Inspectioneering

Fired Heater Health Monitoring and Reliability Management

In partnership with

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Inspectioneering would like to thank all of those that contributed to the development of this work. For more downloadable resources, visit **inspectioneering.com/downloads**.

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Introduction

The reliable operation of fired heaters is crucial to the successful performance of any facility. Because furnace tubes operate under such extreme conditions, their lifetimes are often limited by creep, corrosion, and oxidation. This eBook covers many essential elements for optimizing the performance and reliability of fired heaters. Facilities benefit from having short- and long-term strategic optimization plans that aim to improve the reliability and performance of fired heater assets, resulting in cost reductions and a decreased risk of unplanned asset failures.

The standards for successfully managing assets have changed with the expectations of plant leadership in the current industry climate. Historically, facilities were satisfied with programs that repaired equipment as quickly as possible, using a reactive approach. However, today's leaders demand more from their managers. Given the ongoing volatility in crude oil prices, demands for cost-effective unit reliability and performance continue to rise. Operations managers now have to meet and exceed the challenges from these high expectations in order to ensure and maintain longstanding fired heater health and reliability.

Fired Heater Health Monitoring and Reliability Management

Due to the high demand for continuous reliability and productivity of fired heater assets, it is important to develop a systematic strategy based on best practices. This strategy should identify and address all of the essential elements for achieving optimum performance and reliability for each fired heater asset. These essential elements provide the refinery's fired heater manager with the necessary knowledge to achieve the optimum balance between reliability and performance. These elements (**Figure 1**) include:

- Reliability and performance optimization accomplished through on-line and off-line monitoring of the fired heater's health
- Fitness-for-service and remaining life assessment of the detected damage mechanisms
- Risk assessment of the fired heater process and steam tubes and auxiliary components
- Failure analysis of components that suffer premature failures

Figure 1. Essential Elements in a Successful Asset Reliability Management Program.

In this management program, the performance data is fully integrated with the reliability data to provide managers with the knowledge to manage the reliability of key components and identify opportunities to improve heater operation to meet performance goals.

The Importance of Performance

Achieving fired heater reliability in conjunction with meeting performance standards can be a challenging feat. In this context, performance is a measure of the degree to which the fired heater is in an operable condition at any given time. The difficult factor of meeting performance standards is that the required fired heater operation (mission) is ever-changing at random frequencies.

Measures of asset performance are shown in **Figure 2**. These measures define what operators want a fired heater to accomplish at any given time. For example, if the heater was designed for a 30,000 barrels per day (bpd) feed rate, the charge heater must be able to process this charge capacity; otherwise, the mission has failed.

The fired heater asset manager's main goal is to *achieve a balance between reliability and demand/performance*. The manager can achieve this goal provided the reliability (what the fired heater can do) exceeds or is equal to the performance demand.

However, if the reverse situation occurs (performance demand exceeds the inherent reliability of individual components), asset failure is certain to happen at some point in the future. Regardless of what is done to maintain the asset, eventually demanding more from the fired heater than it is capable of delivering will result in asset failure. In addition to the failure occurring randomly, the results are often catastrophic.

Figure 2. Fired Heater Performance Standards.

For example, internal fouling of process fired heater tubes leads to higher tube metal temperatures, eventually affecting the reliability of the heater. Failure to detect this reduction in reliability could lead to damage negatively affecting the performance and desired reliability of the asset. The first indication of this imbalance could be a disastrous tube failure (**Figure 3**).

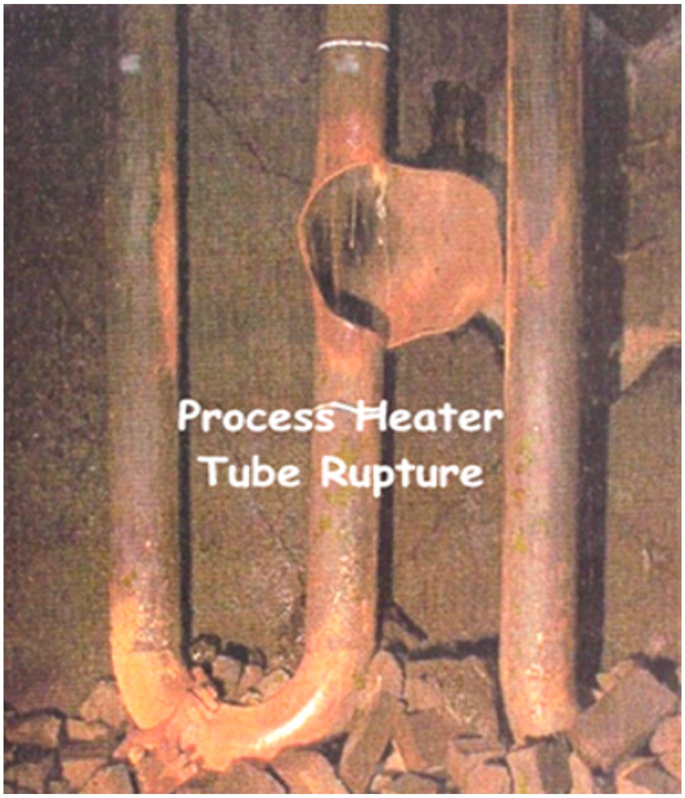


Figure 3. Impact of failure to manage risk, resulting in tube failure. This coil was designed for dry feed only. However, wet feed was going into the coil. Internal tube fouling occurred as liquid vaporized within the coil. Fouling was not detected, leading to localized corrosion damage in the fouled areas. Improper burner operation led to flame impingement on the fouled tube areas. Due to this damage, the tube overheated and ruptured. The cost to the refinery was an 8-week outage to rebuild the asset.

Ensuring the optimal performance of a fired heater begins well before commissioning. Flaws can be inadvertently introduced in new equipment during manufacturing, assembly, transportation, and setup, adversely affecting the operation of a heater. A complete understanding of the actual condition of equipment prior to commissioning can significantly reduce operational risk by eliminating unforeseen integrity issues up to and including failures.

Heater Health Monitoring

The first step in establishing an effective health monitoring program define what is happening inside the process heater while in operation. This involves monitoring critical operating parameters that define the reliability and performance capability of the heater, such as tube metal temperature. Key monitoring tools include infrared thermography, flue gas conditions analyzer, combustion emissions, and isothermal and heat flux profiles. Reliability limits (i.e., integrity operating windows) for the key components are established, and the performance measurements are compared to these limits to identify potential failures and operating risk.

After assessing the on-line factors affecting the performance and reliability of fired heater assets, the next step is off-line health monitoring. Every 4 to 7 years, the fired heater is shut down for a short period, during which the condition of components must be quickly assessed and action taken to repair or replace damaged components. Shutdown plans based on the major tube damage mechanisms and major reliability and performance concerns must be prepared and executed.

Effective offline health monitoring programs have employed advanced condition assessment tools to identify, map, and quantify the rate of deterioration and future impact of flaws present in the material condition of the refinery's fired heater tubes. Whether the primary concern has been bulging, creep strain, isolated corrosion, or other material flaws in tube wall thickness, an optimum program must start with inspection and detection of these flaws during shutdown. Ultrasonic-based smart pig inspection technology can be used to provide a quick and comprehensive inspection to both convection and radiant sections in serpentine fired heater coils. The smart pig is propelled with water throughout the length of a heater coil. The use of custom ultrasonic sensor technologies combined with a powerful graphical data analysis package has resulted in high-resolution, digital, and quantitative inspection data for the entire piping coil (**Figure 4**). Data is obtained in a matter of minutes after being collected without removing return bends or entering the furnace firebox. Some of today's smart pigging technologies are capable of inspecting coils with nominal diameter dimensions of 2 – 12 inches.

Fitness for Service and Remaining Life Assessment

There are several standards to assist the fired heater manager in assessing the fitness-for-service of heater components: API 530 Annex A, API 573 and API 579-1. Each of these documents provides the necessary knowledge to accomplish the assessment tasks. The reliability and performance data collected during heater health monitoring is used to calculate the fitness-for-service and remaining life.

