SAUDI ARAMCO NDT METHODS APPLICATION ON HEAT EXCHANGERS

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ABSTRACT:

Inspection Nondestructive Testing (NDT) techniques are vital to determine the continuity of Heat Exchanger operation in plants, there are a wide ranges of NDT selection that may vary slightly from one manufacturer to other in stages of heat exchangers fabrication, and even more selection of NDT methods once it comes in repairing heat exchanger. Saudi Aramco Heat Exchanger Shops is receiving with an averaged 289 units/year and intensively depends on NDT techniques to accept the provided services. This paper will describe Nondestructive Testing (NDT) applications for Saudi Aramco Heat Exchangers and how to choose between various NDT and addresses the advantages through success cases and strategic partnership to maintain reliable services.

INTRODUCTION

Inspection is done to determine metallurgical structure, mechanical properties and corrosion resistance of used material in manufacturing Heat Exchanger. These materials should be suitable for the operating conditions for the operating condition they will be subjected to during their service life. It should be possible to subject these materials to the various fabrication processes, such as bending, welding or forming and without improperly impairing the material properties, in which inspection or testing helps determining that the material being used as designed parameters.

Saying that, the two main types for testing are either to destroy the material (Destructive) or not destroying the material as Nondestructive Testing. Taking in to consideration, there are cases required to conduct destructive testing when Nondestructive Testing fail. There are several types of nondestructive testing, the ASME code Section V and section VIII (American society of Mechanical engineers) specifies basic techniques; Radiographic examination, Ultrasonic examination, liquid penetrant examination, magnetic particle examination, eddy current examination, visual examination and leak/hydrostatic/pneumatic testing.

In the field of heat exchangers whether it is manufactured or repaired, inspection side will certainly use one or more of above NDT method, these are very important activities to helps in locating the faults on material surface or subsurface; such as discontinuities, changes in thickness, nicks, or even in welding joints of slag entrapment, porosity, cracks, lack of penetration, under cutting,,etc. below are illustrations of some damaged and likely location of corrosion on heat exchangers components.
Figure 1: Tube Pitting

Figure 2: Erosion-Corrosion Attack at Tube Ends

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Figure 4: severe corrosion in Air cooled HE Frame and partition plate

Figure 5: excessive clearance between baffle and tubes from accelerated corrosion cause mechanical damage and vibration

Figure 6: Graphitic corrosion & a 6 o’clock crack on tube and thinning at tube wall by erosion at tuber inner
Figure 7: Fouling with and corrosion beneath marine growth

Figure 8: Tube Sheet Corroded Beneath Marine Growth

Figure 9: Internal Corrosion in a Pressure Vessel

Figure 10: Hydrogen Blistering

Figure 11: Erosion in a U-Bend tube

HEAT EXCHANGER REPAIR PROCESS

The heat exchanger vessel is imperative to plant operation in Petroleum Industries Operations, to some extent in shutdown, the plant’s operation turn to potential loss or even to some Plant to actual loss, where it is a role to Saudi Aramco Heat Exchanger Shop to exert all its resources to provide reliable, cost effective, and timely services.

Maintaining heat exchanger(s) can be cost effective if it is planned ahead by forecasting the required material and proper scope of work, and determine inspection plan to meet the
deadlines. Inspection agency plays role to return the heat exchanger back to services or maintenance cost raise questions such as, Shall we go for replacing individual tubes, Shall we partially retube or Shall we fully retubes?,

Shop maintenance process is falls under key steps of starting with,

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These steps determine the lead time to complete the repair for any vessel(s), in which shop practices requires to exploit any task helps to improve the turnaround time. The following are major NDT methods and practices that demonstrates inspection technique.

Photos 1 & 2
Receiving Heat Exchanger and Removing Tube Bundle

Photos 3 & 4
Dismantling the Heat Exchanger and Steam Cleaning Tubebundle

Photos 5 & 6
Fabricating Tubesheet and Welding Damaged Header Thread
Photos 7 & 8
Tube-to-Tubesheet Joint by Seal Welded & Expanded

Photos 9
Hydrotesting of Repaired Heat Exchanger

RADIOGRAPHIC EXAMINATION

This NDT method is used to examine the welded joint in the metal using Radiation source (most frequently of iridium). The radiation source is placed on one side while the film is placed in holder on the other side of the weld to be examined as showing on Figure 12.

