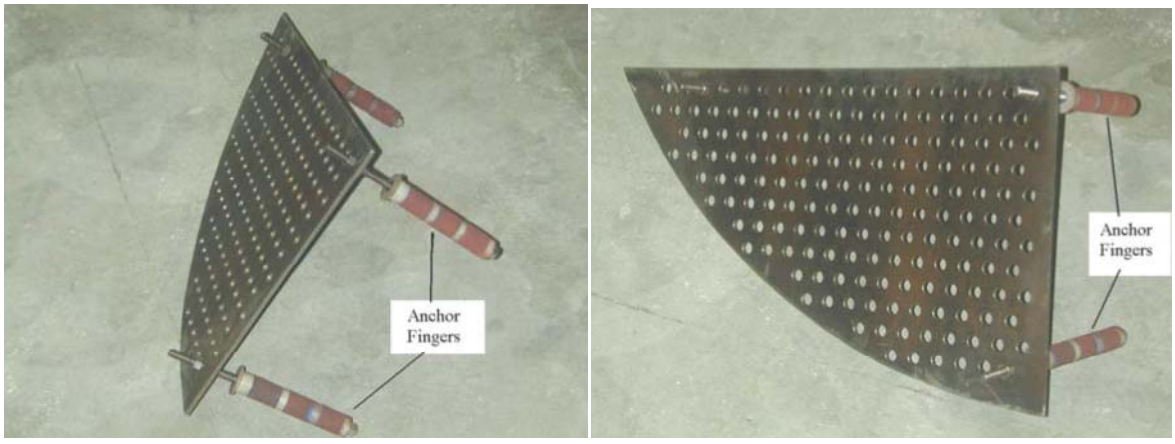


Figure 3-22
Example of Plug Removal Protection Plate

Plug removal techniques vary with the type of plug used. Hammer-in plugs can be removed by drilling and tapping the end of the plug to insert a tube spear or threaded rod. A slide hammer can then be used to remove the plug. A typical tube plug removal tool is shown in Figure 3-23.

For the two-piece hammer-in plugs, the tapered pin or plug assembly can be removed using the techniques outlined above for tapered plugs. If the pin is removed, the ring within the tube can be removed using:

- Thread a tapered tube pulling spear or plug removal tool into the bore of the ring. Attach a slide hammer or tube puller to the spear.
- Using the bore of the ring as a drill guide, drill through the ring with successively larger drill bits until the ring can be withdrawn. Exercise caution to prevent the drill from moving off center or drilling at an angle. Damage to the tube or tubesheet could occur that will make re-plugging difficult.
- Use successively larger, stiff bristle, metal brushes to wear away the ring material from the ID. Exercise caution to prevent the brushes from damaging the tube bore.

Mechanical plugs can typically be removed by reversing the installation process. A tube spear and pulling device is needed to remove the outer expanded ring of some mechanical plugs from the tube.

Elastomer plugs are loosened by unscrewing. Once loosened, the plug may slide out or may require use of a claw hammer or tube pulling device.

Welded plugs require the weld material to be removed. Then the plug can be drilled, tapped, and pulled. Explosively welded plugs are often the most difficult type of plug to remove because they must be drilled out. Care should be used when attempting to drill out any plug type because the drill can move off-center and enter at an angle to the tube axis. Severe damage to the tube end and tubesheet may occur.

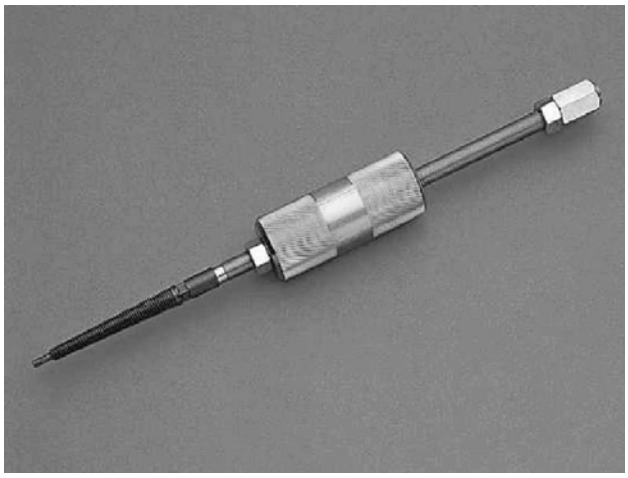


Figure 3-23
Plug Removal Tool

3.7 Post-Plugging Actions

After tubes are plugged, several actions are often needed. Verification the correct tubes were plugged is a recommended action for all heat exchangers, and other actions may include updating tubesheet maps, databases, plugging margin and/or remaining life assessments, and system or program health indicators.

3.7.1 Plug Verification

Tube plug verification is recommended for all heat exchangers following tube plugging. There have been numerous industry experience reports regarding errors in plug installation. While not a common occurrence if viewed as a percentage of installed plugs, the issue is common when the overall quantity of installed plugs is considered.

Safety Related Heat Exchanger Plug Verification

General regulatory requirements addressing the need to verify or validate that actions that affect safety related equipment have been properly implemented may be applicable to tube plugging verification. For example, 10CFR50 Appendix B, Criterion V states (bolding added):

> *"Activities affecting quality s**hall be prescribed by documented instructions, procedures**, or drawings, of a type appropriate to the circumstances and shall be accomplished in accordance with these instructions, procedures, or drawings. Instructions, procedures, or drawings **shall include** appropriate quantitative or qualitative **acceptance criteria** for determining that important activities have been satisfactorily accomplished."*

Preventive maintenance (PM) actions performed on safety related heat exchangers are "*activities affecting quality*". They require:

1. "instructions…appropriate to the circumstances"
2. "acceptance criteria" to verify they "have been satisfactorily accomplished."

