DESIGNING A ROBUST WASTE HEAT BOILER

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ABSTRACT

The reliability of Sulfur Recovery Units (SRUs) is ever more important for maintaining acceptable environmental discharge criteria. The SRUs used in gas conditioning and refining applications are typically based on the Claus process, employing a reaction furnace (RF) and fire tube type waste heat boiler (WHB).

The reliability of the WHB is a significant factor in the overall SRU reliability. Understanding the root causes for WHB failures provides the basis for establishing the parameters necessary for a robust WHB design and also operating guidelines needed for reliable operation.

Typically WHB failures are due to three factors: excessive temperatures, excessive mass flux (process through-put) and excessive water- or process-side fouling. Each of these three factors can independently or in combination cause a WHB to fail. This paper discusses these factors, the need to learn from prior failures, the corresponding considerations necessary for designing a robust WHB, and the necessary considerations for operational parameters and procedures to improve the reliability of this critical equipment.

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Introduction

The reliability of the Waste Heat Boiler (WHB) is a significant factor in overall SRU reliability. Understanding why WHBs fail provides the insight for establishing a robust WHB design as well as the operational guidelines and procedures necessary for reliable operation.

It is our experience that typical WHB failures are due to three factors: excessive temperatures, excessive mass flux (process through put) and excessive water-side or process-side fouling. Typically, WHB failures are not identified until water leakage occurs and results in unscheduled shutdowns. These factors are discussed and the corresponding considerations necessary for designing a robust WHB are provided in this paper. Also discussed are the necessary considerations for operational parameters to improve the reliability of this critical equipment.

Acid gas flow rates that vary significantly are often not controllable by the SRU operators and can reduce the reliability of the SRU. This is a fact of life. At the same time, the SRU units must successfully operate and maintain acceptable environmental discharge levels. During these varying conditions, the unit can experience excessive temperatures and mass flux rates reducing the reliability of the SRU.

To obtain greater utilization of existing unit capacity the SRU industry has increased mass flux (process flow) rates and also has increased operating temperatures including the use of oxygen-enriched combustion air (particularly in the refining sector). This has been taken to such an extent that WHB reliability can and has been compromised.

Learning From WHB Failures

Learning from WHB failures is a very important tool in improving the operational reliability of existing WHBs. It is also instructive for determining what changes in operational and design parameters changes would increase the reliability for replacement WHBs and WHBs for new units. When a WHB does not provide reasonable reliability, it is imperative to understand the root cause(s) of the failure. The principle inputs for reliability evaluation are the inspection observations, evaluation of the historical operating conditions, operating procedures, installed materials, and installation procedures.

Inspection activities are critical for information gathering to support failure analysis and improvement of reliability considerations. Inspection during a scheduled or un-scheduled unit shutdowns often are conducted quickly to determine the scope of possible necessary repairs before returning to service. These inspections do not typically provide sufficient to understand the failures or provide input for a root cause analysis and a more thorough inspection and collection of critical information is required. For example, if an inspection indicates tube sheet protection system damage and/or ferrule and refractory glazing is observed, the unit has likely been operated at high temperatures that probably compromised the integrity of the tube sheet protection system. Damage to the tube sheet protection system typically leads to corrosion of the metal parts. When the tube sheet protection system damage is observed, collection and documentation of material samples for further internal and vendor evaluation is necessary. Tube sheet, tube sheet-to-tube welds and tube corrosion characteristics observed during inspection may indicate a local problem or a general problem that may have differing root causes. Inspection of a WHB inlet tube sheet should be conducted after a thorough removal of all scale (including from the I.D. of the tubes within the ferrule length) to provide reliable information. This will assist in determining the apparent corrosion mechanism and corrosion rate to support the failure root cause and remaining life analysis.

Inspection observations can also indicate when more than one cause or type of damage exists, such as damage or failure of tubes (Figure F) and tube collapse (Figure G), which may both be due to inadequate boiler water quality, loss of water level in the boiler, or excessive temperature or mass flux. The control of water level may be a contributing factor to tube failures. A root cause analysis may indicate that water level control instrumentation improvements are necessary [1].

Review of historical operating data is one of the most effective tools for input for root cause analysis of WHB failures. Such reviews often confirm operating conditions that are distinctly different from plant personnel's perceptions. As example~~s~~:

- Was the unit started up, placed in hot standby and shut down appropriately and per standard operating procedures?
- What were the principle operating parameters of temperature and mass flux during normal and abnormal operating conditions?