Figure 12: X-Ray Radiography, single wall, No Reinforcement, Side And Top Views Of Hole-Type IQI Placements

The examination is used for heat exchanger designed to contain lethal substance, operating at high pressure, or heat exchanger that made out of thick plates (38 mm or above), or heat exchanger that required to have a minimum thickness by increase welded joint efficiency, This can be demonstrated in such as, to determine for instance the vessel that has MAWP(Maximum Allowable Working Pressure) of design pressure 370 psig, E=1, Material of construction ASTM515Gr70, Corrosion Allowance 3 mm, and shell diameter 1200 mm. to use the following formula

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Figure 13: detection ultrasound through transmission, A Scan and B Scan
One of area that Saudi Aramco Heat Exchanger shop benefit’s for using this method is to meet Seams’ weld requirement in which was cut, rewelded and inspected using Phase Array testing NDT method (Phased arrays consist of number of ultrasonic elements arranged in a single instrument. The multiple elements are used to create an ultrasonic beam. The beam can be “steered” to optimize the orientation of the beam to the object being studied, which increase the probability of detection of flaws), phased array technique was used instead of X-ray for post welded of tubesheet/shell joint without removing the newly inserted tubes out from the shell. The outcome of achieving these tasks had added value to safety for avoiding the radiation source out of using RT as well as reducing the turnaround time.

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conductive base materials, the depth of penetration restricts testing to depths of less than ¼ in in most cases. The presence of strong magnetic fields will cause erroneous readings, in which required to training for interpretations of visual defects and indications.

Figure 16: Using Eddy Current for inspection Incoloy Tube

**PENETRANT EXAMINATION**

This method is widely used in industry and classified in either using Dye or Fluorescent; for penetrant inspection (dye) for locating surface defects, where a liquid dye penetrant is applied to a dry clean surface and allowed to soak long enough to penetrate only surface defects. After a time internal of up to 1 hour, the excess penetrant is wiped off or cleaned with a cleaner and a thin coating of developer is applied. The penetrant entrapped in defect will be drawn to the surface by developer, and the defect will be indicated by the contrast between the color of the penetrant and that of the developer, as far for Penetrant inspection in Florescent, which is using for locating defects that run through the surface, in penetrant to be applied by sparing, dripping, or brushing. The excess penetrant is washed from surface with a water spray or other appropriate solution to allow the surface then to dry. Dry powder or water-suspension developer is applied to part to draw penetrant to surface. Penetrant glows under black (ultraviolet) light. For leak test, penetrant is applied to one side, and the other side is examined under black light indications of glow.

The advantage of Fluorescent Penetrant Inspection is easy to perform, defects show clearly under black light. The limitation however in Penetrant inspection, it is only detect the defects that are open to the surface, in which add another cons which is not practical on rough surfaces. And for fluorescent, the black light requires a source of electricity, and applied only for nonmagnetic material, and not very effective as lead test for plates more than ¼ inch thick.
Figure 17: Penetrant inspection application in heat exchanger tubesheet and headers after weld buildup repair.

MAGNETIC PARTICLE EXAMINATION

This method Magnetic particle (MT) is for locating surface and sub-surface defects that are not too deep. The technique employs either electric coils wound around the part or prods to create a magnetic field. A magnetic powder applied to the surface will show up defects as local magnetic fields. The nature of the defects will be revealed by the way the powder is attracted. The advantages of using MT is useful for the inspection of nozzle and manhole welds for which radiography would be difficult at best and most impossible, the vantage to detect small surface defects especially once weld repair took place in defects. MT can also use to detect laminations at plate edges.

The limitation of MT is used only for magnetic material. It is also not suitable for detects parallel to magnetic field.

Figure 18: yoke technique of Magnetic particle (MT)
VISUAL EXAMINATION

This method is done to determine the surface condition and shape of plates, tubes, fabricated parts, thus to check the alignment of mating surfaces or to look for leaks when performing leak test, pneumatic or hydrostatic test.