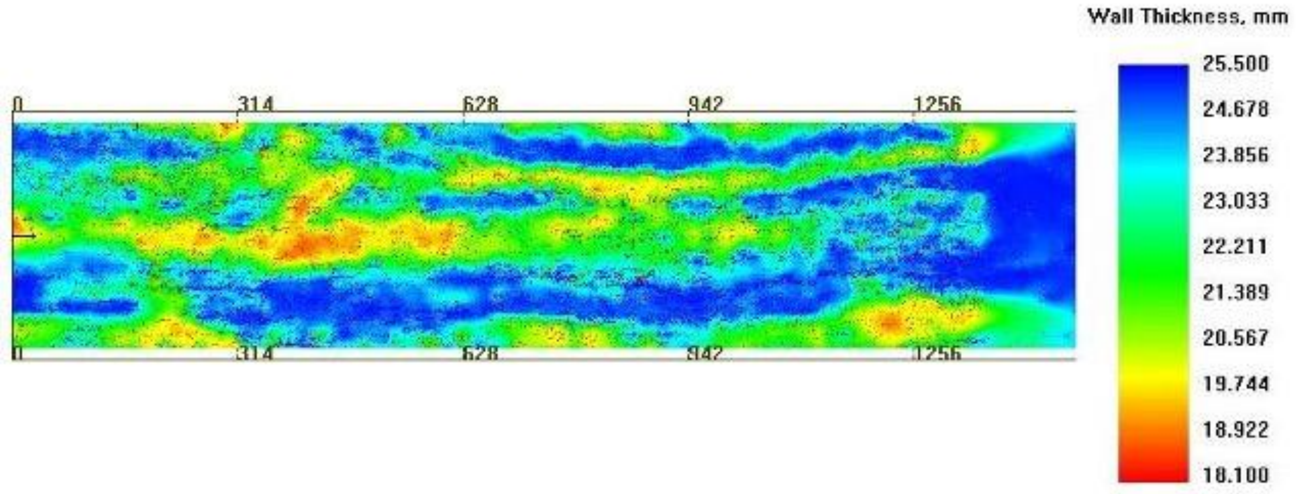


Figure 4. View of Data Obtained During Inspection.

Annex A of API 530, *Calculation of Heater-tube Thickness for Petroleum Refineries*, has recently been updated to include important methodologies for establishing operating tube metal temperature limits and tube retirement wall thicknesses. The operating limits may be used to prevent catastrophic tube failures, as well as manage the balance between tube reliability and performance demands. The retirement wall thicknesses are used to quickly assess a particular tube's fitness-for-service, and is a pass-or-fail assessment. If the tube failed the Annex A assessment, the more rigorous API 579-1 assessment steps should be performed, or a tube replacement should be considered.

Risk-Based Inspection and Assessment

After accomplishing heater health monitoring of the performance and condition of the fired heater, a risk assessment can be conducted. Risk assessment methodologies in API RP 580 and 581 may be followed to obtain a more detailed understanding of how a component is likely to fail and what shortfalls currently exist that can lead to an unexpected on-line failure event.

Risk is conventionally described, as shown below, as a function of likelihood of failure (LoF) and consequences of failure (CoF):

Risk = LoF x CoF

The risk assessment method employed may be qualitative, quantitative, or semi-quantitative. For each piece of equipment, the risk is determined by assigning scores to a series of questions concerning the design, operation, and history of each component. The LoF and CoF are further subdivided to enable a paired type analysis of the various factors, which comprise the risk of failure (RoF). These scores are then used to establish numerical values for the LoF and CoF. These factors are qualitatively graded, allowing a risk value to be determined and compared to the refinery and industry benchmarks (**Figure 5**).

Failure Analysis

Failures, and even near-misses, should be investigated and corrective action should be taken to prevent re-occurrence. There are numerous methodologies available to asset managers to accomplish these investigations, as well as API 585, *Pressure Equipment Integrity Incident Investigation*. Whatever investigation technique is utilized, it must be well-understood by the investigation team and lead to the identification of the root cause(s). An example of a root cause investigation for the catastrophic tube failure of **Figure 3** is shown in **Figure 6**. The chain of events identified in **Figure 6** indicates the logical conclusions regarding the root causes of the tube failure. The asset manager is now able to identify corrective actions to prevent the re-occurrence of the event. It is worth noting that corrective actions should be specific to the action taken, measurable, acted upon, relevant and achievable, and time-based.

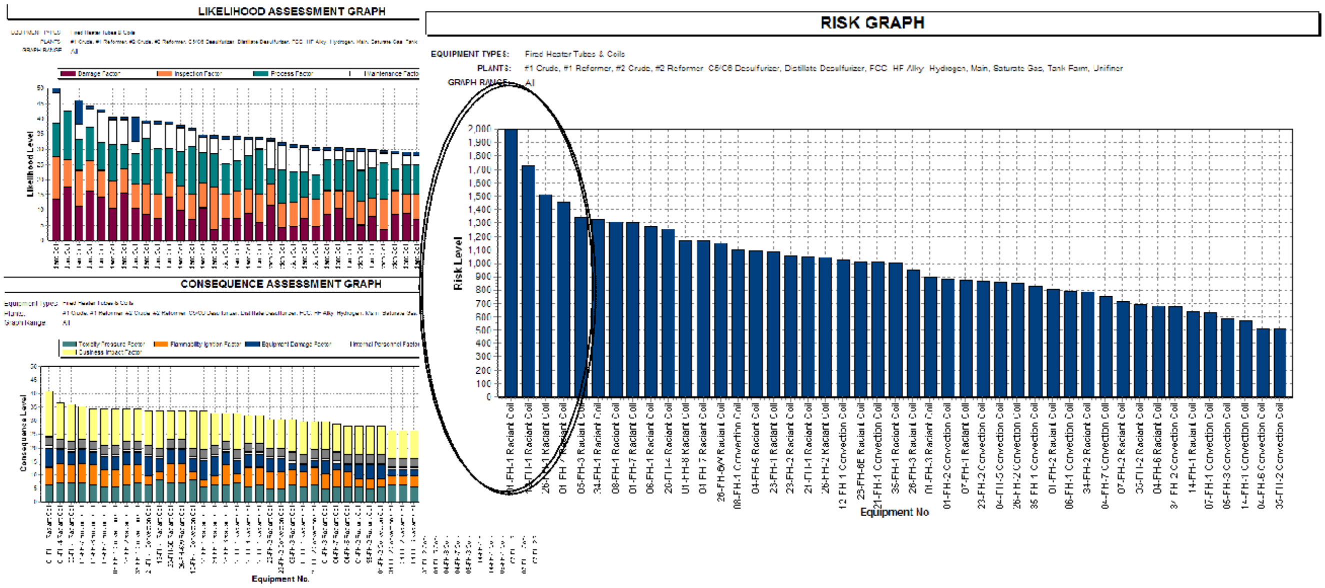


Figure 5. Example Refinery Wide Risk Ranking of Fired Heater Tubes.

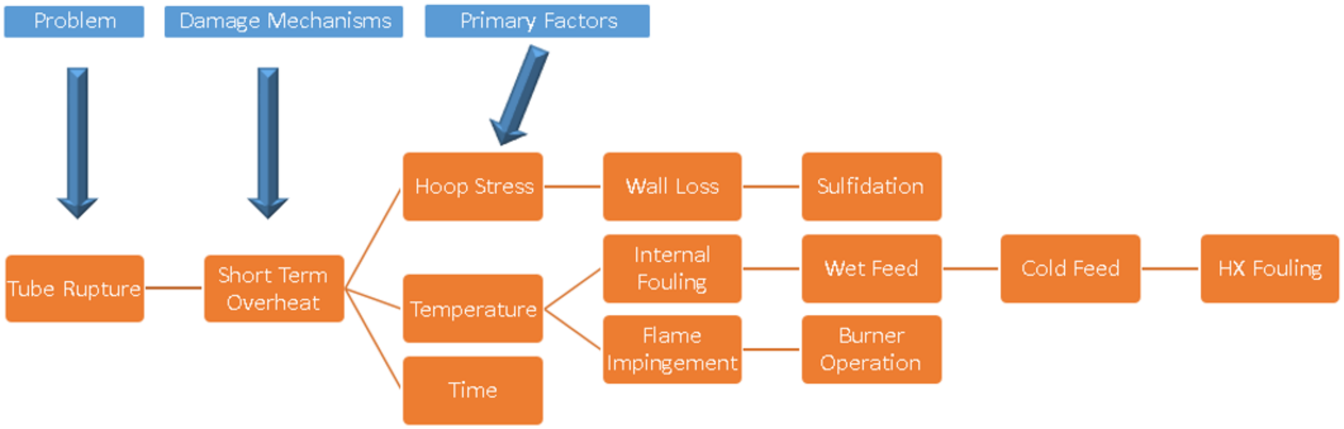


Figure 6. Example Cause / Effect Diagram.

Developing a Strategic Action Plan

Finally, a strategic action plan that is customized to each fired heater must be prepared. The essential elements of the described reliability management program provide valuable information to enable a refinery to determine where the management shortfalls lie with each fired heater, and what corrective actions must be taken. A reliability strategy should be developed that addresses the major concerns and potential risks identified in the assessment (**Figure 7**). The strategy for each fired heater will include policy and procedure changes, capital improvements, inspection and test plans, performance monitoring and maintenance plans, and tube replacement plans. As the action plan is executed, the strategy should be updated and plans adjusted to manage the balance between reliability and performance demand.

