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Repair of Pressure Equipment and Piping

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Article 312

Inspection and Repair of Shell and Tube Heat Exchangers

312-1 DESCRIPTION

This Article provides general good recommendations and requirements for the following repair techniques:

(a) determining the type of inspection technique to use for the inspection of the tubes and tube bundle of a shell and tube heat exchanger

(b) determining the type of inspection technique to use for the inspection of the tubesheet and the tube-to-tubesheet assembly of a shell and tube heat exchanger

(c) determining the type of inspection to use for the other pressure containing components of a shell and tube heat exchanger

(d) providing repair techniques for common mechanical failures of various components in a heat exchanger

312-2 LIMITATIONS

312-2.1 General

Part 1 of this Standard, "Scope, Organization, and Intent," contains additional requirements and limitations. This Article shall be used in conjunction with Part 1.

312-2.2 Exclusions

(a) This Article shall not be applied to heat exchangers constructed in accordance with ASME BPVC, Section VIII, Division 3.

(b) Heat exchangers other than shell and tube design are not included in the scope of this Article.

312-3 DESIGN

This section provides guidelines for consideration when determining repairs to components of heat exchangers. It may be necessary for the user to have completed an inspection of the components, consider previous damage experienced, or consider lessons learned in the operation of similar equipment prior to beginning design work.

312-3.1 Existing Conditions

Existing conditions are as follows:

- (a) the original design conditions and calculations.
- (b) ensuring that the design conditions, with an appropriate margin, correspond to the actual normal operating modes including startup, shutdown, and upset conditions.

(c) current operating parameters, i.e., pressures, temperatures, changes from normal to peaking service.

(d) determination if a pressure and/or temperature rerate is required.

(e) determination if there is a need for conducting failure analysis to reduce the potential for future damage. Reference also API 579/ASME FFS-1.

312-3.2 General

(a) Materials used for replacement components shall be of the same material type as the original component unless an engineering analysis is performed indicating the need to change the material due to the damage mechanism(s). This analysis shall account for new mechanisms introduced due to potential material interactions. When selecting the material to use, this analysis shall also consider the need to match strength, toughness, and P-number, and to meet the current toughness requirements of the applicable construction code.

(b) Replacement components shall be of equal or greater thickness unless an engineering analysis is performed indicating the need for a thickness less than the original component thickness.

(c) When considering the repair method for tubes and tube bundles, the user shall consider the impact on the efficiency and other operational characteristics of the heat exchanger due to the potential reduction of heat transfer area. Consultation with a heat transfer specialist may be necessary.

(d) The following additional factors should be considered:

(1) Determination of acceptable wall loss will depend on a number of factors that include

(-a) duration of current service run

(-b) time to the next planned outage

(-c) the criticality of the exchanger operation

(-d) damage mechanisms that the tubes are exposed to including the rate of corrosion

(-e) historical rate of failure and whether that rate has been increasing

(-f) potential for metallurgical upgrade

(-g) the potential consequence due to tube failure

(-h) equipment accessibility

(-i) the scope of the inspection work

(-j) the accuracy and effectiveness of the inspection method

(2) For heat exchangers deemed critical to the operation and/or process safety of the facility, the following should also be considered:

(-a) total replacement of the tube bundle when tubes inspected indicate a wall loss of 40% or more of the initial, nominal thickness

(-b) tube bundle replacement or individual tube replacement when tubes inspected indicate a wall loss of 20% to 40% of the initial, nominal thickness

312-3.3 Tubes and Tube Bundles

(a) Tubes and tube bundles should be assessed using the data obtained by inspection performed in accordance with [Mandatory Appendix 312-I](#) for the types of repairs to perform; plugging by welded, mechanical, or friction fit plugs, partial replacement of the tube bundle, or full replacement of the tube bundle.

(b) When considering the use of mechanical or friction fit plugs, the user should consider the impact on the efficiency and other operational characteristics of the heat exchanger due to the reduction of heat transfer area, especially for heat exchangers that are deemed as critical to the operation and/or process safety of the facility. Consultation with a heat transfer specialist may be necessary.

(c) Sleeves may be installed in tubes to line a region of tube damage or to restore tubes that have thinned. They are not typically used for protection of tube ends; see [para. 312-4.4](#) and (d) below.

(d) Ferrules may be installed in tubes for entrance erosion protection or for thermal protection of tube ends. They are not typically used for general tube damage; see [para. 312-4.3](#) and (c) above.