There are major different methods for leak testing. These are done along with apparatus;
- Gas and bubble formation testing (Gas; air, nitrogen or helium) and bubble forming solution, pressure indicator.
- Vacuum box testing; vacuum box, vacuum creating equipment, and vacuum indicator.
- Halogen diode detector testing (Sniffer method)
- Helium mass spectrometer testing (reverse probe-sniffer method or hood method)

Hydrostatic testing is using water to ascertain whether the heat exchanger will withstand the design pressure at the design temperature without developing any leaks. The heat exchanger is using to 1.3 or 1.5 (depend on year or code design) times the maximum design pressure multiplied by the lowest ratio for the Heat Exchanger construction materials of the stress value at the test temperature to that at the design temperature. The typically number for testing shell and tube heat exchanger are three times, thus to check free leaks at gaskets.

![Figure 19: Designated Gaskets areas for hydrostatic Testing](image)

Pneumatic Testing is using air to ascertain whether the heat exchanger will withstand the design pressure at the design temperature without developing any leaks. It has advantage to be performed when the heat exchanger cannot safely be filled with water to conduct a hydrostatic or cannot be completely drained and dried of water after a hydrostatic test. This of course with highly consideration that the pneumatic test results in a reduced stress level since it is conducted at a pressure lower than for the hydrostatic test. In addition, the pneumatic is more dangerous and should be performed in precaution to certain set pressure. The air compresses a lot more than does water when it is pressurized, hence, the air would expand suddenly to many times the volume of the heat exchanger.
The above examination are the majors method that are applied in heat exchanger inspection, in which can be derived to other examination techniques that will be shedlight to next heading, to elaborate more how NDT methods can be used, ASME V Table A-110 lists imperfections in material, components and welds and the suggested NDE methods capable to detect them. The imperfection types are service induced imperfections, welding imperfections and product form.

<table>
<thead>
<tr>
<th>Surface Induced Imperfections</th>
<th>Subsurface [Note 12]</th>
<th>Volumetric [Note 13]</th>
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<tr>
<td>Abrasive Wear (Localized)</td>
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<td>Corrosion Creep</td>
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<tr>
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<td>Incomplete Fusion</td>
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<td>Incomplete Penetration</td>
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<tr>
<td>Cold Swages (Forgings)</td>
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<td>Cracks (All Product Forms)</td>
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<tr>
<td>Heat Treat (Forgings)</td>
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<td>Poresity (Forgings)</td>
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<td>●</td>
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<tr>
<td>Slitting (Bar, Pipe)</td>
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OTHER EXAMINATION

Heat exchangers NDT are applied mainly in three areas external, internal and tube bundle, the following are other advanced techniques that are derived basic NDT methods

- Eddy Current Examination (ET) is selected for non-ferromagnetic tubes, taken in consideration that the sensitivity is limited for U-tubes at bend portion.

![Figure 22: Eddy Current testing principle](image)

- Remote Field Eddy Current (RFET) is selected for inspection a ferromagnetic tubes, detect large pitting and wall loss with limitation of low sensitivity.

![Figure 23: RFT Testing Principle](image)
• Magnetic Flux Leakage (MFL) is selected for ferromagnetic tubes, with taken into consideration has poor sensitive on carbon steel, the method can determine Tube ID vs OD defect discrimination.

![MFL Testing Principle](image)

**Figure 24:** MFL Testing Principle

• Ultrasonic Examination system is more accurate method that can be demonstrated to measure tube thickness such as in system of Internal Rotary Ultrasonic Inspection (IRIS) or Shear Wave IRIS (SWIRIS), however, these systems are required to have clean tubes, and some to be filled on water media. IRIS slow measuring technique, provide wall thickness and detect external and internal defects.

![Ultrasonic (IRIS) Principle](image)

**Figure 25:** Ultrasonic (IRIS) Principle

**RECOMMENDATION**

The MTBF (Mean Time Between Failure) for any heat exchangers can be improved and even avoided for major maintenance with several recommendations such as,

• The inspection authority should check fabricator’s quality assurance program, documentation, mechanical design calculation, material used and their dimensions, corrosion allowance, weld detailed…etc

• The organization should always maintain history NDT records for future consideration.
• Under hydrostatic testing; Ensure bundles are cleaned/tested with fresh water containing less than 50 PPM chlorides.