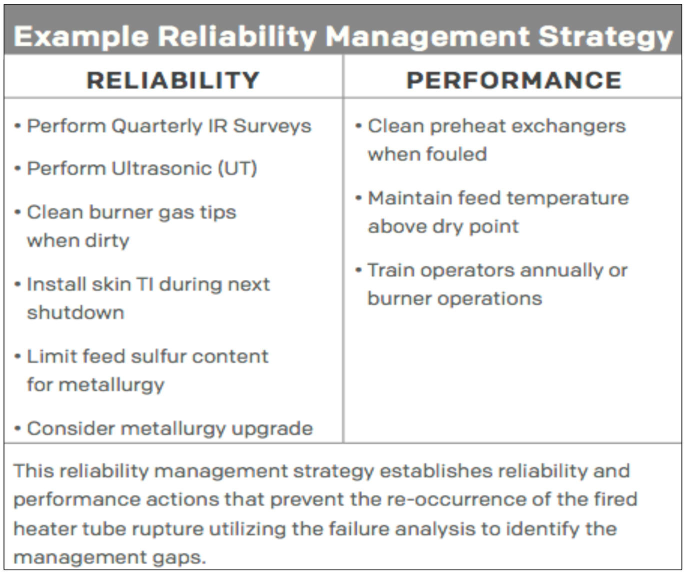
Fired Heater Inspection, Monitoring, and Maintenance

Smart Pigging

Matching the proper inspection techniques to detect specific types of damage to an asset is a critical component for achieving long-term reliability and performance. Universally, smart or intelligent pigging is now standard practice for the inspection of fired heater and serpentine boiler coils. Its growth in popularity and industry acceptance as a superior method for the inspection of coils prompted the addition of smart pigging into API Recommended Practice (RP) 573, Inspection of Fired Boilers and Heaters, in 2013. The growth in popularity also led to a surge in the number of smart pigging companies in the market, creating additional complexities for asset owners when aligning tool capabilities with inspection needs.

In API RP 573, verification of a provider's intelligent pig operating range is strongly recommended prior to selection, as capabilities may vary among the companies offering this service.

The tool's measurement grid, also known as ultrasonic testing (UT) sample spacing, and the minimum detectable wall thickness should be the main capabilities verified to ensure the various types of damage mechanisms commonly found in fired heater and boiler coils are detectable (see **Figure 8**).

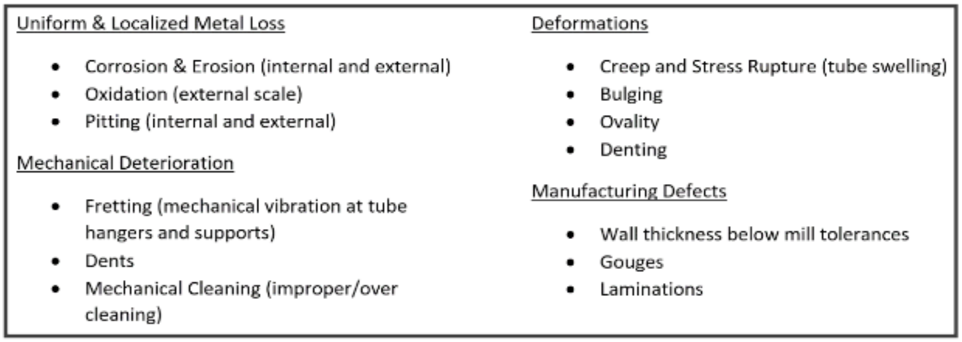


Example Reliability Management Strategy

RELIABILITY	PERFORMANCE
• Perform Quarterly IR Surveys • Perform Ultrasonic (UT) • Clean burner gas tips when dirty • Install skin TI during next shutdown • Limit feed sulfur content for metallurgy • Consider metallurgy upgrade	• Clean preheat exchangers when fouled • Maintain feed temperature above dry point • Train operators annually or burner operations

This reliability management strategy establishes reliability and performance actions that prevent the re-occurrence of the fired heater tube rupture utilizing the failure analysis to identify the management gaps.

Figure 7. Reliability and Performance Actions.



Uniform & Localized Metal Loss

- Corrosion & Erosion (internal and external)
- Oxidation (external scale)
- Pitting (internal and external)

Mechanical Deterioration

- Fretting (mechanical vibration at tube hangers and supports)
- Dents
- Mechanical Cleaning (improper/over cleaning)

Deformations

- Creep and Stress Rupture (tube swelling)
- Bulging
- Ovality
- Denting

Manufacturing Defects

- Wall thickness below mill tolerances
- Gouges
- Laminations

Figure 8. Fired heater and boiler tube damage mechanisms.

In addition, the tool's probability of detection (POD) capability, which is established by the service provider, should be confirmed. POD is derived from a tool's UT transducer resolution and measurement grid and can be described as the ability to confidently detect a flaw based on a minimum flaw size. This is usually expressed using a confidence level: for example, a 90% probability of detection of wall loss ½" width x ½" length or larger. In this example, a tool will detect and accurately size a localized area of wall loss that is ½" x ½" or larger nine out of ten times. This provides asset owners with some assurances that a flaw, such as localized wall loss, will be detected and quantified with a high degree of confidence.

Since POD is such an important metric for gauging performance acceptability, it is worth taking some time to elaborate on two elements that affect POD: UT transducer resolution and measurement grid density. The UT transducer resolution is the diameter of the UT beam that is projected onto the tube surface and is commonly referred to as the UT "footprint." The diameter of the footprint is governed by the diameter of the transducer and other factors such as transducer frequency and standoff. The measurement grid is the center-to-center spacing between UT readings. If the spacing equals the diameter of the transducer footprint, the resolution and measurement grid are the same. However, if there are gaps between readings, the measurement grid is larger than the transducer footprint, thus effectively reducing detection capabilities. The transducer footprint along with the number of transducers and tool speed establishes the measurement grid or UT sample spacing, which in turn determines the POD.

Understanding these principles and how to apply them to an asset can greatly assist with maintenance planning and the prevention of unexpected failures.

Smart pigging providers use immersion-based ultrasonics (UT) to measure a pipe's wall thickness and radius. Most providers use tools that are equipped with multiple fixed UT transducers housed around the exterior of the tool's body to achieve various levels of data sampling density. The density of usable UT readings plays a critical role in determining a tool's ability to reliably and repeatedly detect the various damage mechanisms seen in fired heater and boiler coils. When selecting a smart pigging technology/tool, some important things to consider are:

1. Number and size of ultrasonic transducers
2. Tool speed
3. Tool size
4. Minimum wall thickness detection

All these factors help to determine the probability or certainty that a flaw will be detected and accurately sized.

Number and Size of Ultrasonic Transducers

Many smart pigging service providers have tools designed to inspect 4" piping, among other sizes, with measurement grids (UT sample spacing) ranging from 0.158" width x 0.158" length to 0.790" width x 0.300" length depending on the company. The minimum detectable flaw size and POD for the most common type of smart pigs for fired heater and boiler coil applications are largely determined by the size and number of transducers on the tool.

For example, when a tool utilizing 0.375" diameter transducers with a measurement grid of 0.790" width x 0.300" length is used to inspect 4" nominal size schedule 40 piping, approximately 640 wall thickness and radius readings are taken every linear foot. This may seem like a lot at first, but, in reality, the overall internal surface coverage is no better than 47%. This is because gaps in pipe coverage exist circumferentially (the "width" dimension), severely limiting the tool's ability to detect localized metal loss, which is common in fired heater and boiler coils. This diminished detection capability is a result of the limited number of fixed transducers around the body of the tool.

Utilizing a tool with 0.250" diameter transducers and a measurement grid of 0.395" width x 0.250" length provides marginally better metal loss detection capabilities with 1,536 wall thickness and radius readings per linear foot. This equates to a pipe surface coverage of 63%, but there are still large gaps in coverage where localized metal loss can be missed.

Tools containing the highest number of transducers with the smallest transducer diameter provide the best ultrasonic surface coverage and resolution for the detection of localized metal loss. To that point, a high-resolution tool with 100% surface coverage would provide the best detection capabilities (see **Figures 9** and **10**).

Tool Speed

Each smart pigging company designs and develops tools with a fixed UT firing rate. This rate is set at an appropriate level to ensure 100% UT surface coverage in the axial direction when the tool is traveling through a coil at the optimal speed. The tool speed is set via a flow meter during smart pigging operations and needs to be at or below the optimal speed for proper coverage. During pigging operations, tool overspeed conditions can exist if flow meters are not utilized, or the pumping equipment that pushes the smart pig is faulty. A good on-site project manager should be able to remedy any in-field issues to establish proper tool speeds and confirm during the post-tool run verification that complete coverage was obtained.

Another useful indicator of surface coverage is the overall number of UT readings obtained axially and circumferentially. However, this indicator can sometimes be misleading depending on how a company advertises its capabilities. For instance, a company may claim in its specification, or through advertising, a higher number of UT readings per foot than is typically obtained during an inspection. This can be achieved by slowing down the movement of the tool through a pipe well below the optimal speed, which allows the UT footprints to overlap, effectively reducing the center-to-center axial spacing between readings (see **Figure 11**). However, this method does not improve the overall surface coverage, since 100% axial coverage is already obtained once a tool is operated at the optimal travel speed.

Every smart pigging provider can achieve a smaller or improved axial grid measurement (the "length" dimension) with this approach. However, the benefits are limited since flaws smaller than the circumferential grid measurement (the "width" dimension) are not detectable. This is a limiting factor in detection capabilities for tools with less than 100% surface coverage.