(e) For (c) and (d), one should consider the following:

(1) uniformity of contact between the sleeve or ferrule and tube, see [paras. 312-4.3\(b\)](#) and [312-4.4](#)

(2) possibility of crevice corrosion between the sleeve or ferrule and tube

(3) possibility of bulging the tube, which can make retubing difficult

(4) additional pressure drop

(5) reduction of tube fluid flow due to the sleeve or ferrule

(6) additional heat transfer resistance

(7) differential radial and axial thermal expansion between sleeve or ferrule and tube

(f) The tube bundle supports should be assessed using the data obtained by inspection performed in accordance with [Mandatory Appendix 312-I](#). If data indicates that failure of tubes is due to damaged support plates, consideration should be given to replacing with alternative designs. Specific items to consider include the following:

(1) The corrosion allowance provided for the support plate should be twice the value for the shell side due to the potential for the plates to corrode at the regions where the tubes penetrate the supports and lead to tube vibration induced issues. If zero, consid-

eration should be given to assigning a nominal value of 3 mm ($\frac{1}{8}$ in.).

(2) Consideration should be given to use of alloy support plates/baffles instead of thicker carbon steel; however, harder material may result in more damage to the tubes rather than the support plates/baffles. Also, the effects of differential thermal expansion should be considered. Consultation with a materials/corrosions specialist may also be necessary.

(3) The spacing between the support plates should be evaluated and adjusted if analysis indicates potential vibration of tubes resulting in damaged tubes and/or support plates. Evaluation per TEMA RCB Section 5 and Section 6 should be considered. Consultation with a heat transfer specialist may also be necessary.

(4) Tube stakes are rods, strips, or other devices inserted between tubes for bracing and/or support. They may be used to add tube support to an existing bundle for the purpose of eliminating tube vibration. Installation requires access from the shell side, and the main advantage is that disassembly of the tube bundle is not required. Special consideration may be necessary for the use of stakes in U-tube bends because some stake designs require that the tubes be round and evenly spaced.

Tube stakes were developed for use when a change in tube material or an increased flow rate requires additional tube supports, and increasing the number of support plates is not possible or desirable. They can be used any time additional tube support is required such as to provide additional support for deteriorated or damaged support plates, to provide additional support between segmented baffles, or to provide additional support at inlet nozzles. If tube stakes are fabricated from flat bar and inserted in every other tube row, it may be necessary to vary the bar thickness such that each tube is contacted or even displaced from its original position.

Evaluation of the shell-side pressure drop, and changes in shell-side flow are necessary. The compatibility of tube and stake materials should be evaluated. Also, the effects of differential thermal expansion should be considered.

(g) If impingement protection is required to prevent flow-induced erosion, refer to applicable standards such as API Standard 660, TEMA, and HEI for design requirements.

312-3.4 Tubesheet

(a) Material used to replace a tubesheet shall be of the same or greater allowable stress as used for the original component.

(b) If an engineering analysis indicates tube replacement of a larger diameter is required, additional analysis on the tubesheet shall be performed to determine if the ligament efficiency is acceptable. The analysis shall meet the original construction code, or if this is not known, the

analysis shall meet the requirements of ASME BPVC, Section VIII, Division 1.

(c) Tubesheets should be assessed using the data obtained by inspection performed by a method listed in [Mandatory Appendix 312-II](#) for determination of repair or replacement of the tubesheet. Common conditions for consideration include

(1) cracking (not through the total thickness) of tubesheet on shell side; more typical in vertical units. Installation of a tubesheet vent and drain should be considered to promote liquid full operation. The vent should be a 19 mm ($\frac{3}{4}$ in.) nozzle welded to the edge of the tubesheet, with a 16 mm ($\frac{5}{8}$ in.) hole in the tubesheet that is parallel to the tubes to the midsection of the tubesheet, then normal to the tubes to the edge of the tubesheet. A gate or ball valve should be installed on the nozzle along with a blind flange or plug.

(2) separation of weld overlay cladding resulting from wire drawing of high-pressure tubeside fluid leaking through tube-to-tubesheet joints.

(3) cracking in the ligament of the tubesheet. A failure analysis should be performed to determine the damage mechanism. The decision to repair versus replace the tubesheet should be based on the damage mechanism along with the extent of the ligament cracking.

(4) corrosion of the tubesheet can occur on the backside (shell side) of the tubesheet. When the corrosion allowance on the backside has been consumed, the tubesheet should either be replaced or an engineering evaluation performed to determine its fitness for service.