• A guideline for retubing decisions should be based on the calculated minimum thickness (tm) or One third (1/3) original tube thickness (this considers minimum structural integrity), the tube thickness can be calculated by following formula (ASME Section VII Div1, Appendix 1)

\[ t = \frac{PR_o}{SE + 0.4P} \rightarrow (2) \]

Where,

\( P = \) Internal Design Pressure
\( S = \) Maximum Allowable Stress Value
\( E = \) Joint efficiency
\( t = \) Minimum required thickness of shell
\( R = \) Outside radius of the Tube

• Refer to a reliable Code and company standard to accept the discontinuity, ASME V for Nondestructive Examination or API 510 Pressure Vessel Inspection Code: In-Service Inspection, Rating, Repair, and Alteration for remaining life and corrosion rate

\[ \text{Remaining Life} = \frac{\text{Remaining Corrosion Allowance}}{\text{Corrosion Rate}} \]

\[ \text{Corrosion Rate} = \frac{\text{Metal Loss over a period}}{\text{Period of metal loss}} \]

• Conduct a Periodic inspection thus to detect early symptoms to allow for timely correction of small problems before they can become large problems

• NDE Inspector plays a significant role in the performance NDT techniques for tubing inspection. A large variation in results can be expected depending on the skill of the inspector. It is therefore important that some kind of a performance demonstration be established to determine the ability of the inspector for 1) detection, 2) discrimination (valid defects vs. false calls) and 3) sizing of all types of defects

• Utilize best effective Inspection Method (ASME PCC-2 Table I-1)

CONCLUSION

Inspection necessity is stage wise for any organization thus to ensure that the equipment has been designed and fabricated or repaired in accordance to the applicable codes using the correct materials and procedures that are allowed by the codes or standards. The major reasons for maintaining NDT inspection methods are for safety, continuity and efficiency of operation and reduction in maintenance costs.
Shops services is challenged to return units back to Plant through finding innovative ideas for improving the turnaround repairing time and avoid unnecessary maintenance, where it is NDT to determine whether to proceed with the repair or stop all activities and place new order to manufacture Heat Exchangers.

NDT methods are evolving process, and there is always a need to challenge having desire results by deploying new technique, as for instance, there are currently under potential or validation method for application (Ex, guided wave tube inspection, twisted tube inspection and Acoustic eye).

ACKNOWLEDGMENT

This paper has benefited by greatly commented by Saudi Aramco Inspection Department personnel from Technology Unit as well as inspection department effort in producing engineering procedures, in addition to Ras Tanura Refinery Inspection unit whom involved to Saudi Aramco Heat Exchanger Shop inspection that is located at Juaymah. I am gratitude toward those units.

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9. SAEP-317 Testing and Inspection (T&I) of Shell and Tube Heat Exchangers
10. SAEP-325 Inspection Requirements for Pressurized Equipment
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**Figure 15:** Gas-Gas Heat Exchanger and Phased Array Inspection Technique

**EDDY CURRENT EXAMINATION**

This method is based upon the principles involving circulating currents into an electrically conductive article and observing the interaction between the article and the currents. This method mainly exploit for non-ferrous tube material, the method detects small discontinuities with high speed, accurate measurement of conductivity to check variation in wall thickness, however, it is limited to use with conductive materials or
conductive base materials, the depth of penetration restricts testing to depths of less than ¼ in in most cases. The presence of strong magnetic fields will cause erroneous readings, in which required to training for interpretations of visual defects and indications.

![Image](image.png)

**Figure 16:** Using Eddy Current for inspection Incoloy Tube

**PENETRANT EXAMINATION**

This method is widely used in industry and classified in either using Dye or Fluorescent; for penetrant inspection (dye) for locating surface defects, where a liquid dye penetrant is applied to a dry clean surface and allowed to soak long enough to penetrate only surface defects. After a time internal of up to 1 hour, the excess penetrant is wiped off or cleaned with a cleaner and a thin coating of developer is applied. The penetrant entrapped in defect will be drawn to the surface by developer, and the defect will be indicated by the contrast between the color of the penetrant and that of the developer, as far for Penetrant inspection in Florescent, which is using for locating defects that run through the surface, in penetrant to be applied by sparing, dripping, or brushing.. The excess penetrant is washed from surface with a water spray or other appropriate solution to allow the surface then to dry. Dry powder or water-suspension developer is applied to part to draw penetrant to surface. Penetrant glows under black (ultraviolet) light. For leak test, penetrant is applied to one side, and the other side is examined under black light indications of glow.