The historical data review should include the total time of operation since the last thorough inspection or a minimum of two years of operation. This type of review is necessary to capture the abnormal operating conditions to which an SRU unit has been subjected. Examples are short duration high mass flux required due to facility operational conditions, or hydrocarbon carry-over in the acid gas feed stream(s). The ability of the operators and the process control systems to maintain the operational reliability of the SRU is often impacted by variations in the feed stream composition, rates, and multiple unit load sharing requirements.

Comparison of WHB steam production to the mass flux and the calculated pseudo-duty (the product of the mass flux and the indicated temperature) is appropriate to confirm that the historical data is reasonable. The indicated process temperatures are also important for comparison to the inspection observations. If the indicated steam production and calculated pseudo-duty are not in agreement, the measurement accuracy of the temperature instrumentation may be a concern. The response time of the process control systems and analyzer feedback to the control system for feed rate variations is critical for controlling process temperatures and to achieving a reliable WHB service result. This can also be evaluated using the historical data.

A thorough engineering analysis of a WHB using state-of–the-art tools can provide insight as to root cause of failure mechanisms. Analysis tools such as computational fluid dynamics (CFD) [8], can also assist in determining the most accurate and closest-to-actuality refractory, ferrule and metal temperatures. Appropriate temperature and mass flux operating conditions can also be established to provide reliable service for a specific WHB [5]. The limitations of heat flux in the turbulent region at the end of the ferrule and ability of the tube sheet protection system to maintain suitable metal temperatures can be studied with these engineering tools. The effect of the burner flame pattern and the resulting refractory and tube sheet protection system ferrule temperatures can also be analyzed. The CFD analysis, which can include both the process and water services of the WHB, can indicate what physical and process parameter changes could be possible to improve the reliability of the WHB [4][5].

Excessive Process Temperature

The reaction furnace operating temperature varies depending on the feed gas composition and the portion of the H_2S content that is combusted to SO_2 in the reaction furnace. Generally, only about one third of the H_2S is combusted in the reaction furnace. This is a necessary process condition for the conversion of the balance of the H_2S and the SO_2 to elemental sulfur in the downstream Claus process catalyst beds. Oxygen enrichment can also be used to maintain a minimum temperature in the reaction furnace for lower H_2S concentration feed gas.

Typical reaction furnace temperatures range from approximately 982 °C (1800 °F) - the minimum often found in gas conditioning units - to a 1540°C (~2800° F) maximum (often found in refinery units). Cold starts, hot restarts, hot standby, and unusual operating conditions can increase these temperatures and the rate of component temperature changes. These can all affect the reliability of components such as the tube sheet protection system.

In gas plant service, Claus reaction furnaces typically operate with acid gas in a sub-stoichiometric combustion environment using atmospheric air as the oxygen source. Co-firing natural gas is sometimes necessary to maintain sufficient reaction furnace temperatures for suitable Claus processing of 982 °C (1800 °F) and approximately 1093 °C (2000 °F) minimum temperature for destruction of BTEX components if these are present in the feed gas. Oxygen enrichment of the combustion air can reduce or replace co-firing of natural gas, but can also contribute to potential excessive temperatures during variances from normal operations.

In refinery service, Claus reaction furnaces typically operate with a combination of amine acid gas and sour water acid gas [9] burning in a sub-stoichiometric combustion environment using atmospheric air as the oxygen source. As plants were de-bottlenecked for needed increased sulfur capacity, it was determined that increasing the oxygen content to the burner would allow increased capacity with the same furnace, WHB, and balance of the train. Improved burner technology allowed even greater increases in oxygen enrichment and allowing more sulfur to be produced with the same plant. The incorporation of oxygen enrichment technology has become a standard option for new SRU units. However, the higher temperatures encountered with the oxygen-enriched operations can exceed the maximum temperature limitations of industry best practices for design and materials and have resulted in reduced reliability and increased failures.

The continuous operating temperature limit for industry best practice thermal protection systems (both refractory and tube sheet protection systems) materials, design and installation, is approximately 1540°C (~2800° F). A well designed *system* (note the emphasis on the word *system*) can operate successfully for very brief periods of time at temperatures above 1540°C (~2800° F), but only by sacrificing reliability. If a 3-4 year life is desired for the thermal protection systems and, in particular, the tube sheet protection system, the design operating temperature should be somewhat less than 1540°C (2800°F).