(5) corrosion of the tubesheet can occur on the front face (tube side) of the tubesheet. When the corrosion allowance on the face has been consumed, the tubesheet should either be replaced or an engineering evaluation performed to determine its fitness for service. Alternatively, the face of the tubesheet may be repaired by weld buildup that is conditioned by grinding or other mechanical means such that it is returned to the original thickness of the tubesheet. Factors to consider when pursuing this option include

(-a) minimum distance between the front face of the tubesheet and the groove for tube-to-tubesheet joints

(-b) the need for welding, strength or seal, of the tube-to-tubesheet joint and the need for setback from the front face

312-3.5 Tube-to-Tubesheet Joints

Tube-to-tubesheet joints should be assessed using the data obtained by inspection performed by one of the methods listed in [para. 312-5.3](#) for determination of repair type. Repair types for leaking joints include

(a) replacement of a damaged tube, see [para. 312-4.6](#).

(b) plugging a tube, see [para. 312-4.2](#).

(c) removing the tube and performing weld buildup of the tube hole and then remachining the tube hole to the original tube hole diameter. Design of the mechanical joint

should be made to the original construction code or applicable post-construction code, or to ASME BPVC, Section VIII, Division 1, Nonmandatory Appendix A. Caution must be exercised to avoid damage to adjacent tubes.

(d) seal welding or strength welding of the joint. Design of the welded joint, if previously welded, should be made to the original construction code or applicable post-construction code, or to ASME BPVC, Section VIII, Division 1, Nonmandatory Appendix A. Consideration should be given to the cleanliness of the joint considering potential residue from the fluids.

(e) consideration shall also be given to the effect of style of heat exchanger on loading of the tube-to-tubesheet joint. For example, a fixed tube exchanger may have higher loadings due to differential thermal expansion than a U-tube exchanger.

312-3.6 Bimetallic Shell-to-Tubesheet Welds

When the shell and tubesheet are made of different materials, the thermal stress between the shell and tubesheet should be considered. A common solution to cracking of this weld is to change the shell material to match the tubesheet. An entire shell may be replaced, or bands or shell material may be installed adjacent to the tubesheet. Reevaluation of the heat exchanger mechanical design due to the change in thermal expansion or strength of the shell may be required.

312-3.7 Shell, Channel, or Other Pressure-Retaining Components

(a) Materials used to replace or repair pressure-retaining portions of a shell or channel shall be of the same allowable stress as the original component, unless additional analysis is performed to justify changing the material.

(b) Replacement of these or other pressure-retaining components shall comply with the applicable construction code. For additional guidance on replacement, see [Article 301](#).

(c) Non-pressure-retaining portions of components shall meet the original construction code or applicable post-construction code.

(d) Additional guidance on pass-partition plates may be found in API Standard 660.

312-4 FABRICATION

312-4.1 General Considerations

(a) When multiple heat exchangers are in use in a parallel configuration, consideration should be given to the flow requirements for each exchanger. Experience has shown that a single heat exchanger removed from service can result in higher flows to the other heat exchanger(s) that may cause damage from erosion, tube bundle vibrations, or other mechanical damage.

Figure 312-4.2-1
Typical Friction Fit Tapered Tube Plug



(b) Prior to repairs and to increase accuracy of inspection, the tubes should be evaluated for the need to be cleaned. Cleaning may be performed by high pressure water blasting, chemical solutions, or abrasive blasting/scrubbing. Selection of a cleaning methodology shall give consideration to the nature of fouling, tube material type, and tube enhancements.

(1) High pressure water blasting is normally performed at 70 MPa (10,000 psi). In some cases, ultra-high pressure water blasting may be necessary at pressures up to 275 MPa (40,000 psi). Other factors essential to removal of deposits include water flow rate and the spray tip configuration.

(2) When cleaning with chemical solutions, a materials engineer should be consulted to ensure no detrimental effects occur to the tubes and/or shell of the heat exchanger. For example, a caustic solution should not be used in 300 series stainless steel tubes.

(3) When performing abrasive blasting/scrubbing, care shall be exercised to ensure no adverse damage to the tubes occurs. Deterioration of heat transfer capability shall be considered when cleaning tubes with internal components designed to enhance heat transfer by increasing turbulence through the tubes.

(c) Inspection of the tubes periodically during the cleaning process should be made to ensure consistent results. Use of a boroscope may improve inspection results.