Thus, acceptance criteria are required for actions on safety related heat exchangers. The need for as-left inspections with acceptance criteria, even if qualitative, to determine the "*activities have been satisfactorily accomplished*" following PM activity may be overlooked. A documented verification of tube plugs having been correctly installed (that is, right quantity and location of plugs) in safety related heat exchangers will suport meeting the intent of this requirement.

3.7.2 Plug Leak Testing

Leak testing following tube plugging is recommended in EPRI reports 1003470 and TR-108009. This recommendation warrants clarification that it is only applicable to tubes with existing leaks or intentionally pierced. The justification for such an action will vary according to plug leak consequences. Plug leak testing may not be justified without extenuating circumstances for nuclear feedwater heaters, but may be warranted for condenser plugs with high chloride circulating water, for which very small plug leaks (<1 gpd) can be detected by condenser hotwell chemistry monitoring.

3.7.3 Mechanical Plug Break-Away Tip Removal

A popular type of mechanical plug utilizes a shear-pin type connection threaded into the plug to achieve the desired amount of expansion in the plug sealing ring. In FME sensitive systems (such as condensate and feedwater) it is necessary to remove the half of the break-away pin remaining in the plug to avoid the potential for this piece to become a source of foreign material in the system.

Post-installation actions for this type plug should include verification the threaded break-away pin has been removed from the plug.

3.8 Plugging Configuration Control

Tube plugging configuration control for safety related heat exchangers consists of permanent record documentation of the quantity and location of tube plugs. At most stations a tubesheet map for each safety related heat exchanger (with plugged tubes) is maintained as a design drawing and updated each time tubes are plugged.

Methods of maintaining tube plugging configuration control for non-safety related heat exchangers vary. It is recommended that a consistent methodology be established and followed for non-safety related heat exchangers. Some stations rely upon NDE vendor tubemap software to generate a tubesheet map included with the NDE report. A tubesheet map showing the as-left plugging can then be included in the maintenance work package performing the heat exchanger inspection and tube plugging to capture the information as a permanent record.

Some heat exchanger programs maintain a non-permanent record (that is, spreadsheet or database) of the type of plug installed (when multiple types exist in a heat exchanger), the outage or date the plug was installed and the general reason for plugging (for example, leak, NDE data, insurance plugging, and so on).

Tracking the total quantity of plugs installed, and if possible the plugging progression with time, against the tube plugging limit is a beneficial practice for life cycle management/long-range planning as well as margin management. Actions to address low plugging margin could include replacement or a variety of margin recovery actions, as discussed in Section 5 of this report.

4
TUBE STABILIZATION AND TUBE PIERCING

4.1 Stabilizing Tubes

Stabilizers consist of material placed inside a tube that is being plugged in order to strengthen or reinforce the tube. Since the tube being stabilized is also being plugged, the purpose of stabilizing the tube is to protect other active tubes in the heat exchanger from potential damage and/or to reduce the potential for the tube to become loose material or debris in the heat exchanger or shell-side system.

Stabilizing to Protect Other Tubes

Tube stabilizers are normally used to protect nearby in-service tubes. This protection may be associated with:

1. Avoiding damage to surrounding tubes from an existing or potential sheared/severed tube
2. Strengthening tubes as a barrier against shell-side flow induced damage from progressing to interior tubes in the tube bundle.

A sheared tube may impact adjacent tubes due to shell-side flow turbulence across the tube. The greatest risk exists with high velocity steam flow, such as in feedwater heaters or main condensers. For single phase heat exchanger service, the risk of plugged tube damage progressing to a sheared tube and impact occurring to adjacent tubes with sufficient energy to jeopardize tube integrity is low, unless symptoms of unusually high tube vibration are present. Accordingly, feedwater heater tubes may be stabilized for wear damage while a single-phase heat exchanger with a tube plugged for wear may not warrant stabilization. In high velocity steam service, such as feedwater heaters and main condensers, tubes being plugged due to wear or circumferential cracking are candidates for stabilization in addition to plugging to reduce the future risk to nearby tubes.

As discussed in Section 2.3, tubes may also be plugged to serve as an impingement barrier to protect interior tubes from debris and/or shell-side flow impingement.

Stabilizing to Avoid Tube Fracture Debris

The fracture of a plugged tube into loose fragments may not pose a threat to surrounding tubes if they are already plugged, but the fragments may result in adverse impacts to the heat exchanger or system as foreign material debris. Tube fragments may cause added pressure drop reducing shell-side flow capability or if able to exit the shell they may become lodged in valves, pumps, or other components.

The risk of tubes becoming debris in the shell and potentially the shell-side system is sufficiently low for most service conditions other than feedwater heaters that tube stabilization for this purpose is not warranted. While damage mechanisms such as flow-induced vibration fatigue cracking and wear at baffle and support plates is likely to continue after tube plugging, the potential for sections of plugged tubes to become completely separated or severed from the rest of the tube at two locations is extremely low, other than in special circumstances.

Conditions at risk of generating loose tube fragments that are fully separated from the remainder of the tube are most often found with heat exchangers having two-phase high velocity steam flow. Relative to the scope of this report, that is limited to feedwater heaters and main condensers at most plants, with some PWR blowdown heat exchangers potentially included.