Increased temperature affects the reliability of the WHB by degrading the tube sheet protection system. As an example, excessive temperature was determined to be the root cause of the failure shown in Figure A. The indicated failure scenario was excessive temperature degrading of the tube sheet protection. This resulted in increased temperature of the metal parts, which resulted in a corrosion related failure of the tube-to-tube sheet weld. This resulted in leaking of boiler water into the reaction furnace.

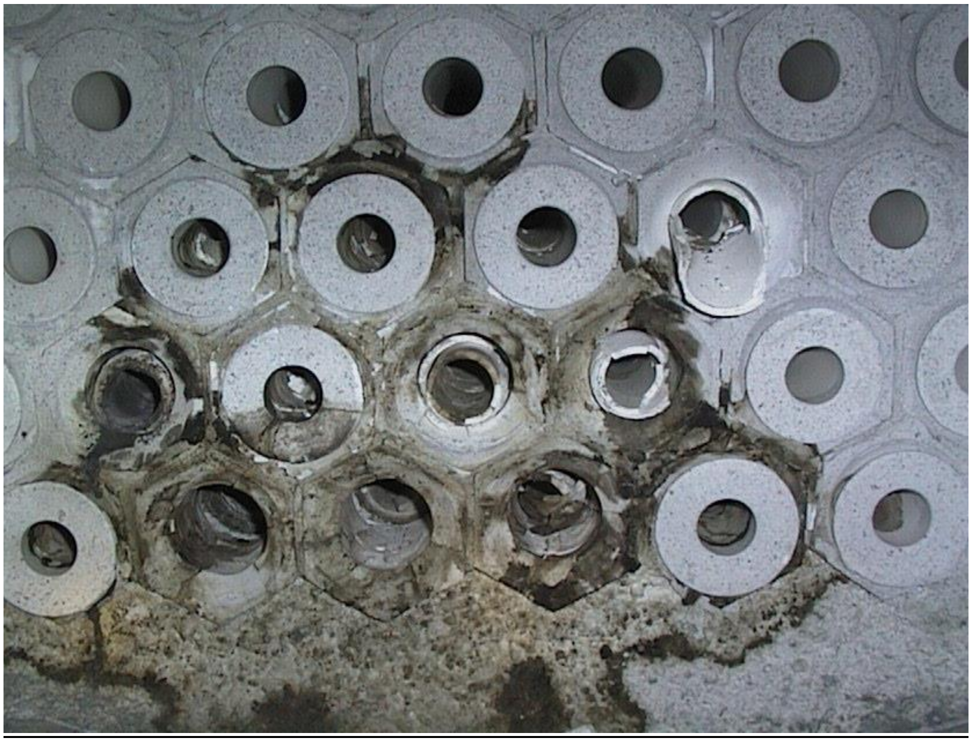

Figure A - Tube Sheet Protection System Failure with Boiler Water Leakage

Hot standby operations have the potential to produce excessive temperatures. Therefore, tempering of the sub-stoichiometric hydrocarbon or hydrogen combustion is necessary [1]. Short term hot standby operation of well less than an hour (without adequate tempering) can significantly impact the reliably of the refractory and ferrule systems. Temperatures significantly in excess of 1650°C (3000°F) can occur without adequate tempering. At or near stoichiometric firing, high temperature for natural gas can exceed 1871°C (3400°F) [1]. Hydrogen and propane stoichiometric temperatures are even higher. This high temperature situation results in significant tube sheet protection system failure, refractory system failure and reduced reliability.

It should be noted that pyrometer temperature measurements may be highly influenced by the process gas analysis change, such as those that occur with oxygen enrichment. Pyrometers set for "air-only" will normally read low by as much as several hundred degrees during oxygen enrichment operation. As a caution, we would suggest that there are inherent inaccuracies of ALL temperature measurement devices due to issues such as installation, location, calibration, interference, maintenance, etc. Therefore, any specific plant readings might be off (normally low) by as much several hundred degrees F. Figure B is an example of a severely damaged tube sheet protection system where the high alumna ferrule inlets were melted. This melting indicated temperatures in excess of 1815 °C (3300 °F). The temperature instrumentation did not report temperatures that were anywhere near this high.