The advantage of Fluorescent Penetrant Inspection is easy to perform, defects show clearly under black light. The limitation however in Penetrant inspection, it is only detect the defects that are open to the surface, in which add another cons which is not practical on rough surfaces. And for fluorescent, the black light requires a source of electricity, and applied only for nonmagnetic material, and not very effective as lead test for plates more than ¼ inch thick.
Figure 17: Penetrant inspection application in heat exchanger tubesheet and headers after weld buildup repair.

MAGNETIC PARTICLE EXAMINATION

This method Magnetic particle (MT) is for locating surface and sub-surface defects that are not too deep. The technique employs either electric coils wound around the part or prods to create a magnetic field. A magnetic powder applied to the surface will show up defects as local magnetic fields. The nature of the defects will be revealed by the way the powder is attracted. The advantages of using MT is useful for the inspection of nozzle and manhole welds for which radiography would be difficult at best and most impossible, the vantage to detect small surface defects especially once weld repair took place in defects. MT can also use to detect laminations at plate edges.

The limitation of MT is used only for magnetic material. It is also not suitable for detects parallel to magnetic field.

Figure 18: yoke technique of Magnetic particle (MT)
VISUAL EXAMINATION

This method is done to determine the surface condition and shape of plates, tubes, fabricated parts, thus to check the alignment of mating surfaces or to look for leaks when performing leak test, pneumatic or hydrostatic test.

There are major different methods for leak testing. These are done along with apparatus;

- Gas and bubble formation testing (Gas; air, nitrogen or helium) and bubble forming solution, pressure indicator.
- Vacuum box testing; vacuum box, vacuum creating equipment, and vacuum indicator.
- Halogen diode detector testing (Sniffer method)
- Helium mass spectrometer testing (reverse probe-sniffer method or hood method)

Hydrostatic testing is using water to ascertain whether the heat exchanger will withstand the design pressure at the design temperature without developing any leaks. The heat exchanger is using to 1.3 or 1.5 (depend on year or code design) times the maximum design pressure multiplied by the lowest ratio for the Heat Exchanger construction materials of the stress value at the test temperature to that at the design temperature. The typically number for testing shell and tube heat exchanger are three times, thus to check free leaks at gaskets.

Pneumatic Testing is using air to ascertain whether the heat exchanger will withstand the design pressure at the design temperature without developing any leaks. It has advantage to be performed when the heat exchanger cannot safely be filled with water to conduct a hydrostatic or cannot be completely drained and dried of water after a hydrostatic test. This of course with highly consideration that the pneumatic test results in a reduced stress level since it is conducted at a pressure lower that for the hydrostatic test. In addition, the pneumatic is more dangerous and should be performed in precaution to certain set pressure. The air compresses a lot more than does water when it is pressurized, hence, the air would expand suddenly to many times the volume of the heat exchanger.
The above examination are the majors method that are applied in heat exchanger inspection, in which can be derived to other examination techniques that will be shed light to next heading, to elaborate more how NDT methods can be used, ASME V Table A-110 lists imperfections in material, components and welds and the suggested NDE methods capable to detect them. The imperfection types are service induced imperfections, welding imperfections and product form.

<table>
<thead>
<tr>
<th>Service-Induced Imperfections</th>
<th>Surface [Note 11]</th>
<th>Subsurf [Note 21]</th>
<th>Volumetric [Note 31]</th>
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<tbody>
<tr>
<td></td>
<td>VT</td>
<td>PT</td>
<td>MT</td>
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<tr>
<td>Abrasive Wear (Localized)</td>
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<tr>
<td>Baffle Wear (Heat Exchangers)</td>
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<td>Corrosion-Assisted Fatigue Cracks</td>
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<tr>
<td>Corrosion Crevice</td>
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<tr>
<td>Crevice / Uniform</td>
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<td>●</td>
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<tr>
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<tr>
<td>Hydrogen-Induced Cracking</td>
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<td>Intergranular Stress-Corrosion Cracks</td>
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<td>Incomplete Penetration</td>
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<tr>
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<td>Cold Shots (Castings)</td>
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<td>Heat Treat (Castings)</td>
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<tr>
<td>Penetracy (Castings)</td>
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<tr>
<td>Scratches (Castings)</td>
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</tr>
<tr>
<td>Stains (Pipe, Plate)</td>
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</tbody>
</table>

Figure 20: Helium Testing Method

Figure 21: Hydrostatic Testing
OTHER EXAMINATION

Heat exchangers NDT are applied mainly in three areas external, internal and tube bundle, the following are other advanced techniques that are derived basic NDT methods

- Eddy Current Examination (ET) is selected for non-ferromagnetic tubes, taken in consideration that the sensitivity is limited for U-tubes at bend portion.