Tool Size

Ideally, smart pigging technology companies design ultrasonic tools that provide a consistently high level of coverage and resolution for the full range of pipe sizes found in fired heaters and boilers. With the inspection coverage and surface resolution dependent on the number and size of transducers, multiple tool sizes with a varying number of transducers are necessary to cover the entire pipe size range found in fired heaters and boilers. Essentially, the larger the pipe, the more transducers are required to maintain the same level of coverage.

Reduced ultrasonic coverage will occur if an undersized tool is used. For instance, when a tool uniquely sized for 4" piping is used to inspect 6" piping, the UT measurement grid and surface coverage diminishes, as compared to that same tool in 4" piping, since the surface area of a 6" pipe is greater. Given the previous example where a tool with a measurement grid of 0.395" width x 0.250" length is utilized, the coverage drops from 63% to 42%, further reducing flaw detection capabilities (see **Figure 12**).

Achieving as close to 100% high-resolution coverage as possible by "right-sizing" the smart pigging tool for the correct application ensures the greatest level of detection while preventing missed calls and possible pipe failures.

Minimum Wall Thickness Detection

The minimum wall thickness that smart pigging tools can detect varies and can impact the outcome of an inspection as much as any of the other previously mentioned factors.

Several years ago, a prominent refining company ruptured a tube during a hydrotest shortly after performing a smart pigging inspection on fired heater coils.[2] Follow-up testing by another smart pigging company revealed numerous areas of wall thinning that were not reported during the first inspection (see **Figure 13**). Upon further investigation, it was discovered that the smart pigging company's tools could not detect wall thickness readings below the refinery's minimum allowable wall thickness (T_{min}).

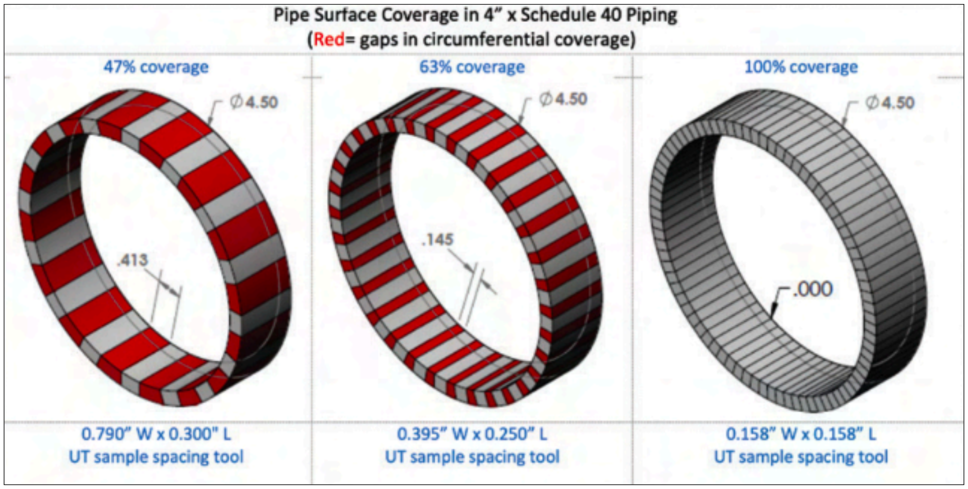


Figure 9. UT sample spacing comparison of pipe cross-section.

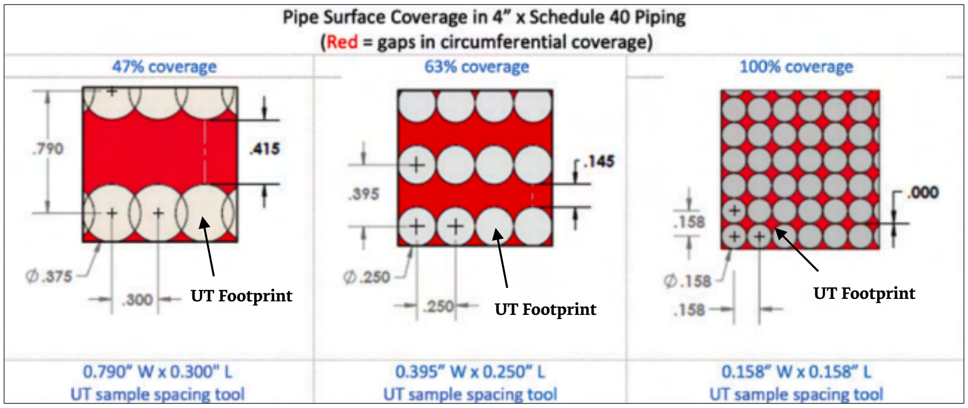


Figure 10. UT sample spacing comparison of 1" x 1" pipe surface grid.

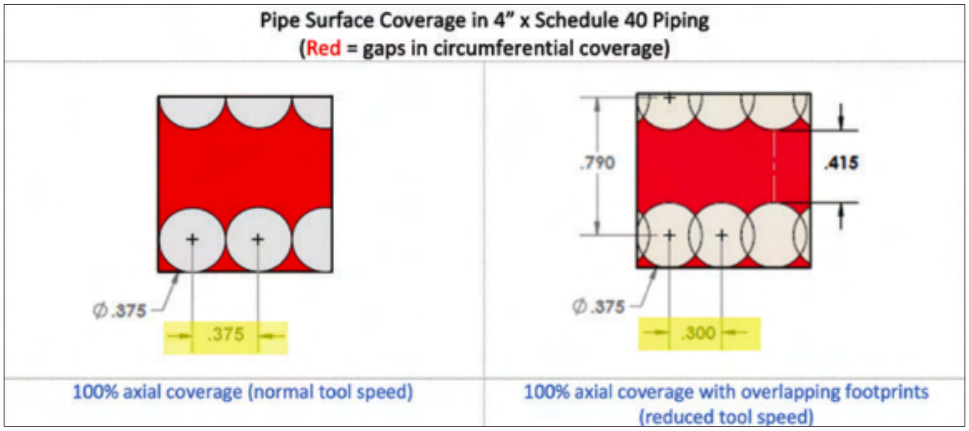


Figure 11. Impact on coverage at or below optimal tool travel speed.

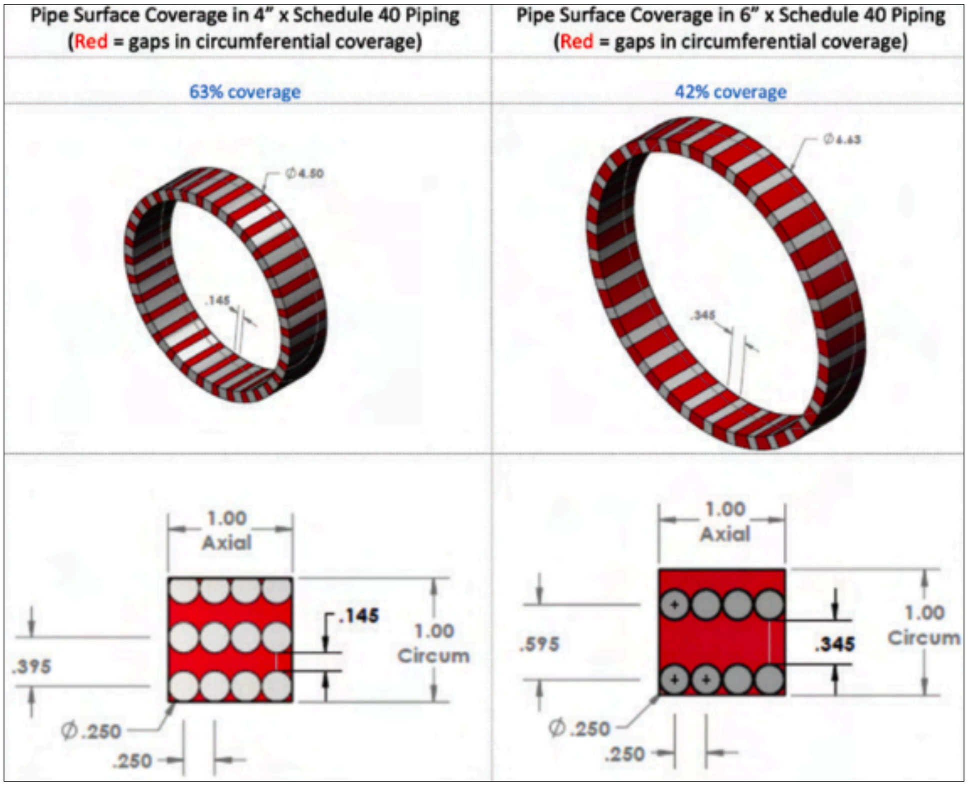


Figure 12. Using one tool for multiple pipe sizes.