Other special circumstances include heat exchangers with tubes having multiple circumferential cracks in a given tube and/or aggressive wear rates at multiple adjacent baffle plates. These conditions are not common in cooling water type heat exchangers. Circumferential cracking does occur in low energy cooling water service heat exchangers, particularly in brass tubes, but it most often occurs at the back of the tubesheet and is unlikely to include multiple circumferential cracks in a given tube such that the tube could fragment into discrete pieces. Wear may be found to be occurring at a sufficient rate at multiple baffle plates such as below a shell inlet nozzle to generate the concern for loss of tube segments, but typically this would be associated with excessive shell-side flow, inadequate original design, or failure of an internal impingement plate.

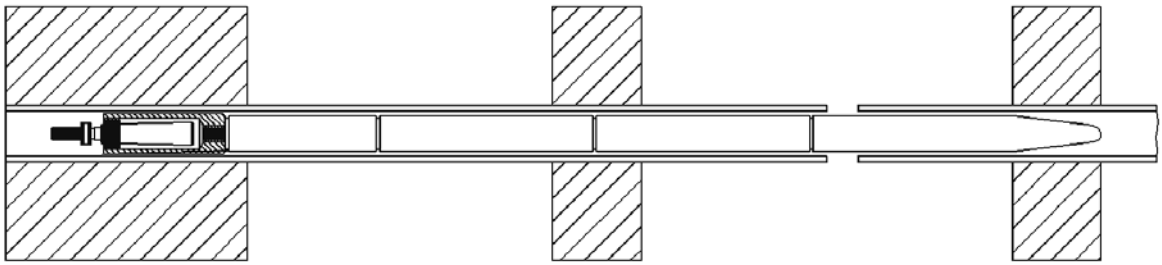


Figure 4-1
Segmented Rod Stabilizer

Types of Tube Stabilizers

Tube stabilizers most often consist of bar stock or wire rope (cable) sized close to the tube inside diameter (that is, 1/16 to 1/8 inch smaller than the tube inside diameter). 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.

If the tube is suspected of being sheared or severed, such as due to a very large leak indication, performing a videoprobe inspection of the tube will identify if tube is sheared, if the other tube end is visible or missing, and if visible if it is sufficiently aligned to allow stabilization. This inspection will minimize the risk of the stabilizer being pushed into the shell and becoming a potential source of debris/foreign material. A tapered or angled tip can be attached to the nose of the stabilizer to allow partially off-set tube ends to be realigned.



Figure 4-2
Cable and Rod Stabilizers

Stabilizer Length

An anchored stabilizer length may extend only part of the tube length. In order to provide the intended protective function, the stabilizing rods or cable must be long enough to bridge the defective region of the tube and extend at least past the next support/baffle plate, preferably the next two plates. Unanchored stabilizers must extend the full tube length minus the length needed for the tube plugs in a straight tube heat exchanger. In a u-tube unanchored stabilizers should extend to the u-bend. Unanchored stabilizing cables should the length of tube if the cable is flexible enough to navigate the bend radius. 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.

Partial length stabilizers relying upon anchors should consider the severity of impingement and vibration energy associated with the service conditions and reason for stabilization. Stabilizers serving as an alternative impingement barrier in a feedwater heater either below the steam inlet or cascading drain inlet nozzle may be subject to severe vibratory energy that could result in failure of anchor connection devices.



Figure 4-3
Example of a Stabilizer Anchor Plug

Stabilizer Materials and Cleanliness

It is conservative to assume the stabilizer will eventually be exposed to the shell-side fluid, even if the stabilized tube is not presently breached. Accordingly, the materials selected and cleanliness requirements should be appropriate for the shell-side system. The presence of grease, an oily 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.

4.2 Piercing Tubes

Several references, such as EPRI reports 1003470 and TR-106741, and ASME PCC-2, include recommendations to intentionally perforate intact tubes prior to plugging to eliminate the risk of pressure buildup in the plugged tube, although some include caveats “if there is no intention of returning the tube to service”. Documenting the basis for the decision regarding the perforation of intact tubes prior to plugging for a heat exchanger set or group provides a means to ensure consistent application and responde to related operating experience reports. Considerations for a tube perforation prior to plugging basis include industry experience reports for tube plug ejection, tube cleanliness requirements (to minimize chemical or other contamination of the shell-side system), the robustness of the plug designs to be installed regarding the margin between their differential pressure rating and the service pressure, the potential stored energy behind a plug based on the service application, and the hazards associated with the type of fluid in the system.

EPRI report 1022980, *Guidance for an Effective Heat Exchanger Program, (Section 4.6.1)* includes the following discussion on the topic:

- "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."
- "Plugs may have trapped pressurized fluid behind them."
- "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. The lower operating pressure of most circulating water systems (for example, 5-50 psig) reduces the potential for serious personnel injury due to impact from a condenser tube plug ejection, provided normal personnel protective equipment is used (that is, safety glasses, hard hat, and gloves). However, the potential for secondary injury associated with worker reflex actions (for example, back or neck injury, recoil into scaffolding, and so on) from a condenser tube plug ejection remain and warrant precautions to ensure worker awareness. When retightening or removing plugs with lower differential pressure rating (that is, grip strength) an added precaution may be warranted to avoid having personnel in the path of the plugs being checked. Industry experience examples of condenser tube plug ejections can be reviewed in pre-job briefs and/or included in work packages involved with retightening or removal of lower dp rated plugs.

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

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 feedwater heater 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 feedwater heater or high pressure service tubes prior to plugging is a site 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, and so on) 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; and 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.

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.

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."

See also EPRI reports 1004022, *Feedwater Heater Technology Seminar and Symposium,* October 2001; and 1004121, *Feedwater Heater Technology Symposium,* August 2004.