![Eddy Current testing principle](image)

**Figure 22:** Eddy Current testing principle

- Remote Field Eddy Current (RFET) is selected for inspection a ferromagnetic tubes, detect large pitting and wall loss with limitation of low sensitivity.

![RFT Testing Principle](image)

**Figure 23:** RFT Testing Principle
- Magnetic Flux Leakage (MFL) is selected for ferromagnetic tubes, with taken into consideration has poor sensitive on carbon steel, the method can determine Tube ID vs OD defect discrimination.

![MFL Testing Principle](image)

**Figure 24:** MFL Testing Principle

- Ultrasonic Examination system is more accurate method that can be demonstrated to measure tube thickness such as in system of Internal Rotary Ultrasonic Inspection (IRIS) or Shear Wave IRIS (SWIRIS), however, these systems are required to have clean tubes, and some to be filled on water media. IRIS slow measuring technique, provide wall thickness and detect external and internal defects.

![Ultrasonic (IRIS) Principle](image)

**Figure 25:** Ultrasonic (IRIS) Principle

**RECOMMENDATION**

The MTBF (Mean Time Between Failure) for any heat exchangers can be improved and even avoided for major maintenance with several recommendations such as,

- The inspection authority should check fabricator’s quality assurance program, documentation, mechanical design calculation, material used and their dimensions, corrosion allowance, weld detailed….etc
- The organization should always maintain history NDT records for future consideration.
• Under hydrostatic testing; Ensure bundles are cleaned/tested with fresh water containing less than 50 PPM chlorides.
• A guideline for retubing decisions should be based on the calculated minimum thickness (tm) or One third (1/3) original tube thickness (this considers minimum structural integrity), the tube thickness can be calculated by following formula (ASME Section VII Div1, Appendix 1)

\[ t = \frac{PR_o}{SE + 0.4P} \rightarrow (2) \]

Where,
\[ P = \text{Internal Design Pressure} \]
\[ S = \text{Maximum Allowable Stress Value} \]
\[ E = \text{Joint efficiency} \]
\[ t = \text{Minimum required thickness of shell} \]
\[ R = \text{Outside radius of the Tube} \]

• Refer to a reliable Code and company standard to accept the discontinuity, ASME V for Nondestructive Examination or API 510 Pressure Vessel Inspection Code: In-Service Inspection, Rating, Repair, and Alteration for remaining life and corrosion rate

\[ \text{Remaining Life} = \frac{\text{Remaining Corrosion Allowance}}{\text{Corrosion Rate}} \]

\[ \text{Metal Loss over a period} = \frac{\text{Corrosion Rate}}{\text{Period of metal loss}} \]

• Conduct a Periodic inspection thus to detect early symptoms to allow for timely correction of small problems before they can become large problems
• NDE Inspector plays a significant role in the performance NDT techniques for tubing inspection. A large variation in results can be expected depending on the skill of the inspector. It is therefore important that some kind of a performance demonstration be established to determine the ability of the inspector for 1) detection, 2) discrimination (valid defects vs. false calls) and 3) sizing of all types of defects
• Utilize best effective Inspection Method (ASME PCC-2 Table I-1)

CONCLUSION

Inspection necessity is stage wise for any organization thus to ensure that the equipment has been designed and fabricated or repaired in accordance to the applicable codes using the correct materials and procedures that are allowed by the codes or standards. The major reasons for maintaining NDT inspection methods are for safety, continuity and efficiency of operation and reduction in maintenance costs.
Shops services is challenged to return units back to Plant through finding innovative ideas for improving the turnaround repairing time and avoidance unnecessary maintenance, where it is NDT to determine whether to proceed with the repair or stop all activities and place new order to manufacture Heat Exchangers.

NDT methods are evolving process, and there is always a need to challenge having desire results by deploying new technique, as for instance, there are currently under potential or validation method for application (Ex, guided wave tube inspection, twisted tube inspection and Acoustic eye).

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