Figure B - Example of Ferrule Damage Due to Excessive Operating Temperature

Sudden changes in process temperature can be detrimental to the WHB tube sheet protection system, resulting in a loss of system reliability. This is also increases corrosion potential for the tube sheet and tube-to-tube sheet welds. Significant changes of the WHB steam pressure during startup or shutdown can potentially over-stress the tubes in compression or tension, depending on the developed temperature differential between the relatively thin tube wall versus the much thicker shell. For example, the lowering of the steam pressure during a unit shutdown has been identified as overstressing and cracking of tube-to-tube sheet welds that were already thinned due to corrosion.

Hot restarts have been identified as subjecting the tube sheet protection system to significant temperature changes. The loss of process gas flow for a short period of time (less than 15 minutes) allows the ferrules to be cooled by the boiler water while the gas in the furnace stays essentially at the hot refractory face temperature. When the burner is fired again, the hot gas from the furnace flowing through the ferrules subjects them to significant rates of temperature change (which can occur in less than 5 minutes) and which can result in ceramic ferrule cracking.

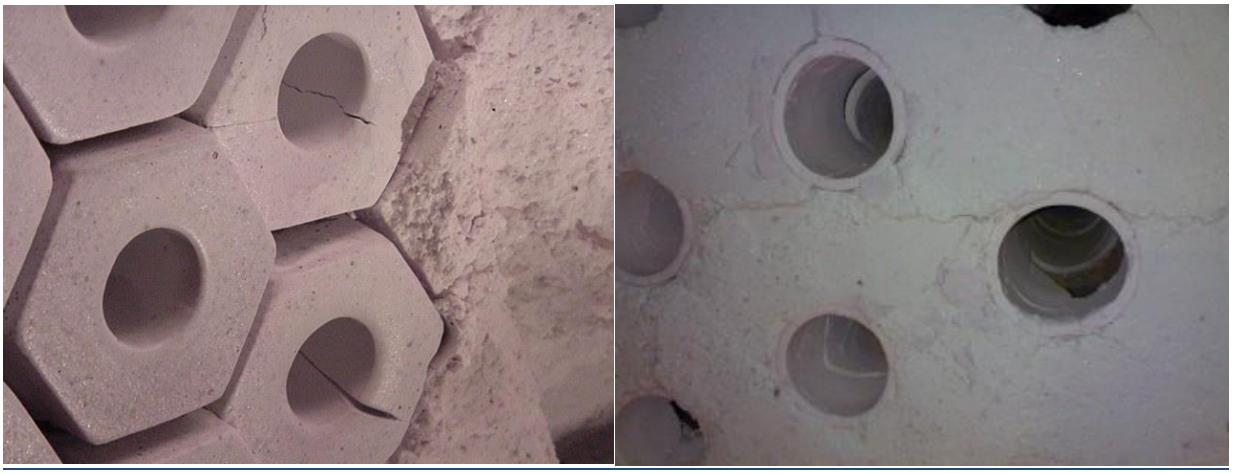

Figure C - Ferrule Cracking Examples

It is important to note here that the thermal protection of the tubes and tube sheet is almost entirely governed by the paper/board between the ceramic ferrule and the metal. The typical ceramic ferrules are not good thermal insulators. Their primary function is to protect the paper/board from the gas flow. The temperature drop occurs almost entirely across the paper [4].

Excessive Process Mass Flux

Mass flux refers to the mass flow rate through the tube set. It is the total mass flow through the unit divided by the open area of all the tubes. As with temperatures, industry practice has been to increase the mass flux rate as a means of achieving increased capacity without increasing the tube area. It is common today to have design and operating mass flux rates that are twice the design and operating mass fluxes from 20 to 30 years ago. Excessive mass flux will result in significantly increased pressure drop at the entrance to the ferrules. This pressure drop can increase the gas bypass of an individual ferrule, leading to significant increases in the metal temperature, which results in corrosion [4]. This higher temperature leads to accelerated sulfidation corrosion of the tube sheet and tube welds. Thus, the increased mass flux rate adversely affects the WHB tube sheet protection system's reliability [4]. This is true for both removable ferrule and non-removable ferrule systems. Figure D illustrates a tube sheet (on the left) where severe corrosion has occurred after only two years of service. The welds between the tubes and tube sheet have almost corroded away and some were leaking. The replacement WHB tube sheet, on the right, after five years in the same service, looks almost pristine [5][6]. Although the normal process operating temperature was essentially the same, the difference is that the tube sheet on the left has seen much higher mass flux in operation than the one on the right. The replacement WHB was designed to provide a significantly reduced mass flux, which greatly improved reliability.