(d) When a tube bundle must be removed from its shell for purposes of inspection or repair, caution should be exercised to avoid damage to the tubes or other components.

(e) When it is known that a tube or multiple tubes are leaking, consideration shall be given to pulling a tube for failure analysis to aid in determination of the damage mechanism.

(f) All welded repairs shall be made using qualified welding procedures. Welders and welding operators shall be qualified in accordance with the requirements of the applicable construction code or post-construction code. Welding procedure qualifications shall include impact tests if required by the applicable construction code for the component being repaired.

(g) Welding materials and processes shall be as currently permitted by the applicable construction code or post-construction code for the component. Welding of carbon and low alloy steels should be performed with low hydrogen electrodes and processes.

312-4.2 Tubeside Repair by Plugging

Repair of tubes may be accomplished by plugging the tube at the tubesheet with a welded or mechanical attachment.

(a) All tubes that are plugged should be pierced to provide for venting and draining. When doing so, vertical tubes should be pierced at each end, and horizontal tubes should be pierced on top and bottom of the tube. Piercing of each tube prevents possible plug blowout and permits the validation of the integrity of the tube plug, see (b)(4). Large temperature differential between tubeside and shell side may require the tube to be cut in two.

(b) Friction fit tapered plugs (Figure 312-4.2-1) shall 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 1.5 MPa (200 psi) or less.

(2) shell-side operating temperature 205°C (400°F) or less.

(3) tube-to-tubesheet joints are expanded and not welded.

NOTE: Inspection of the expanded tube for tube thinning should be made to ensure that installation of the plug does not further damage the tube leading to seal failure between the plug and the tubes.

(4) tapered plugs that are installed where tubes are not pierced can present a serious safety hazard. If the tube cannot be pierced, the tube should be pulled or other measures should be taken to ensure personnel protection, such as welding the plug to the tubesheet and draining all liquids from the tube being plugged.

(c) Mechanical plugs (Figure 312-4.2-2) should be considered in situations where friction fit tapered plugs are not appropriate for the pressure and/or temperature of service or other mechanical/environmental conditions. These types of plugs have been used in services of up to 50 MPa (7,000 psi) and 595°C

Figure 312-4.2-2
Typical Mechanical Fit Tube Plugs



(1,100°F). Mechanical plugs are typically installed by a pneumatic or hydraulic system. See [Figure 312-4.2-3](#). Other styles of plugs may be considered for higher pressures. Consideration shall also be given to the following:

(1) tubes with internal surface severely corroded or cracked

(2) when the tube and the plug have dissimilar metallurgy

(3) installation in severely corrosive service

(4) condition of the mechanical joint of the tube-to-tubesheet in rolled tube situations

(d) A plug map should be developed to record the number and location of tubes that have been plugged. Additionally, the number of tubes, cumulative number of tubes versus the duration, should be charted. When the sharp turn in tube failure numbers occurs, replacement of the tube bundle should be considered. See [Figure 312-4.2-4](#) for example chart.

(e) Tracking of pressure loss due to tube pluggage should be considered as some exchanger types cannot function properly beyond certain tubeside pressure losses. Provisions for internal bypass should be considered if repair is not performed in order to prevent failure of pass partitions. Proper design of this bypass can be determined from industry references in [section 312-7](#) of this Article.

Figure 312-4.2-3
Typical Installation of Mechanical Fit Tube Plugs



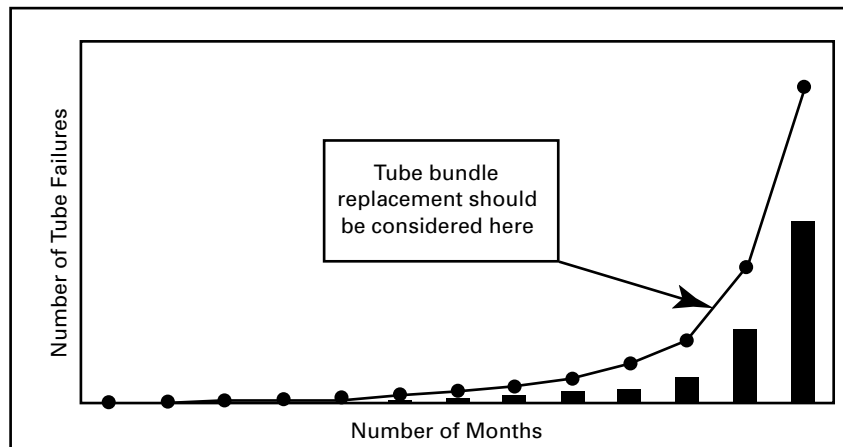
GENERAL NOTE: ©2006 Photo courtesy of EST Group Inc., used with permission.