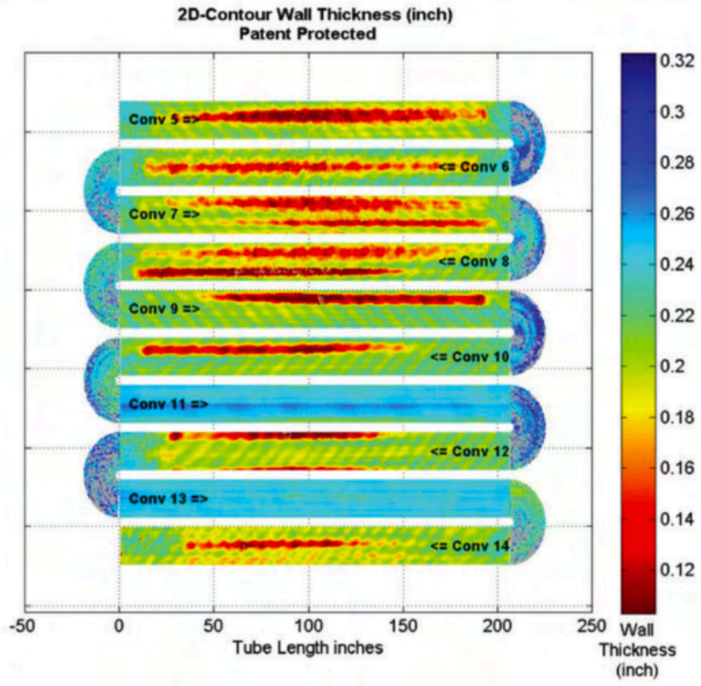


Figure 13. Damaged coil (many areas in red were missed during initial inspection).

Had the heater been brought back on-line after the repair from the hydrotest failure and without a follow-up inspection, more in-service tube ruptures or leaks would have occurred resulting in another unexpected and costly outage.

Understanding Inspection Limitations

Managing the integrity of heater and boiler coils is made easier with the advent of smart pigging technology. Large amounts of UT data now make it possible to accurately assess the condition of fired heater and boiler coils. However, differences in flaw detection capabilities, such as UT measurement grid, probability of detection, and minimum detectable wall thickness, do exist between companies offering these services. Understanding how these differences can impact the accuracy of an inspection and ability to detect common damage mechanisms found in heaters and boiler coils can help guide better decisions when it comes to ensuring the long-term reliability and performance of an asset.

Infrared Thermometry

For over 30 years, infrared (IR) thermometry has been used to monitor tube metal temperatures in refining and chemical furnaces. Tracking temperature levels and variations determine performance capability limits and reliable tube life. However, the application of IR thermometry has often been characterized as highly operator dependent, which can result in less-than-optimal data accuracy as a consequence of poorly applied and interpreted results.

IR thermometry is an excellent diagnostic tool for detecting tube hot spots from internal fouling or non-uniform heat distribution in fired heaters, but to ensure the full capability of IR thermometry, operators should employ the right instruments for the job and implement a proven methodology to measure accurate temperatures in a repeatable process. With an effective IR thermometry health monitoring program, operators can manage the mechanical integrity of fired heaters and optimize production rates.

Instrument Types

IR thermometry is primarily accomplished with two instrument types: thermal imaging cameras and pyrometers. A thermal imaging camera forms a two-dimensional thermal image of the target surface, while a pyrometer provides only a single target point temperature. Because each instrument has its own inherent advantages and disadvantages, an effective inspection program should incorporate both types of instrumentation. For example:

- The imaging camera should be used to provide meaningful images and measurements for a historical record that can be used to assess tube creep damage rates and long-term performance changes.

Figure 14. Imaging camera

- The pyrometer should be used for accurate field measurements to compare specific tubes and troubleshoot real-time performance issues.

Figure 15. Pyrometer

Measurement Factors

All infrared measurements, whether made by an imaging camera or pyrometer, are subject to measurement factors which can affect the accuracy and repeatability of the measurement. The fired heater's environmental measurement factors are the target tube's emissivity, target reflectance, and the flue gas effect on the measured temperature. The instrument factors affecting the temperature measurement are the instrument infrared wavelength, calibration, size of source effect, vignetting, and the emissivity setting. Each of these factors must be understood to achieve an effective infrared inspection program. Without an adequate understanding, measurement errors as much as 180 °F can occur, which also affects the repeatability of the measurements.

Fortunately, a comprehensive and effective infrared health monitoring program designed for fired heaters (or reformers) can account for these measurement factors. By following simple field data collection practices and then applying rigorous correction calculations, the tube's surface temperature can be accurately measured. This process allows any operator using either IR instrument to collect repeatable tube temperature measurements. The correction calculations employ algorithms based on well-established physical principles of blackbody infrared radiation and radiation exchange, including a specific geometrical model of the subject fired heater and characteristics of the measurement instruments. Software is now commercially available that can automate the rigorous correction calculations.

Infrared measurement factors that should be considered are:

- True tube temperature—desired outcome
- Environment factors—tube emissivity (including angle of incidence), target reflectance (including fired heater geometry) and flue gas absorption and emission
- Instrument factors—wavelength, calibration and size of source effect, vignetting and instrument emissivity setting

Environmental Factors

Emissivity (ε). As an environmental factor, emissivity refers to the ratio of radiation flux emitted by the target tube to that emitted by a blackbody at the same temperature as the target. For example, an **ε** of 0.85 absorbs and emits 85% of a blackbody radiation amount at the same temperature and reflects 15% of the surrounding radiation. Emissivity is a surface phenomenon and is affected by radiation wavelength. Target tube **ε** is typically 0.85 (@ 1μm), 0.82 (@ 3.9μm), but it can vary depending on the condition of the tube's surface.

Reflection. Reflection errors occur inherently due to the emissivity of the target tube. The reflected radiation from the tube is captured by the instrument and must be removed from the measured radiation to achieve the desired outcome. Imaging cameras that include reflection error correction assign one number to describe the surrounding objects. Reflection error cannot accurately be represented by one number. The effective background temperature depends on the geometry and position of the target tube and is a weighted average of the sum of all the surrounding surfaces like walls, the floor, roof, and tubes.

Flue gas effect. Absorption and emission errors can be introduced via flue gas (atmospheric) as the target radiation travels from the tube to the instrument. Specifically, spectral emission lines, at which radiation is absorbed and emitted by flue gas, must be taken into consideration. By selecting the appropriate instrument, the flue gas effect can be minimized, but not eliminated. The magnitude of flue gas absorption and emission errors is affected by the flue gas temperature and the travel path length. Operators who measure the same tube over two different path lengths should be able to identify the effect.

Instrumental Factors

Wavelength. The wavelength of the instrument is chosen based on the expected target tube temperature and to minimize the flue-gas emission errors. For fired heater applications, either a 1μm or 3.9μm wavelength instrument should be used.

Emissivity setting. Most instruments have the ability to set an emissivity value. Since the instrument is calibrated to a blackbody temperature, the emissivity value of the target tube must be applied to correct the indication. As discussed, reflection errors significantly affect the radiation from a target tube's surface, causing the target tube's apparent (or effective) emissivity to be higher than its inherent surface value. Setting the instrument's emissivity value to the inherent target value will not adequately correct the indication from a blackbody value to the target's value. For this reason, it is recommended that the instrument emissivity setting be set to 1.0 (assuming the target is a blackbody) and then apply correction calculations outside of the instrument for target emissivity and reflection error. The tube's radiance temperature (i.e., total emitted and reflected radiation) is measured when instrument $\varepsilon_I = 1.0$.

Size of source effect. Ideally, the instrument should detect only the radiant flux within its well-defined field of view. Yet, the reality is that some of the flux within the field of view will miss the detector, and some of the flux from outside the field of view will be detected. This phenomenon is called size of source effect (SSE). Some factors of SSE correction to consider are:

- Imaging cameras have a large SSE correction, primarily due to the large surface area covered.

- Pyrometers usually have a small SSE correction (i.e., can be ignored).
- SSE correction for each instrument must be laboratory-measured and then applied to radiance temperature measurements.
- The SSE typically causes the radiance temperature to be higher than the actual radiance value.
- To minimize SSE error, operators should keep lens dust and scratch-free and ensure that the field of view is well overfilled with neighboring objects at the same temperature as target area.

Vignetting. Vignetting refers to the obscuring of the lens' field of view, resulting in a reduction in radiation falling on the detector (i.e., temperature reading will be low). This is a common problem for operators when they are working with furnaces and are looking through a sight door. Capturing portions of the sight door wall in the image will lead to vignetting.

Proven Methodology

To correct for common problems and ensure reliable and repeatable results, the following field data collection procedures should be followed:

- Set the instrument emissivity to 1.00 and the background to ambient.
- Determine the effect of flue gas absorption or emission on the thermometer readings.
    - Select the target tube that is viewable from two different sight doors.
    - Sight doors should have different path lengths to target tube and similar background.
    - Open sight doors and wait for the furnace to reach equilibrium; then take a series of measurements.
- Measure short-term target temperature fluctuations by selecting one tube and record the temperatures.
    - Can be the same tube used to measure flue gas effect.
- Measure radiance temperature of target tubes.
    - Take readings quickly to avoid target influence from open sight door.
    - Ensure that the tube is in focus and avoid viewing through flames.
    - Ensure that the edge of the sight door does not overlap the field of view.
    - Target tubes should overfill the focus circle and avoid capturing non-uniform temperature objects in field of view.
- Record the radiance temperatures of each surrounding object.
    - Follow image-sighting guidelines of the target tube.
    - Dividing the surrounding object into sampling parts increases the accuracy of the target tube temperature.