Just to repeat, the only difference between severe corrosion in two years (on the left) and almost no corrosion in five years (on the right) is a lower mass flux.

Figure D – Severly Corroded Original and Non-Corroded Replacement WHB Tube Sheets

The carbon steel metal rate of corrosion is a function of the metal temperature and H_2S concentration. ASM [7] has published a series of curves by Couper-Gorman that relate the rate of corrosion in carbon and stainless steels for several refinery sulfidation environments. It has been our experience that these Couper-Gorman curves are somewhat conservative for the SRU environment. For a number of years, we have used a modified Couper-Gorman curve (Figure E) that we find correlates better to the actual experience in SRUs. [5][6].

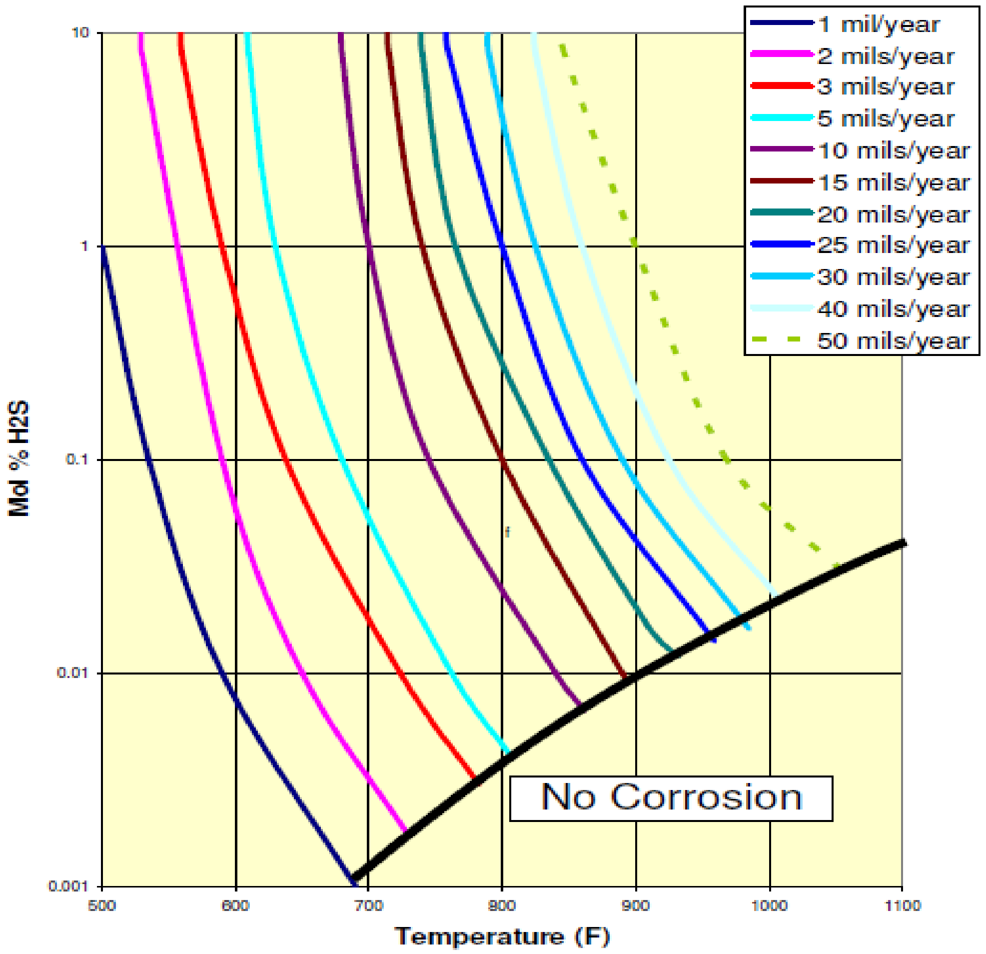

Figure E - Modified Couper-Gorman Curves for SRU Service

The increased mass flux rate also increases the heat flux through the tubes. This can result in a Leidenfrost steam blanketing or tube dry-out condition that usually occurs at the end of the ferrules. [2][3]. When this happens, the tube metal temperature can go up by 300°C (540°F) or more in a matter of minutes. This can result in short-term creep tube partial collapse, as illustrated in Figure F or a tube failure, as indicated in Figure G. This condition occurs more frequently in kettle type boilers but can also occur in those with a separate steam drum.