312-4.3 Tubeside Repair by Sleeving Tubes

(a) Sleeving versus tube replacement may be advantageous when repairing previously plugged tubes because of perforations in discreet identifiable locations, or to bridge failures in discreet locations of tubes that are otherwise intact.

(b) The methods of sleeve installation include the following: forcing a ball through the sleeve, welding the ends of the sleeve, roller expansion of the sleeve, explosive bonding of the sleeve and hydraulic expansion of the sleeve. One should consider the possibility of bulging

Figure 312-4.2-4
Sample Chart: Number of Tube Failures by Month



the tube, which can make retubing difficult. A mock-up may be advisable to ensure weld or expansion quality.

(c) A map should be developed to record the number and location of tubes that have been sleeved. Additionally, the number of tubes, cumulative number of tubes versus the service time should be charted. If a sharp increase in tube failures occurs, replacement of the tube bundle should be considered. See Figure 312-4.2-4 for example chart.

312-4.4 Tubeside Repair by Ferrule Installation

Ferrules may be held in place by a flanged end with a tight fit to the tube inside diameter, by expanding the ends of the ferrule into the tube at the tubesheet, or by welding. Uniform contact with the tube may be achieved by roller or hydraulic expansion of the ferrule. One should consider the possibility of bulging the tube, which can make retubing difficult. A mock-up may be advisable to ensure weld or expansion quality.

312-4.5 Tubeside Repair by Pulling Tubes

(a) Pulling the tube from the exchanger and plugging the tubesheet as described in para. 312-4.2 should be considered as a repair option when plugging is not a viable alternative, or when the tube will be retained for laboratory metallurgical analysis or other specific examination.

(b) When pulling a tube and not replacing, potential damage to the baffle could occur and consideration to replacing the tube should be made. Consultation with a heat transfer specialist may also be necessary.

312-4.6 Tubeside Repair by Replacement

Repair may be performed by tube replacement, which may be accomplished in one of the following methods:

(a) replacing individual tubes, which may include repair/refurbishing of the tubesheet in the area of the subject tube.

(b) replacement of the entire tube bundle. See para. 312-3.2(c).

312-4.7 Tubesheet Repair

312-4.7.1 Weld Repair of Cracks

(a) Repair of general cracks that are not completely through the thickness of the tubesheet and are not in the ligaments may be made in accordance with the guidelines of Article 304.

(b) Repair of general cracks that are through the thickness of the tubesheet and not in the ligaments may be repaired by preparing a U- or V-shaped groove to the full depth and length of the crack and then filling the groove with weld metal in accordance with paras. 312-4.7.1 and 312-4.7.2.

(c) Repair of cracks in the ligament area of the tubesheet may be made in accordance with (a) or (b) above. Consideration may also be given to performing an engineering analysis to determine if the equipment may continue to operate with the damaged tubesheet. This analysis may be performed in accordance with API 579-1/ASME FFS-1 or other post-construction standard.

(d) When making tubesheet repairs, consideration should be given to the impact of this repair on the tubes in the general area of the repair. The following actions may be necessary:

(1) removal of tubes in the general area of the repair. See para. 312-4.5(b).

(2) repair of the tube-to-tubesheet joints.

312-4.7.2 Face Repair by Overlay and Machining

(a) General and localized thinning of tubesheets may be repaired by overlay welding and remachining of the face.

(b) See [Article 202](#) for additional items of consideration.

312-4.8 Tube-to-Tubesheet Joint Repair

312-4.8.1 Re-Expanding

(a) Cleaning and inspection shall be performed to determine the condition of the tube-to-tubesheet joint prior to performing this type of repair. See [para. 312-4.1](#).

(b) Tube-to-tubesheet joints with leaks of a small flow rate, otherwise known as weeping tubes, where no apparent damage has occurred to the seating surfaces, may be re-expanded to obtain an acceptable mechanical fit of tube to tubesheet. Rerolling is one acceptable method of re-expanding.

(c) Prior to re-expanding, the existing inside diameter of the tube in the tubesheet shall be determined as well as the loss of material due to corrosion/erosion. Calculations for allowable maximum inside diameter shall be based on measured field conditions, tube properties, and tubesheet ligament condition.