After the above field procedures, the collected data should then be corrected with rigorous calculations. For example, operators should correct the radiance measurements for emissivity and reflection error, SSE, flue gas emissions, and other instrument and environmental errors. They should calculate the uncertainty associated with these factors. And they should calculate the effective background temperature taking into account the geometry of each target tube.

IR Temperature Correction Case Studies

The following two case studies show operational improvements using an IR temperature correction program to manage the health of reformers and fired heaters. Software is used to automate correction calculations in order to remove common errors from IR thermometry tube temperature measurements.

Reformer case study. The first case study focuses on a complex refinery with more than 40 fired heaters. The refinery's hydrogen reformer was challenged with tube metal temperatures that were limiting hydrogen production. In addition, poor heat distribution constrained output. The operator was also concerned with the equipment's creep damage rate.

- In 1998, the refinery implemented a full-time heater health monitoring program with an on-site contractor.
- In 2003, the operator shifted the program to part-time monitoring, serviced by an on-site NDE contractor.
- In 2011, the refinery implemented the above-described IR temperature correction program to improve the accuracy and repeatability of IR measurements.

As part of the program implementation, the on-site NDE contractor was trained in proper IR data collection procedures

Statistic, °F	Conventional Uncorrected Temperature	Corrected Temperature
Maximum	1757	1659
Average	1656	1574
Minimum	1547	1467
St. Dev.	63	41

Table 1. Uncorrected temperatures versus the corrected temperatures for the hydrogen reformer tubes.

and software applications. The IR camera SSE error was measured and corrections were applied. The corrected temperatures were well below operating limits, therefore the reformer operation was continued at the same production rate, and the creep damage rate concerns were alleviated (see **Table 1**).

Fired heater case study. The second case study focuses on a complex refinery with more than 20 fired heaters in practically all possible services. The refinery operator wanted to increase the plant's run length between decokes of the coker heater. The run length of the coker heater was limited by skin thermocouple indications (TI). The IR monitoring activities at the thermocouple locations indicated that the thermocouple readings were too high.

In 2010, the refinery began a heater health monitoring program with an off-site contractor performing periodic routine monitoring. In 2013, the refinery shifted the program to in-house NDE staff performing the routine monitoring and implemented the above-described IR temperature correction program to improve the accuracy and repeatability of IR measurements.

As a result, a significant difference between actual tube metal temperatures and skin thermocouple readings were documented. Specifically, the skin TI readings were reading higher than actual. The IR temperature correction program confirmed the reading difference, thus the operator was able to gain confidence in the plant's tube integrity program by having accurate and repeatable data upon which to base decisions (see **Figure 16**).

Clearly, an effective infrared health monitoring program is an absolute necessity to monitor the integrity of the fired heater tubes, as well as provide a wealth of diagnostic information that may be used to evaluate the performance and reliability of major fired heater parts (e.g., tubes, tube supports, burners, refractory and structural systems). By fully understanding the IR measurement factors and employing field collection practices and IR temperature correction calculations, accurate and repeatable infrared temperature measurements are achievable.

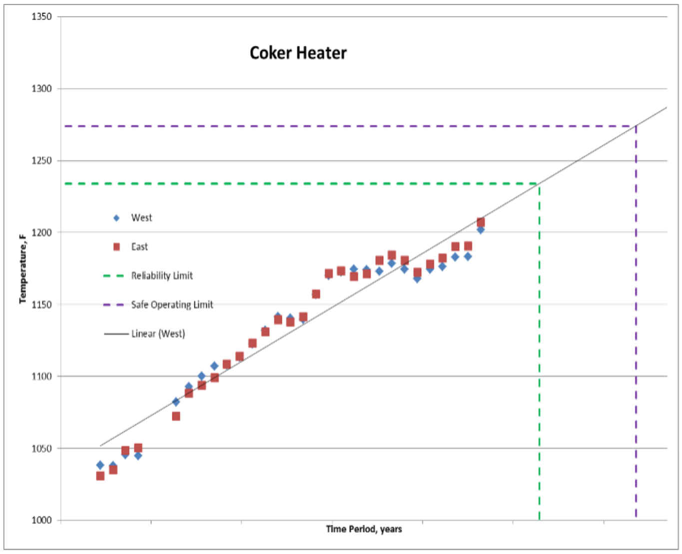


Figure 16. Tube metal temperature trend for coker heater allowing optimum de-coke planning to occur.

Tube Decoking

Mechanical cleaning of fired heaters, otherwise known as mechanical decoking or descaling, helps ensure the optimal performance of many heaters found in the refining and petrochemical industry. Internal fouling can reduce production throughput by restricting the flow of product through a coil. It can also prevent the proper transfer of heat to the feedstock, which can lead to elevated tube temperatures and eventual tube failures. As such, it is imperative that all fouling is removed to achieve target run times and throughput.

The manner in which mechanical cleaning is carried out has changed very little since its inception in the early 1990s. Cleaning pigs with metal cleaning appendages or studs are placed into a coil flooded with water (typical medium) and pushed from one end of the coil to the other via a pump (see **Figure 17**). The studded cleaning pig travels through the coil scrapping the fouling off the walls. Additional cleaning is achieved by employing a method of an incremental increase in cleaning pig sizes based on the coil's nominal internal diameter and the estimated thickness of the fouling.

Figure 17. Mechanical Decoking

The cleaning process continues until fouling is no longer removed from the coil, as evident by the color of the water and lack of particulates at the coil output. As further evidence that a coil is clean, some companies may also run an oversized light-colored foam pig through the coil, assuming any leftover fouling would discolor and potentially damage the foam pig.

Comparing the pre-cleaning coil pressure and flow rate to the post-cleaning pressure and flow rate is another common method for verifying cleanliness. A decrease in pressure and increase in flow after the final cleaning runs indicates a reduction in fouling, although whether the coil is completely clean is unknown.

The Mechanical Decoking Challenge

While the mechanical cleaning process can be quite effective, the methods to confirm the overall cleanliness of a coil do not provide adequate assurances that all of the fouling has been removed. In fact, smart pigging inspections have discovered varying amounts of leftover fouling that have followed decoking activities in a vast majority of heaters since 2001.* In some instances, owner/operators noted elevated tube temperatures following a startup, leading to either immediate and unexpected shutdowns for additional cleaning or reduced run times when additional cleaning was not possible. In these instances, leftover fouling resulted in lost production and significant revenue losses.

A New Approach to an Old Problem

In response to the concern that all fouling may not have been adequately removed, a technology-based technique has been developed to verify both decoking and cleanliness. The new technique empirically detects and measures internal fouling eliminating any uncertainties in coil cleanliness. This is accomplished using specialized ultrasonic-based technology, software, and proprietary cleaning methods.

This service also includes additional benefits for fired heater owner-operators. Performing a fouling verification tool run early on in the cleaning process creates a baseline of the fouling that can be used to identify where concentrations of fouling exist in a coil. With this information, cleaning efforts can be focused on specific locations of fouling. For example, if no fouling is present in convection tubes, the verification tool runs are limited to just the radiant tubes. This front-end step eliminates unnecessary travel through the portions of the coil free of fouling resulting in reduced mechanical cleaning run times and wear and tear on the coil. When coupled with periodic verification runs to gauge the progress of the cleaning efforts throughout the decoking process, you can significantly reduce cleaning times, which can be of great importance for heaters in a critical path.

Another added benefit of this modern approach is the ability to identify operational concerns with the heater by evaluating the location and thickness of fouling. The presence of fouling in the upper part of a convection section or excessively thick areas of fouling in radiant tubes could reveal underlying operational issues, such as improper burner operation or inadequate process flow, which may lead to uneven heat distribution and elevated tube metal and process temperatures that will cause internal fouling. This level of information can lead to more effective temperature monitoring programs and allows operators to make informed decisions on future operating and shutdown procedures.

Case Study

The heater was configured with a horizontal convection section and two separate vertical radiant cells (see **Figure 18**).

Shortly into the mechanical cleaning portion of the project, a verification tool was deployed in both coils to establish fouling levels and determine where cleaning efforts should be focused. The verification runs detected a higher-than-expected buildup of fouling in one of the radiant cells (see **Figure 19**).

The other radiant cell showed much less fouling. This discovery provided excellent operational information showing that the temperature in the first radiant cell was too high. As a result, the

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** Quest Integrity obtained this information from over 2,400 heater inspections.*

tube metal temperature (TMT) limit for the tubes in the cell with heavy fouling was reached much sooner. Had the temperature been more evenly spread across both radiant cells, the TMT limit would have been reached much later, resulting in a longer run time and improved profitability.