5
PLUGGING LIMITS

5.1 Rule-of-Thumb Plugging Limit

The tube plugging limit for a heat exchanger is the maximum number of tubes which can be removed from service while continuing to meet its most limiting design requirement. In most cases, the most limiting design requirement is heat transfer capability at the available or credited flow and temperature conditions for the fluid streams. However, the tube plugging limit may be based upon other design constraints for sub-components in the heat exchanger or components/ analysis in the associated operating systems. For example, the allowable stresses resulting from increased differential pressure with high tube plugging may be more limiting for internal parts such as the divider/partition plate in the channel (or shell side) than the thermal performance requirements. System flow requirements for functions beyond the heat exchanger or maximum design temperatures for downstream piping may result in more limiting constraints on tube plugging than the heat transfer duty of the heat exchanger. Tube plugging limits for non-safety related heat exchangers may not be defined in design documents. Generic tube plugging allowances are applied at some utilities to these heat exchangers, below which no further engineering evaluation is required for tube plugging.

The widely held “rule-of-thumb” of a 10% plugging limit being available and acceptable for most heat exchangers does not have a sound basis. The heat exchanger manufacturers have not applied a fixed or consistent amount of excess thermal margin, 10% or other, in heat exchanger design. The TEMA standards allow plugging of 1% of the tubes or two tubes, whichever is greater, for u-tube heat exchangers prior to shipping to allow for a reasonable repair or disposition of tube damage detected during the manufacturing and testing processes.

Excess tube surface area or heat exchanger overdesign refers to the amount of additional heat transfer capability beyond what is needed to achieve the design operating point conditions on the data sheet (including the tube plugging limit in the specification). The design point on the heat exchanger data sheet represents guaranteed performance by the manufacturer. To ensure this performance guarantee is met, some additional margin is typically built into the heat exchanger. In general, the magnitude of heat exchanger overdesign has been decreasing with time, partly in response to improved confidence in the accuracy of heat exchanger performance models and partly in response to competitive pressures. A heat exchanger built in the 1970’s may have had overdesign or thermal margin equivalent to 10% of the tube quantity. The same heat exchanger designed in the late 1980’s may have included 5% surface area margin, while that heat exchanger designed and built in the 21st century may contain only 1% tube plugging margin, beyond what was required in the purchase specification.

In general, larger heat exchangers have smaller thermal margins, as a percentage of excess tubes, than smaller heat exchangers. Using the above time periods for comparison, a 2000 tube heat exchanger designed in the 1970's is less likely to have had 10% excess surface area than a 200 tube heat exchanger. The amount of excess surface area would have also varied based upon the vendor and their experience with a given design and service application. Applications such as surface condensers and feedwater heaters, which have been produced on a large scale with consistent designs for many years, result in higher confidence in meeting design performance and therefore could be supplied with less excess surface area margin.

When purchasing a heat exchanger, it is necessary to specify the desired tube plugging allowance. It is unwise to assume significant excess surface area margin would be supplied in today's large heat exchangers.

5.2 Safety Related Heat Exchanger Plugging Limits

The maximum allowable tube plugging limit for safety related heat exchangers is normally found in design documents. These may include calculations, specifications, drawings, vendor manuals, or similar design documents. 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. Heat exchanger thermal performance software is used by the engineering departments at many nuclear utilities to support such analysis.

If the plugging limit does not exist in design documents, then requesting a limit from the Design Engineering group is recommended prior to a scheduled tube inspection.

In the absence of tube plugging limits in design documents, the Corrective Action Program (CAP) is relied upon for safety related heat exchangers to addresses operability for the as-left tube plugging prior to returning the heat exchanger to service. Subsequent CAP actions are expected to require development of a technical document addressing the tube plugging prior to closure of the CAP issue.

5.3 Heat Exchanger Thermal Performance and Tube Plugging Limits

The significance of reduced heat exchanger thermal performance due to tube plugging varies according to the importance of the heat exchanger's performance to plant safety analysis and/or generation capability. For safety related heat exchangers, exceeding the analyzed tube plugging limit requires evaluation of the effect on operability, such as through a corrective action program (CAP) process. While exceeding tube plugging limits in a generation critical non-safety related heat exchangers could result in a unit derate during summer months.

The thermal performance of a heat exchanger is directly influenced by tube plugging through the loss of heat transfer surface area. Overall heat transfer capability of the heat exchanger is also a function of parameters which may have operational or analytical margin, which include the shell-side flow and inlet temperature, tube-side flow and inlet temperature and the tube cleanliness or fouling factor (both tube ID and OD fouling).

It may be appropriate to reallocate available margin from other parameters to increase the tube plugging limit, or conversely, the tube plugging limit is sometimes reduced to compensate for the loss of margin in other parameters. For example, to maintain the required heat removal, additional tube-side or shell-side flow may need to be provided or credited to support tube plugging needs until a replacement heat exchanger or other margin recovery actions can be implemented.

The tube plugging limit for safety related heat exchangers are sometimes changed by reallocating existing margins in related heat transfer variables (that is, flows, temperatures, and fouling factors) via the applicable engineering change processes. This process is described in EPRI Report 1012129, *Heat Exchanger Thermal Performance Margin Guidelines.* Examples include:

1. Increase tube-side minimum flow requirement (that is, take credit for available tube-side flow margin).
2. Increase shell-side minimum flow requirement (that is, take credit for available shell-side flow margin).
3. Lower design fouling (that is, take credit for fouling margin shown by thermal test data).
4. Lower heat load by removing overly conservative assumptions.
5. Allow hotter process fluid.
6. Credit lower Ultimate Heat Sink (UHS) peak temperature.