(d) See ASME BPVC, Section VIII, Division 1, Nonmandatory Appendix HH for additional considerations.

312-4.8.2 Weld Buildup Repair of Tube Holes and Machining

(a) When a tube is replaced and the tube hole has been damaged, repair may be effected by weld buildup and machining of the hole.

(b) All welded tube hole repairs shall be made using qualified welding procedures. Welders and welding operators shall be qualified in accordance with the requirements of the applicable construction code or post-construction code. Welding procedure qualifications shall include impact tests if required by the applicable construction code for the tubesheet.

(c) Welding materials and processes shall be as currently permitted by the applicable construction code or post-construction code for the tubesheet. Welding of carbon and low alloy steels should be performed with low hydrogen electrodes and processes.

(d) Machining of the hole shall be to original manufacturer's specifications for diameter and grooving.

312-4.8.3 Seal Welding or Strength Welding

(a) Tube-to-tubesheet welds shall be in accordance with the applicable construction code or post-construction code.

(b) If seal welds are to be made, consideration shall be given to the mechanical tube-to-tubesheet joint to ensure its strength. If seal welds are determined to be inadequate,

the weld shall be full strength to ensure the integrity of the joint.

(c) All welds shall be made using qualified welding procedures. Welders and welding operators shall be qualified in accordance with the requirements of the applicable construction code or post-construction code. Welding procedure qualifications shall include impact tests as required by the applicable construction code for the tubesheet.

(d) Welding materials and processes shall be as currently permitted by the applicable construction code or post-construction code for the tubesheet. Welding of carbon and low alloy steels should be performed with low hydrogen electrodes and processes.

312-4.9 Repair of Pressure Containment Components

Repairs to the heat exchanger shell may be performed to the original construction code or applicable post-construction code. See also [Article 201](#) and [Article 202](#).

312-5 EXAMINATION

Examination of heat exchangers typically covers three areas; external, internal, and tube bundle. It is not necessary for each inspection to have the same frequency.

312-5.1 Examination of Tubes and Tube Bundle

It is important for the proper examination technique to be selected for the application at hand. The following non-destructive examination (NDE) techniques should be considered for the given application. See also [Table 312-I-1.3-1](#) for effectiveness of examination methods. Other examination methods may be chosen by the owner/operator, as follows:

(a) Eddy Current Examination (ET) is generally selected for inspection of nonferromagnetic tubes, or those that are slightly magnetic. Note that the sensitivity of this method decreases for the U-bend portion of U-tube bundles.

(b) Remote Field Eddy Current (RFET) is generally used for inspection of ferromagnetic tubes. Its sensitivity and accuracy may be less than desired or required and will require a higher number of tubes to be inspected. It is a quicker method than ultrasonic methods.

(c) Partial Saturation Eddy Current (PSET) can locate and size cracks in ferromagnetic tubes. It might not be sensitive to O.D. defects.

(d) Magnetic Flux Leakage (MFL) may also be selected for inspection of ferromagnetic tubes. However, sensitivity of this method can be poor for carbon steel tubes, and might only be best at determining the overall condition of the tube, not determining individual defect location.

(e) Ultrasonic examination systems designed to measure tube wall thickness may be used for small heat exchangers, where damage may be localized, or for validation of other NDE results. These ultrasonic examination systems are particularly suited for carbon steel tubes due to the lack of sensitivity of other NDE methods. One type of system is the Internal Rotary Ultrasonic Inspection (IRIS) system. IRIS is an accurate NDE method for detecting and sizing I.D. and O.D. metal loss in tubes. Another type of system is Shear Wave IRIS (SWIRIS) and this can be effective for detecting I.D. and O.D. cracks. Both IRIS and SWIRIS require clean tubes.

(f) Other NDE methods may be more appropriate for the inspection. Consideration should be given to the use of radiography (RT) or video probe inspection. These methods may be better suited for inspection of the U-bend portion of U-tube bundles.

(g) Consideration should be given to the monitoring and trending of tube condition as part of a predictive maintenance and/or replacement program.

(h) The minimum number of tubes to be inspected may be determined by the methods provided in [Mandatory Appendix 312-I](#).

312-5.2 Examination of Tube-to-Tubesheet Repair

Repairs shall be examined by one or more of the following methods:

(a) pressure or leak testing on the shell side; see [section 312-6](#)

(b) liquid penetrant examination (PT) in accordance with the applicable construction code or post-construction code

(c) visual examination (VT) in accordance with ASME BPVC, Section V, Article 9

312-5.3 Examination of Tubesheet Repair

(a) VT in-process weld examination shall be performed.