The first fouling verification runs also revealed horizontal grooving patterns on the inside tube walls (see **Figure 19**). Further investigation concluded that the previous cleaning company that had decoked the coils was overly aggressive in its cleaning efforts resulting in damage (wall loss) to the tube walls. This was most likely from the combined effects of using oversized cleaning pigs, extra hard cleaning appendages and excessive cleaning pig runs.

To the last point, without a way to conclusively determine that a coil is completely free of fouling, companies may resort to more cleaning runs than are required, causing unnecessary wear and tear on bare tube walls. Verifying the decoking and cleanliness eliminates this problem by providing 100% assurance on the cleanliness of coils during the decoking process, effectively minimizing the number of cleaning runs to what is required and nothing more. This precise and economical approach to decoking can reduce cleaning times, thereby allowing asset owners to restore operations at a much quicker pace.

Fired Heater Integrity Operating Windows

Understanding and establishing effective Integrity Operating Windows (IOWs) is critical in the operation of refinery fired heaters. IOWs, as described by API 584, are a specific subset of operating limits focused on maintaining the integrity and reliability of process equipment. IOWs address issues involving process parameters that, when not adequately monitored or controlled, can impact the likelihood and rates of damage mechanisms, potentially leading to loss of containment. The establishment, implementation, and maintenance of IOWs require a multi-disciplinary approach and should be considered an essential part of a facility's operation and maintenance strategies.

What are IOWs?

IOWs are the limits within which fired heaters should operate to maintain safe and productive operation. According to API 584, IOWs are *"a vital component of integrity management,"* and should be implemented *"for the express purpose of avoiding unexpected equipment degradation that could lead to loss of containment"* [1].

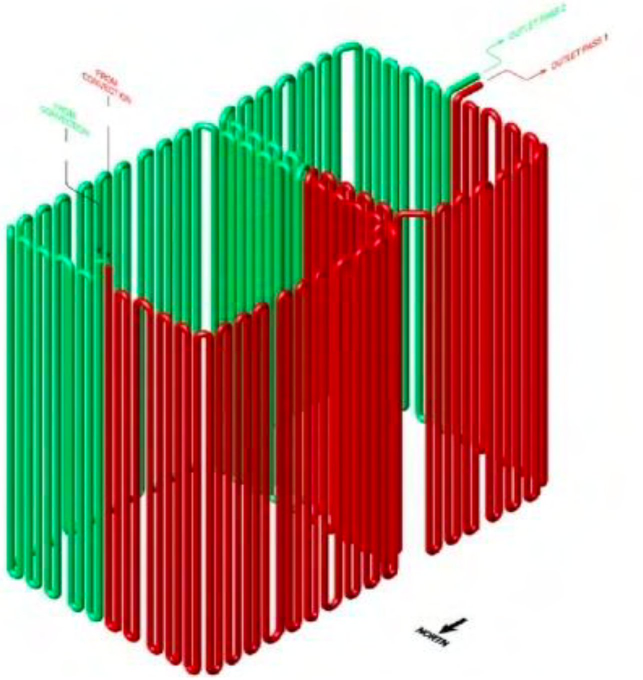

Figure 18: Radiant Coils

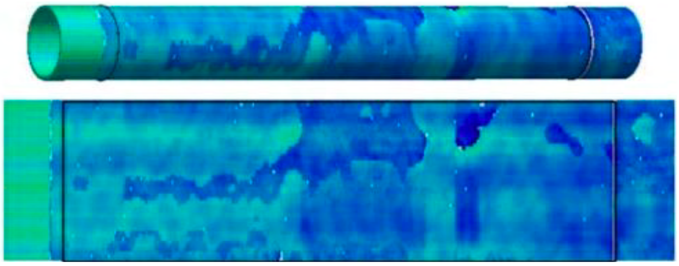

Figure 19. 3D & 2D inside radius of one pipe heavy fouling (dark blue areas)

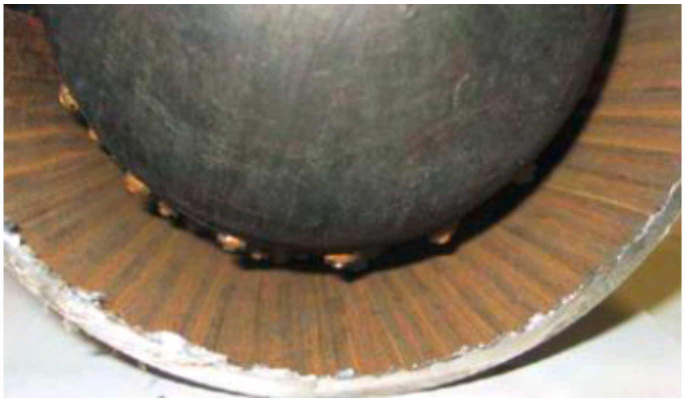

Figure 20. Grooving

Essentially, IOWs offer an operator considerable peace of mind in the condition of their assets, as long as they are operating within determined parameters.

When considering the setup and implementation of IOWs, it is vital to understand how IOWs are used to monitor heater condition, as well as what real-world IOW setup would look like for each fired heater unit.

Establishing IOWs for Fired Heaters

The first critical step in implementing an IOW program is establishing operating limits. These limits are determined by assessing a set of process variables that *"can affect the integrity of equipment if operation were to deviate from the established limits for a predetermined length of time"* [2]. In order to establish these operating limits, specific parameters must be examined. These factors must be considered in relation to their effect on tube integrity, as well as their effect on the combustion process. These parameters define the inherent reliability capability of the fired heater and can be measured when a unit is on-line.

The following parameters in **Table 2** must be considered when determining accurate IOWs. Again, each of these parameters directly or indirectly affects the integrity of the fired heater tube. The parameters are listed in order of priority, whereas tube metal temperature is the most important tube integrity parameter. The other parameters can have a direct impact on tube metal temperature. For example, the Heat Flux Rate (or Heat Transfer Rate) is directly related to the tube metal temperature through a series of known heat transfer calculations. A higher transfer rate will result in a higher tube metal temperature. Additionally, depending upon the particular service, exceeding a certain heat flux rate could result in internal tube fouling (e.g., coke laydown) that would further elevate the tube metal temperature, possibly to a failure point. Monitoring of the Heat Flux Rate is essential to ensure tube integrity is not affected by the on-line operating conditions of the fired heater.

Tube Metal Temperature Limits – API 530 Annex A Assessment

In order to have an effective IOW program for fired heaters, one must consider Tube Metal Temperature Limits. API 530, in its essence, contains procedures and design criteria for calculating required wall thickness for new tubes and fittings. Annex A within this Standard further recommends a simple assessment method for in-service tubes in order to determine allowable skin temperature (TMT), tube retirement thickness, and remaining life.

API 530 Annex A provides a methodology for establishing TMT limits during normal fired heater operation. The TMT limits are conservatively based upon the maximum pressure limit, corroded wall thickness, and the resulting peak operating stress, which can all be determined employing a process logic map using an if/then scenario, similar to what is seen in **Figure 21**. The operating stress based on the maximum pressure limit and the design corroded thickness is calculated using the standard equations for hoop stress provided in API 530. Using the material's creep properties and the calculated stress, the long-term and short-term TMT operating limits can be determined. By applying this assessment methodology, operators can calculate IOWs for TMT limits that ensure the safe and reliable operation of fired heater tubes during an operating period.

Understanding IOW Limits

Once IOWs have been established, they can be used to interpret data and determine repair/replace actions, if necessary. **Table 3** shows the relationship between risk factors and the type of IOW.

1. Tube Metal Temperature	7. Process Charge Rate
2. Process Fluid Temperature	8. Flue Gas Temperature
3. Heat Flux Rate	9. Draft
4. Excess Oxygen	10. Environmental Emissions
5. Fuel Gas Pressure	11. Process Fluid Pressure
6. Process and Fuel Gas Characteristics	12. Structural Component Temperature