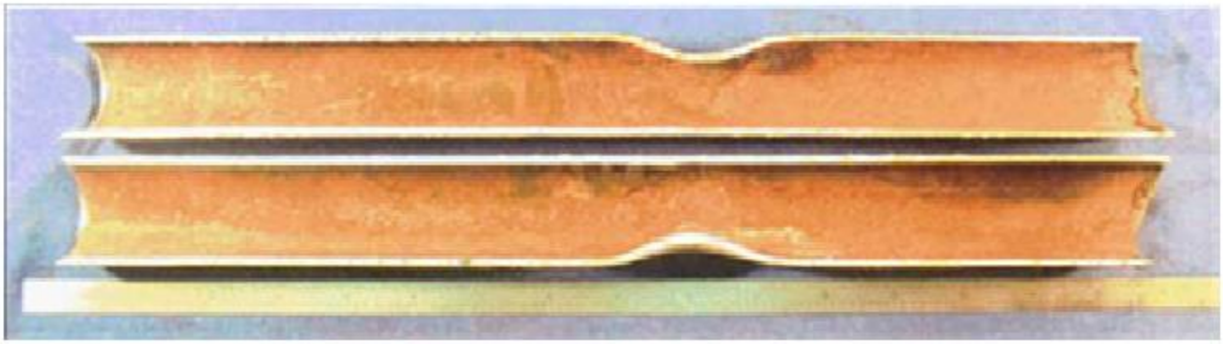

Figure F - Tube Partial Collapse at End of Ferrule Due to Steam Blanketing Conditions

Figure G - Tube Collapse at End of Ferrule Due to Steam Blanketing Condition
OD View on Left and ID View on Right

Excessive Water-Side Fouling

Increases in both operating temperature and mass flux can increase the tube heat flux. This can increase the potential for water-side fouling. The water-side (tube OD) fouling reduces the heat flux on the outside of the tube by insulating it from the water, which results in higher tube metal temperatures. In turn, these higher metal temperatures resulted in significant sulfidation of the tube ID and tube wall loss at the end of the ferrule, as illustrated in Figure [H].

Figure H - Corrosion at end of ferrule due to water side fouling

Water-side fouling is usually associated with either poor boiler feed water quality or inadequate boiler blow-down or chemical treatment, resulting in excessive concentration of the suspended and dissolved solids. In the case illustrated in Figure H, the root cause for the kettle type WHB failure was attributed to water-side fouling. This was identified as being due to the lack of intermittent blow-down use. This resulted in excessive concentration of suspended solids in the boiler water near the bottom of the WHB. However, since the sample point location was on the continuous blow-down line, the presence of concentrated suspended solids was not identified by the routine analysis of boiler water quality. Water quality sampling will not prevent tube-side fouling if the intermittent blow-down is not used appropriately.

The water circulation pattern through the tube bundle is also a factor for fouling. Local areas of low circulation rates can encourage fouling due to an increased vapor volume percentage. Water-side analysis using CFD analysis (Figure I) can be used to confirm adequate water circulation [3]. Water circulation concerns are more prevalent in two pass in one shell design kettle type WHBs and are seldom a concern in well-designed external steam drum WHBs.