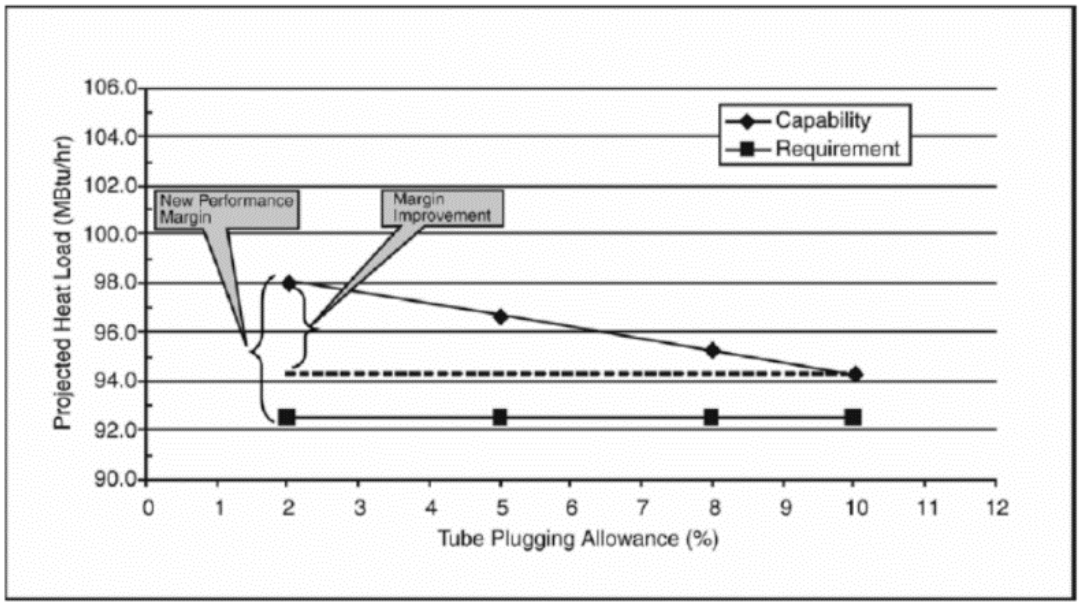


Figure 5-1
HX Performance vs. Plugging

5.4 Plugging Limits and Macrofouling

Tube blockage/macrofouling typically credits the available tube plugging margin to ensure required heat removal function for the heat exchanger is maintained. Tube blockage is a common cause for reduced heat transfer due to the loss of available surface area (that is, in-service tubes) in open cooling water systems, particularly once-through open systems.

The heat transfer capability is impacted by the loss of available tubes due to both tube plugging and tube blockage/macrofouling. Heat exchangers with a history of macrofouling tube blockage may need to allocate a portion of the tube plugging margin to bound historical macrofouling conditions. As permanent tube plugging increases, if the margin allocated to macrofouling tube blockage is reduced below historically observed as-found conditions, then other mitigating actions may be needed. These could include more frequent cleaning, back-flushing, or macrofouling debris reduction actions for screens, strainers, or chemical treatment.

5.5 Multi-Pass Heat Exchanger Tube Plug Distribution

Many heat exchangers are two-pass, and some smaller heat exchangers such as lube oil cooler, refrigerant condensers, and room coolers may have four or more passes. Analysis of the tube plugging limit for multi-pass heat exchangers should acknowledge if there are restrictions on the plug distribution per pass (that is, plugs assumed evenly distributed or all plugs can be in one pass).

Special designs may warrant additional review beyond overall heat transfer requirements. For example some refrigerant condenser designs include a sub-cooling circuit in the bottom of the shell to increase system capacity. Preferential plugging in this region may not result in an equivalent performance impact compared to other regions.

Room cooling coils with serpentine tubes versus a waterbox and baffle arrangement result in differences in affected surface area for a plugged tube. Plugging a tube in a serpentine coil removes a tube from each pass since flow is not mixed between passes as is the case with a waterbox coil design, where only a single pass is affected.

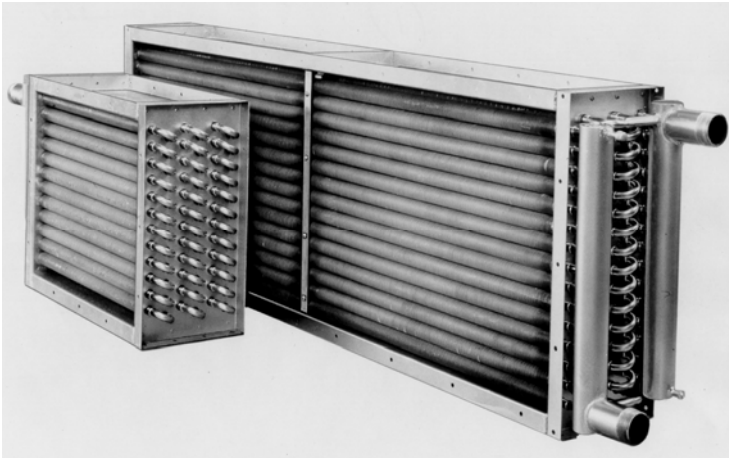


Figure 5-2
Serpentine Cooling Coil

5.6 Tube Plugging Limit and Tube Flow Velocity

EPRI report TR-106741, Heat Exchangers: An Overview of Maintenance and Operations, states, "When fewer tubes are in operation, tubeside velocity increases but should not exceed limits based upon the fluid and the tube material."