(b) Surface examination by PT shall be performed at the completion of the weld repair.

(c) Volumetric examination by UT should be considered when there is a possibility of additional flaws being introduced to the tubesheet during the repair.

312-5.4 Examination of Pressure Containment Components Repairs

(a) All welded repairs should receive VT and PT or MT examination, especially for heat exchangers deemed critical to the operation and/or process safety of the facility.

(b) Where possible, welded repairs shall receive volumetric examination by RT or UT.

312-6 TESTING

Following completion of the inspection, a pressure test or tightness test in accordance with [Article 501](#) should be considered, particularly if the integrity of the tube-to-tubesheet joint is in question.

312-7 REFERENCES

(22)

The following is a list of publications referenced in this Article. Unless otherwise specified, the latest edition shall apply.

API 579-1/ASME FFS-1, Fitness-For-Service, 2nd Edition, 2007

API Standard 660, Shell and Tube Heat Exchangers for General Refinery Services, 2003 Edition

Publisher: American Petroleum Institute (API), 200 Massachusetts Avenue NW, Suite 1100, Washington, DC 20001-5571 (www.api.org)

ASME Boiler and Pressure Vessel Code, 2007 Edition, Section V — Nondestructive Examination

ASME Boiler and Pressure Vessel Code, 2007 Edition, Section VIII, Division 1 — Rules for Construction of Pressure Vessels

ASME PCC-3, Inspection Planning Using Risk Based Methods

Wang, W. David, Ph.D., "Extreme Value Analysis of Heat Exchanger Tube Inspection Data," Proceedings of PVP2006-ICPVT-11, 2006, ASME Pressure Vessels and Piping Division Conference July 2006

Publisher: The American Society of Mechanical Engineers (ASME), Two Park Avenue, New York, NY 10016-5990 (www.asme.org)

ASTM E2283-03, Standard Practice for Extreme Value Analysis of Nonmetallic Inclusions in Steel and Other Microstructural Features

Publisher: American Society for Testing and Materials (ASTM International), 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959 (www.astm.org)

Standards for Closed Feedwater Heater, 7th Edition, 2004
Standards for Power Plant Heat Exchangers, 4th Edition, 2004

Publisher: Heat Exchange Institute, Inc. (HEI), 1300 Sumner Avenue, Cleveland, OH 44115 (www.heatexchange.org)

Standards of the Tubular Exchanger Manufacturers Association, 8th Edition

Publisher: Tubular Exchanger Manufacturers Association, Inc. (TEMA), 25 North Broadway, Tarrytown, NY 10591 (www.tema.org)

Wolf, Gerald M. and Adams, Robert B., An Improved Plugging System for HX Tubing, EPRI BPO Conference paper, June 1996

Publisher: Electric Power Research Institute (EPRI), 3420 Hillview Avenue, Palo Alto, CA 94304 (www.epri.com)

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Mandatory Appendix 312-I

Methods for Determining Minimum Number of Tubes to Inspect

312-I-1 Introduction

This Mandatory Appendix provides general good recommendations and requirements for determining the number of tubes to inspect by different methods. The user may select any method, and may also deviate from the recommendations and requirements of each method based on the requirements of the heat exchanger.

312-I-1.1 Fixed Tube Count

The following minimum number of tubes inspected should be considered:

- (a) 50 tubes or 25% of tube total, whichever is greater, for heat exchangers with a total tube count of less than 500 tubes
- (b) 20% of tube total for heat exchangers with a total tube count of 500 tubes or more, up to 750 tubes
- (c) 15% of tube total for heat exchangers with a total tube count of 750 tubes or more, up to 1,000 tubes
- (d) 10% of tube total for heat exchangers with a total tube count of more than 1,000 tubes

312-I-1.2 Tube Bundle

The following areas of the tube bundle should be examined at a minimum:

- (a) the first three rows adjacent to the inlet nozzle and the last two rows adjacent to the exit nozzle.
- (b) every second tube around the perimeter of the bundle. For multipass heat exchangers, the perimeter of each pass shall be included.
- (c) a selection of tubes in the interior section of the bundle.
- (d) areas with a history of active damage mechanisms.
- (e) areas that have not previously been examined.
- (f) failure of 10% of the tubes examined shall require an additional 10% of tubes to be examined in the examined area, as per (a) through (e).