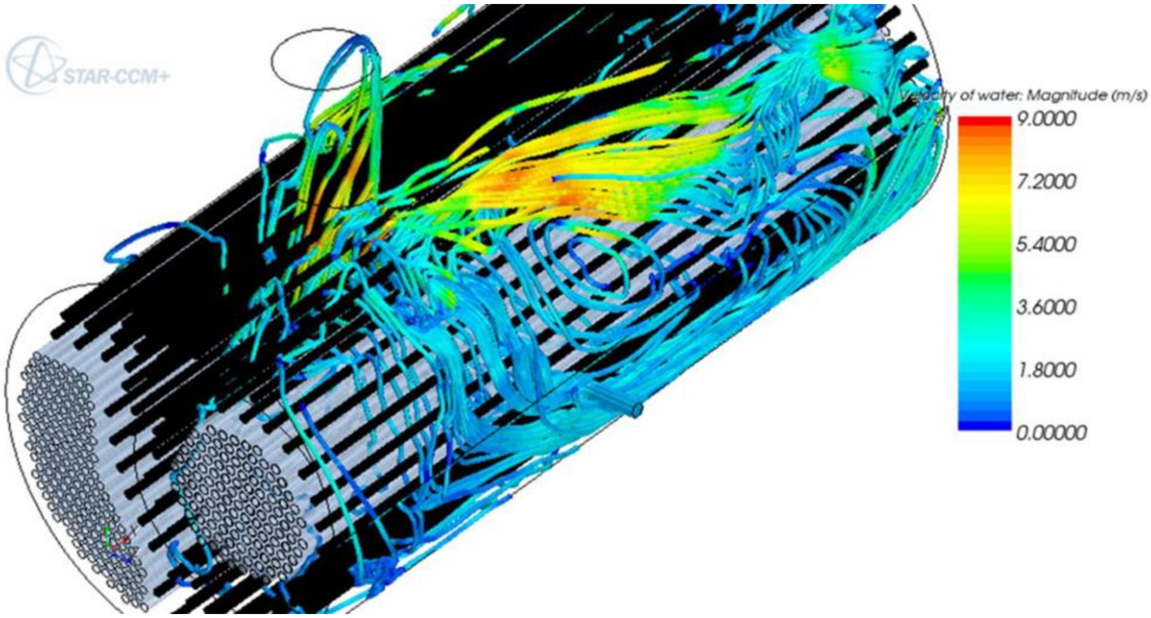

Figure I - CFD of water-side of two pass kettle boiler

Excessive Process Side Fouling

Process fouling on the ID of the tubes does occur and can result in increased process gas temperature exiting the tube and can result in sulfidation corrosion downstream. It should be noted that in a two pass WHB arrangement, fouling on the process-side (ID of tube) typically occurs in the first pass. This can result in sulfidation of unprotected channels and tube sheets at the “cold end” of the first pass and the turbulent area at the entrance to the second pass tubes or, in rare instances, the first sulfur condenser inlet. It is often difficult to determine the source of process fouling even though it is usually expected to come from the acid gas feed(s) or the fuel or, in some cases, from the tempering steam used during operations. Sampling and analysis of the fouling material can provide some information, but even with this information, it is often impossible to determine the source of the fouling.

Removal of the fouling can be as simple as air or steam blowing for soft material;harder material requires a more aggressive approach. It should be noted caution is required to avoid damaging the tubes. Some WHB tube failures have been caused by past (harsh) cleaning procedures (such as high pressure water blasting and media blasting) that damaged/thinned the tubes, which failed when returned to service.

New and Replacement WHB Specifications

There is no industry consensus document to which an owner and operator can refer when specifying the details necessary for a reliable and robust WHB. Guidance can be found in published technical papers and obtained from various subject matter experts. Where reliability and operating parameter experience is available on an existing SRU unit, it should be combined with this guidance information. This will provide the foundation for establishing the physical and operational criteria and specifications for the detailed design of a similar WHB with improved reliability and robustness [5].

For establishing a robust and reliable WHB (fire tube type) design, the authors offer the following guidance:

1. Fully define all intended operating scenarios and add “knowledge” gleaned from any current unit operations.

2. For the water-side service (using ASME code for references):
   a. Confirm and specify the quality of the feed and boiler drum water, per recommendations by ASME and American Boiler Manufactures Association (ABMA)
   b. Confirm the generated steam quality requirement and specify the necessary steam/water separation to be incorporated
   c. Determine if ASME Section 1 or Section VIII is appropriate per applicable jurisdiction
      i. ASME Section I has steam generation specific requirements. These requirements are also directly applicable to an ASME Section VIII boiler. Such Section I requirements as Post Weld Heat treat (PWH), feed water nozzle designs, inspection ports, and the number and sizing of relief valve requirements should be included for a Section VIII WHB. Section VIII boilers may use block valves under relief valves, depending on the jurisdictional requirements.
   d. For kettle type boiler (single pass or two pass in one shell) or an external steam drum [one shell or two shell (two passes)]:
      i. For a kettle type boiler there is very limited public domain guidance for water recirculation design requirements. Recirculation-related parameters such as tube-to-shell clearance, location of feed water nozzle(s), and available water

capacity (steaming time at full rated capacity) from normal water level to shutdown water level will have an effect on the reliability of the WHB. API 538 for industrial boilers (water tube type) does have some information that may be related to a fire tube kettle type boiler. It is recommended that the recirculation-related parameters be based on past successful application or, for better information, CFD analyses. It is imperative that the feed water does not impede distribution along the length of the tube bundle. Poor circulation near the tubesheets is a contributor to many failures.