EPRI report 1022980, Guidance for an Effective Heat Exchanger Program, in Section 4.3 includes a table of common tube materials and flow velocity limits to reduce ID erosion succeptability. Discussion of additional variables affecting tube ID erosion such as the amount and type of suspended solids in open cooling water systems is also discussed. ID erosion in U-bend and H-bend fittings in room cooling coils may become problematic at even lower velocities due to local turbulence effects.

Tube plugging limits generally do not need to be limited by tube velocity values, since tube ID erosion is normally a long-term degradation mechanism, while tube plugging is often addressing a more acute or near-term reliability risk. However, in cases where a tube plugging limit could result in tube velocities that are a potential ID erosion concern, it may be prudent to establish a tiered plugging limit. One that is acceptable for both thermal performance and tube ID erosion, and a 2nd limit that is acceptable thermally but may result in accelerated tube degradation. Actions could be required prior to implementing the 2nd limit such as requiring more frequent tube NDE, ID measurements, and even visual inspections (that is, videoprobe) of the tube inlet region where turbulence associated with the tube entrance may result in more aggressive erosion. Additional actions may include requiring a life cycle management or long-term asset management plan to be generated for the heat exchanger to project remaining service life and the initiation of any replacement actions deemed appropriate by that review.

5.7 Tube Plugging Limit and Minimum Required Flow

Increased tube plugging increases the hydraulic resistance or pressure drop of the heat exchanger and system. The available excess flow margin above the required minimum flow necessary for credited heat removal by the heat exchanger will be reduced as a result of the increase in pressure drop across the heat exchanger.

Plugging limit calculations may assume the ability of the tube-side system to deliver the minimum required flow regardless of the added hydraulic resistance resulting from tube plugging. If the tube-side system has a low margin of excess flow to the affected heat exchanger, the ability to supply the minimum required flow may be challenged as tube plugging increases. Hydraulically rebalancing the system is occasionally required for this reason, with excess flow margin to other heat exchangers redirected by the addition of fixed orifice plates or valve throttling.

5.8 Tube Plugging Limit and Design Pressure Differential

For multi-pass shell-and-tube heat exchangers, the increased pressure drop associated with tube plugging results in additional pressure drop and stress at the pass partition plate. The design of heat exchanger divider plates (pass partition plates) vary between manufacturers. Being an internal, non-pressure boundary component, the design of the partition plate is not governed by ASME Code requirements.

The TEMA Standards until recent editions included limited guidance on partition plate design, specifying a minimum thickness according two ranges of shell diameter. The current TEMA Standards include a pass partition plate formula to determine required plate thickness (ref. RCB-9.132).

The purchase specifications for many safety related heat exchangers failed to include the maximum flow through the tube side of the heat exchangers as well as a tube plugging limit. This has contributed to partition plate under-design in some cases due to failure to identify bounding conditions for tube-side differential pressure. The design point flow included on the data sheet of many safety related heat exchangers represents the minimum required flow to ensure thermal performance capability. Accordingly, normal flow is maintained above this flow, and in some cases significantly above the design minimum flow. In most industries the data sheet flow represents the maximum flow condition. Therefore, heat exchanger vendors may have designed the partition plate based upon the pressure drop at the data sheet flow assuming this to be the most limiting or bounding flow and differential pressure condition.

When carbon steel materials were used for fabrication, the corrosion allowance specified for the channel (that is, tube side) is not required to be applied to the partition plate by the design standards even though the partition plate is exposed to the fluid on both sides versus just the interior surface.

The tube plugging limit should consider the acceptability of the associated differential pressure on the partition plate (if applicable) at the maximum allowed tube-side flow.

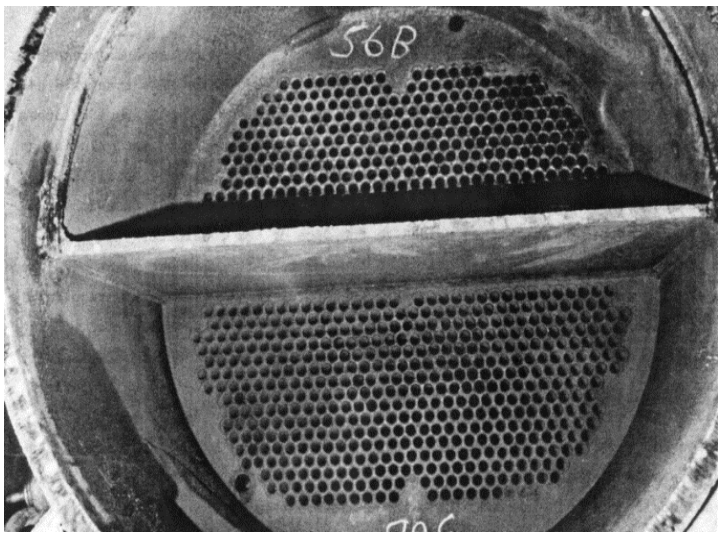


Figure 5-3
HX Partition Plate

Feedwater heater partition plates are typically a more robust design than those found in low pressure cooling water heat exchangers. However, tube plugging, tube velocities, and pressure drop may also be higher. As a result, the review of partition plate acceptability is a good practice when tube plugging reaches 10-15%.

The *Feedwater Heater Maintenance Guide*, EPRI report 1003470, notes the following regarding pass partition plates that have been deformed by high differential pressure,

> *"….future deformation can be prevented by welding a rib across the direction of the bend. The added rib stiffness in the direction of the bending should be adequate to resist the load applied by the pressure differential. A disadvantage is that ribbing causes increased turbulence and a slight pressure drop. The best solution to pass partition bending is to cut out the bent pass partitions and replace them with thicker ones."*

Feedwater heater partition plates are sometimes intentionally bypassed (primarily in fossil stations) by cutting holes of sufficient size to maintain the tube-side pressure drop within desired limits.