Table 2. IOW Parameters for Refinery Fired Heaters

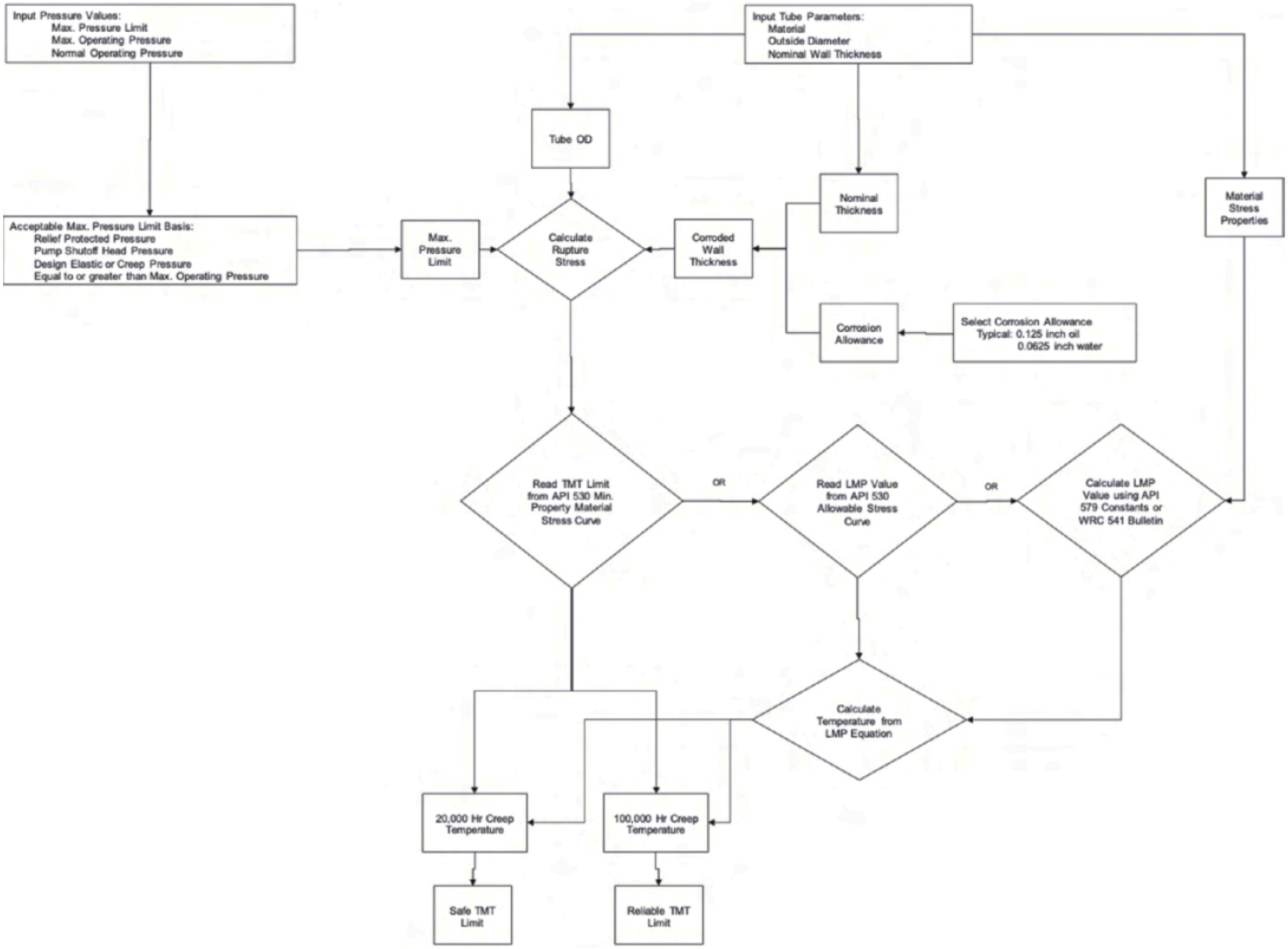

Figure 21. Process Logic Map for Determining TMT Limits

Risk	Type of IOW
High	Critical
Medium High	Critical or Standard
Medium	Standard or Informational
Low	Informational

Table 3. Risk Level in Relation to Type of IOW

Operators are then able to take strategic action based on where an asset falls on the risk-ranked charting system, and the type of action is further defined.

IOW Critical Limit

An asset that falls within the high-risk “Critical” IOW limit can indicate potential rapid deterioration occurring such that the operator must take immediate predetermined actions to return the process variable back within the IOW in order to prevent significant equipment damage or hazardous fluid release.

IOW Standard Limit

An asset that falls within the medium-risk “Standard” IOW limit classifies conditions that, if exceeded over a specified period, could cause increased degradation rates or introduce new damage mechanisms beyond those anticipated. The recommended action is to troubleshoot with planned adjustments to operations, including inspection and maintenance activities that ultimately return the operating parameter to within the Standard limit.

IOW Informational Limit (IIL)

A fired heater parameter that falls within the lower-risk “Informational” IOW limit indicates that the fired heater is currently running under appropriate operational control. It is recommended that these parameter types be monitored by Subject Matter Experts (SMEs) to connect the parameter’s impact on tube integrity and to predict and control the long-term integrity of the tube.

Risk-Based Inspection

Once asset conditions are ranked by IOW type, the priority treatment of high-risk assets can be effectively managed. By implementing IOW programs, operators are provided with the critical information required to undergo immediate remediation for high-risk parameters, while taking strategic action to mitigate other lower-risk parameters in order to avoid the emergence or growth of further problems over time.

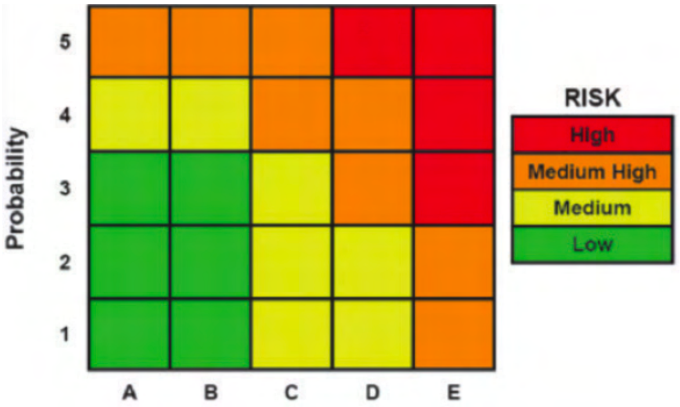

Figure 22. Risk Matrix for Assessing IOW Limits

The assessment portion of Risk-Based Inspection can encompass several evaluations, including equipment condition, a study of operating protocols, remaining life evaluations, and life extension analyses. This process considers the combination of the likelihood and consequence of a fired heater tube failure. This assessment is then used to modify and optimize inspection plans, strategies, audit procedures, operating limits, and safety information.

Next Steps in IOW Management

While the establishment of IOWs is a necessary first step in ensuring long-term integrity optimization, it is important to recognize that IOWs should not be considered “carved in stone.” IOWs should be regularly reviewed and/or revised, in order to ensure that each IOW properly encompasses optimal operational limits. The roles, responsibility, and, ultimately, accountability of an IOW program is highly dependent upon those who help develop it and should ideally include a multi-disciplinary panel of experts, including site corrosion engineers, unit inspectors, pressure equipment engineers, equipment type specialists, and technical facilitators. It is also important to note that changes to IOW limits should be accomplished through a rigorous Management of Change (MOC) practice. Ultimately, the MOC process should be utilized in the implementation of the IOWs to convey the importance of each IOW parameter to the front-line operator and inspection personnel.

Adherence to IOWs has become a standard practice in the long-term optimization of fired heater assets. The establishment, implementation, and maintenance of IOWs are key elements of Process Safety Management (PSM) programs and ultimately allow refineries to optimize the reliability and performance of their fired heaters, further maximizing profitability within their risk threshold.

Conclusion

Achieving a proper balance between the reliability and performance of a facility's fired heaters can be challenging. The health monitoring and reliability management program for fired heaters outlined in this eBook can help refinery management achieve their long-term goals. It is important to develop a strategy that identifies the essential elements for achieving optimum performance and reliability for each fired heater. The strategy should identify the major potential tube damage mechanisms and any significant issues observed for the fired heater. These damage mechanisms and issues, as well as other industry best practices, should be addressed by a strategic action plan. Principled execution towards accomplishing these strategic actions will lead to a higher level of performance and reliability with respect to each individual fired heater. This documented strategy should be periodically reviewed, updated, and changed to ensure fired heaters remain at optimum production. Establishing a fired heater health monitoring and reliability management program will significantly improve fired heater performance and safety by ensuring all risks are understood and accounted for, helping operators reduce the risk while extending run times, and optimizing tube replacements.

References

1. American Petroleum Institute. API Recommended Practice 584. Integrity Operating Windows. First Edition. 2014. https://www.api.org/~/media/files/publications/whats%20new/584%20e1%20pa.pdf.

2. Haugen, T. & Jensen, A. (2016),. Choosing the Right Smart Pigging Technology: Lessons Learned.

About the Authors

Tim Hill, P.E., is a Mechanical Engineer and Principal Consulting Engineer for Quest Integrity Group with 30-plus years of experience, including the evaluation of thermal processes, fired heater operations and maintenance, risk assessment, root cause failure analysis and life assessment for fired heater equipment in the petrochemical, refining and power generation sectors. For 10 years, Tim was responsible for the operation and reliability of all furnaces in a major refinery in the USA. During this period, he developed and implemented effective integrity management tools (including infrared inspection) covering operation, maintenance and risk assessment.

Tim Haugen has worked for Quest Integrity since 2004 providing invaluable insight and innovative solutions in his various roles. He currently serves as the Global Business Director for Process Inspections. Tim works with inspectors and engineers in the Refining and Petrochemical industries to promote industry awareness of best-in-class technologies and services and to provide solutions that improve the integrity and reliability of piping assets. He also has extensive managerial and field experience, having directed Quest Integrity's process inspection operations and managed smart pigging inspections at client facilities worldwide for many years.