312-I-1.3 Use of Inspection Planning

(a) An inspection planning program may be implemented to determine the number of tubes to inspect and the frequency at which the tubes shall be inspected.

(b) Program implementation guidelines are provided in ASME PCC-3. The following factors should be considered:

- (1) inspection effectiveness required, see [Table 312-I-1.3-1](#) for various effectiveness and the associated methods of inspection.
- (2) maximum inspection interval permitted.
- (3) type of inspection required for the suspected damage mechanism. See [Table 312-I-1.3-1](#) for additional details.
- (c) See [para. 312-5.1](#) for inspection methods.

312-I-1.4 Use of Extreme Value Analysis (EVA)

(a) Use of EVA makes it possible to accurately assess the remaining life of large numbers of tubes using relatively minimal data.

(b) EVA assessment is based on ASTM E 2283, "Standard Practice for Extreme Value Analysis of Nonmetallic Inclusions in Steel and Other Microstructural Features."

(c) Use of EVA to assess the maximum wall loss data has been described in conference publications; see [Table 312-I-1.3-1](#), Note (4).

(d) The EVA method and results may be incorporated into an inspection planning assessment.

(e) With smaller sample sizes, ideally 20 to 30 tubes regardless of the number of tubes in the exchanger, the appropriate inspection effectiveness may be achieved by using the lower bound value of 99%, 95%, 90%, and 80% confidence intervals.

**Table 312-I-1.3-1
Inspection Effectiveness Table**

(22)

Inspection Effectiveness Category	Damage to Consider	Inspection Method	Number of Ferromagnetic Tubes by Intrusive Inspection Methods	Number of Nonferromagnetic Tubes by Intrusive Inspection Methods	Number of Tubes by Nonintrusive Inspection Methods
Highly effective	Wall loss [excluding MIC]	IRIS	80% to 100%	80% to 100%	Not applicable
	...	IRIS and EVA 99% CI as lower bound	20 to 30	20 to 30	...
	...	RFET or MFL	100% and pull 2 worst tubes for lab analysis	Not applicable	...
	...	ET	Not applicable	100%	...
	Cracking	SWIRIS	100%	Not applicable	...
	Cracking or MIC	ET	Not applicable	100%	...
Usually effective	Wall loss or localized and general corrosion (excluding MIC)	IRIS	60% to 80%	60% to 80%	Profile RT 50% at 0 deg and 90 deg
	...	IRIS and EVA 95% CI as lower bound	20 to 30	20 to 30	...
	...	RFET or MFL	100% and use IRIS on 2 worst tubes	Not applicable	...
	PSET	90%	Not applicable	...	...
	...	ET	Not applicable	80%	...
	Cracking	SWIRIS	80%	Not applicable	...
	...	PSET	100%	Not applicable	...
	Cracking or MIC	ET	Not applicable	80%	...
Fairly effective	Wall loss (excluding MIC)	IRIS	40% to 60%	40% to 60%	Not applicable
	...	IRIS and EVA 90% CI as lower bound	20 to 30	20 to 30	...
	...	RFET or MFL	80% and use IRIS on 2 worst tubes	Not applicable	...
	PSET	70%	Not applicable	...	...
	...	ET	Not applicable	60%	...
	Cracking	SWIRIS	60%	Not applicable	...
	...	PSET	80%	Not applicable	...
	...	RFET or MFL	100%	...	...
	Cracking or MIC	ET	Not applicable	50%	...
Poorly effective	Wall loss (excluding MIC)	IRIS	20% to 40%	20% to 40%	Not applicable
	...	IRIS and EVA 80% CI as lower bound	20 to 30	20 to 30	...
	...	RFET or MFL	60% and use IRIS on 2 worst tubes	Not applicable	...
	PSET	50%	Not applicable	...	...
	...	ET	Not applicable	40%	...
	Cracking	SWIRIS	40%	Not applicable	...
	...	PSET	60%	Not applicable	...
	...	RFET or MFL	80%	...	...
	Cracking or MIC	ET	Not applicable	30%	...

Table 312-I-1.3-1
Inspection Effectiveness Table (Cont'd)

GENERAL NOTE:

- ET = eddy current testing
- EVA = extreme value analysis
- IRIS = internal rotary inspection system
- MFL = magnetic flux leakage
- MIC = microbiologically induced corrosion
- RFET = remote field eddy current
- PSET = partial saturation eddy current
- SWIRIS = shear wave internal rotary inspection system

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