5.9 Tube Removal – Impacts beyond Reduced Surface Area

EPRI report 1022980, *Guidance for an Effective Heat Exchanger Program,* Appendix D includes considerations related to tube removal. The performance impacts noted include:

- 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.
- In cooling water heat exchangers, a removed tube provides a flow path through the shell side which bypasses 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. Options to maintain the normal cross-flow developed by the baffle plates and avoid bypass flow through the pulled tube baffle holes include installation of a replacement tube (requires rerolling in the tubesheets) or an equivalent OD round bar or stabilizing bar (that is anchored/captured in the tubesheets).

5.10 Vibration Analysis

Tube vibration is a function of the shell-side flow over the tubes, fluid properties, tube material and thickness, unsupported tube span and shell flow geometry. Tube vibration for in-service tubes is not adversely affected by the quantity of tubes plugged for single-phase fluid applications, since the above variables are not changed by tube plugging. The flow velocity inside the remaining unplugged tubes is expected to increase, as discussed in Section 5.6, but the tube-side velocity is not a contributor to tube vibration issues.

Heat exchangers with two-phase fluids on the shell side are also typically not adversely affected with respect to tube plugging quantity and tube vibration due to an impractical quantity of localized plugging necessary to redirect sufficient shell-side flow to increase vibration to a problematic threshold. For safety related heat exchangers with two-phase flow, which is limited to refrigerant condensers for this report since PWR steam generators are not in scope, the potential effect should be included in the evaluation performed for increasing plugging limits.

The vibration response of the plugged tube(s) may become worse or more active if the tube is not breached and remains empty. An empty tube has less vibration damping. Therefore, a tube plugged due to vibration related damage, such as baffle plate wear, may experience greater damage rates after plugging. This is a consideration for the use of a tube stabilizer, as discussed in Section 4.1.

5.11 Replacement and Long-Range Planning

EPRI report 1022980, *Guidance for an Effective Heat Exchanger Program,* Section 3.4.9 includes considerations related to long-range planning and life cycle management for heat exchangers:

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.

Options to extend remaining life vary greatly according to the heat exchanger design, service conditions, degradation mechanism, and similar considerations. These actions could include:

- Retubing, either partial or complete
- Mitigation actions to limit tube damage or return tubes to service
  - Sleeving, inlet/outlet ends, down-tube, or full-length
  - Tube ID coating
- Repairs to shell, shell internals, tubesheets, channel, and so on
- Reanalysis to allow increased tube plugging
- Corrective measures to reduce tube damage types or rates

6
TUBE PLUGGING INDUSTRY EXPERIENCE

Table 6-1
Industry Experience – Tube Plugging Errors/Problems

Month/Year	INPO Report #*	Description
May 1999	180123	Condenser Tube Plugs Leaking: • 14 rubber plugs found leaking. • Assumed possibly over expanded or undersized. • Tube ID was not measured, ordered per spec sheet size.
April 2000	185766	FWH Plug and Break-away Plug Pieces Found in Reactor: • Mechanical expansion plug found was undersized (.500 vs. .520). • Break-away tips from plugs were not removed and came loose.
April 2001	191806	Mechanical Plug Expelled from CCW Heat Exchanger When Filling Shell: • Plug failed immediately after installation due to incorrect installation methods. • Lack of direction/guidance/training for contract mechanics.
May 2005	215926	Mechanical Plug Break-Away Pieces Found Loose in Feedwater Heater: • Similar pieces previously found in Steam Generator feed ring. • Maintenance procedure changed in 2002, did not address existing plugs.
May 2006	221496	Newly Installed Condenser Plug Leaks/Missing: • Plug not found, assumed cause of failure – lack of installation guidance and verification.
October 2007	228304	Heat Exchanger Tube Driven Past Tubesheet with Plug Installation: • Driving a poorly fitting tapered plug pushed the tube ¾" out of back tubesheet.
February 2008	228862	Manual Trip Due to Plug Leak on Vacuum Pump Seal Cooler: • Rubber plug failed due to corrosion of brass bolting in salt water.

Table 6-1 (continued)
Industry Experience – Tube Plugging Errors/Problems

Month/Year	INPO Report #*	Description
September 2009	239246	Steam Generator Tube Plugging Error: • Adjacent tube plugged in error in 2005 on one side (hot leg), found in 2009. • Inadequate verification of tube plugs.
May 2011	249142	Mechanical Plug Set in Lube Oil Heat Exchanger Past Tubesheet: • Instructions not provided to avoid setting plugs beyond rear face of tubesheet. • Thin tubesheets in small diameter low pressure exchangers. • Tube may fail and leak due to expansion past tubesheet.
January 2012	252527	Condenser Failed Plug Causes Downpower to 87% for Repair: • Fiber and brass plug found failed. • Utility concluded corrosion damaged plug installed in 1993. • Not suitable as permanent plug – plans to replace remaining.

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Table 6-2
Industry Experience – Tube Plug Failures

Month/Year	INPO Report #*	Description
September 2000	188546	Feedwater Heater Plug Ejection During Removal Causes Burn Injury: • Delayed work until cooled and built cage structure to restrain ejecting plugs. • Several tapered plugs found to expel with pressurized fluid behind them when removing for sleeving work.
March 2003	203570	Cracked Condenser Tube Plug: • Push in BUNA-N rubber plug failed after 6 months. • 24050 installed plugs since 1995, first failure. • Manufacturer defect with injection molding, debonding.
November 2003	207347	Rubber Plugs Dislodged in Condenser: • Found push-pull hollow core rubber plugs dislodged.
March 2004	209262	Condenser Plug Ejected – Safety Near Miss: • 4 Plugs protruding 1” from tubesheet, when removing the plug expelled from pressurized gas behind it, no water or steam was noted.

Table 6-2 (continued)
Industry Experience – Tube Plug Failures

Month/Year	INPO Report #*	Description
May 2005	216198	Missing Condenser Tube Plug: • Elastomer plugs failed from manufacturer defect in thermoplastic bolts used to compress rubber plugs.
January 2006	219043	Condenser Plugs and Stabilizing Bars in Loss of Condenser Vacuum Event: • Loss of Circulating Water resulted in blown rupture disks. • 3 plugs ejected (installed '91) out of 1026 total .
January 2007	223811	Multiple Condenser Plugs Expelled in Loss of Off-Site Power (LOOP): • Found 165 missing plugs, 17 leaking tubes 10 days after event in startup. • Unit 2 did not experience similar issue (no explanation). • Changing to higher pressure rated plugs. • 2004 LOOP lost 95 plugs and 1 leaking; response: PM to tighten each outage. • Added action to LOOP recovery to check condenser plugs.
March 2008	230653	Condenser Plugs Missing: • 8 of 34 temporary rubber plugs were missing. • Possible shelf-life age related, or lack of installation guidance/verification/training. • Replacing with pop-a-plugs.
April 2008	231700	Feedwater Heater Tube Plug and Stabilizer Cable Ejected with Injury: • Removing tapered plugs, plug ejected with stabilizer cable. • Changed to use remote tooling to complete work.
June 2008	229552	Feedwater Heater Tube Contaminants Foul Polishers After Piercing Tubes: • Oil contaminants from stabilizing cables were not cleaned from tubes unplugged and pierced to address plug ejection risk. Polisher resins damaged.
November 2010	246423	Condenser Tube Plugs Missing Delays Outage Startup 24 Hours: • Chemistry excursion due to missing plugs. • 7 plugs missing (elastomer), others needed retorque. • Previous similar occurrences resulted in change of plugs to different elastomer plug type, replaced after 2nd incident with new style elastomer plugs, now changing to high confidence plugs.

Table 6-2 (continued)
Industry Experience – Tube Plug Failures

Month/Year	INPO Report #*	Description
February 2011	299744	Condenser Plugs Ejected After Circ. Water Pump Trip Forcing Shutdown: • 87 Condenser plugs ejected and 3 dislodged after pump trip. • Chemistry excursion forced shutdown. • Replacing elastomer plugs.
November 2012	302143	Condenser Plug Missing Causes Startup Delay: • Rubber tubesheet plug missing, resulting in chemistry excursion.
November 2015	320527	HP Feedwater Heater Welded Tube Plug Failure: • Welded plug installed in 1978 was found missing when HP FWH was opened in response to a leak. • Plug was in a tubesheet hole without a tube. • Adjacent plug installed at same time was solid bar stock and not tapered. Without an interference fit in the tubesheet hole the plug could eject into the shell after the weld cracked.

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NRC Tube Plugging Violation Examples

NRC Inspection Report 50-315/01-04 & 50-316/01-04, dated March 2, 2001:

> *"One Non-Cited Violation of 10 CFR Part 50 Appendix B, Criterion III "Design Control" was identified, for failure to verify the impact of tube plugging on the heat exchanger design differential pressure limit in a calculation for all safety related heat exchangers."*
>
> *"…heat exchangers could be returned to service with excessive differential pressure…could cause internal structural component failure and loss of heat exchanger function."*
>
> *"…calculation…established acceptable design tube plugging limits for all safety related HXs…based on acceptable thermal performance. …lacked an evaluation of the impact on the design differential pressure caused by plugging tubes.*

NRC Inspection Report 05000395/2006008, dated July 27, 2006:

> *"A Green NCV of 10 CFR 50, Appendix B, Criterion III, Design Control, was identified for non-conservative acceptance criteria … the wall thickness criteria for tube pitting would allow full penetration to occur between tube inspections."*
>
> *"…the tube wall thickness acceptance criteria did not assure that through wall pitting would not develop before tubes were inspected and plugged. The acceptance criterion for tube plugging was 70% of through wall pitting…and had no formal basis. Two tubes were left in service with a measured through wall pitting of 69%. The mean growth rate was 63% in 3 cycles of operation, or 21% per cycle. With 10% margin for eddy current error added, the resulting degradation rate of 31% per cycle would not cause any tube left in service to exceed 100% through wall prior to the next inspection. The team determined this to be non-conservative, since it was based on the mean pitting value (some of the tubes which were removed and had the actual pit depth measured in excess of 90%); but it also allowed a potential for a full tube penetration at the end of the cycle. Although this condition would have not impacted the structural integrity of the heat exchanger; the through wall leak would allow the impurities from the service water to be transported to the clean shell side. Degradation of the shell side water quality could further exacerbate the ability of the heat exchanger to perform its safety related function."*
>
> *"10 CFR 50 Appendix B, Criterion III, Design Control, requires, in part, that measures shall be established to assure that applicable regulatory requirements and the design basis are correctly translated into procedures and instructions and includes the delineation of acceptance criteria for inspection and tests of safety systems and components. Contrary to the above, acceptance criteria for tube wall pitting did not assure that through wall pitting would not occur with potential to degrade the heat removal capability of the cooler."*



Figure 6-1
Over Extended Elastomer Plug



Figure 6-2
Plug Hardware Corrosion Damage



Figure 6-3
Failed Elastomer Plug



Figure 6-4
Inadequately Expanded Plug

7
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