    ii. For a separate steam drum type boiler, the design should be based on a 20:1 recirculation rate (pounds of water : pounds of steam generated). API 538 for industrial boilers (water tube type) does have some information that may be related to a fire tube separate steam drum type boiler. Down comer and riser should be located near the hot end tube sheet
    iii.
        1. There should be a down comer and riser set very near the hot tube sheet.
        2. The feed water should enter the steam drum and include a distributor such that the feed water does not preferentially run down one down comer.
    iv. For both type boilers, the tube support(s) should be designed and located such that the flows of steam generated and water circulation are not restricted, particularly for steam volume exiting the tube bundle.

3. For the process-side service (using ASME code and TEMA Standard for references), post weld heat treat for carbon steel is not necessary for the process conditions however and the code requirement per thickness is applicable.
    a. The use of larger diameter tubes, low mass flux and low heat flux are considered to be important elements for the design of a robust and reliable WHB
    b. Tubes:
        i. Use of 3 inch diameter schedule 80 pipe (SA 106B material) and 3½ inch diameter 2 gauge tubes (SA 210 material) are considered to be best practice. The use of 3 inch diameter tube is the minimum tube size recommended.
    c. Tube sheet carbon steel (SA 516 – 70 or 60) using a flexible tube sheet tube staying design is preferred. Where a flat rigid tube sheet tube, with or without stays is used, a rigorous stress analysis is recommended:
        i. For kettle type, both a flexible and a flat rigid tube sheet are used, depending on the configuration of the boiler.
        ii. For a separate steam drum type single pass design, a flexible tube sheet is preferred.
        iii. Tubes are to be strength-welded using a contact roll prior to welding and a light roll after welding with a 2 - 3 % maximum wall reduction limitation. TEMA type grooves in the tube hole are not recommended.

    iv. For the hot tube sheet, the tube ends should be flush with no or minimal weld material extending from the tube sheet face to avoid a hot fin condition resulting in increased metal temperature and corrosion.
    v. Recommended tube pattern is square or rotated square with a minimum 1.3 pitch to accommodate water distribution and steam traffic. Triangular pitch tube pattern has been used successfully.
    vi. Tube hole spacing for a tube sheet protection system using removable ferrules is important because the gap between the ferrule heads is a potential hot gas bypass location [4]. The tube hole pitch tolerance should be specified and should be developed in conjunction with the ferrule vendor. It should be noted that the standard TEMA ligament width tolerances may be excessive.
    vii. It is recommended that the tube ID be confirmed after welding and rolling with no-go and go gauges to prove suitability for ferrule insertion.

4. The tube sheet protection system should use materials suitable for a 1540 °C (2800 °F) continuous maximum operating temperature. The current industry best practice uses ~ 94% alumina ferrules and castable refractory. The design and installation specifications for the tube sheet protection system should be developed in conjunction with the ferrule vendor. Additional information is available in the reference documents listed in this paper. This is recommended unless fuel gas firing conditions, including tempering steam, can maintain temperatures similar to normal operating temperatures.

5. Depending on the WHB design, the exit temperature from the WHB first pass may be high enough to be a concern for sulfidation of the exit channel. Experience indicates that for process gas temperature exceeding 482 °C (900 °F), it is appropriate to use of refractory linings and tube sheet coverage and ferrules for the inlet of the next tube bundle.

6. The installation of temperature monitoring of the WHB first pass outlet temperature (such as a test thermowell or instrumented temperature indication) is a good practice from both a tube fouling evaluation and potential sulfidation monitoring perspectives.

No universally agreed upon limit exists for the mass flux rate to achieve reliability in a waste heat boiler. The parameters of tube diameter, ferrule dimensions and process temperature are all important for determining the mass flux appropriate for the tube sheet protection system and for avoiding a Leidenfrost condition. However, experience has shown that boilers operating at a mass flux of less than 12.2 kg/m2-sec (2.5 lb/ft^2-sec) have experienced good reliability with some runs exceeding 8 years without failure. Units operating at 25 kg/m^2-sec (5.1 lb/ft^2-sec) or above have typically exhibited failures within two years or less. Based on the information that we have collected, it is recommended that for process gas design temperatures of 1315 °C (2400 °F) and greater, a mass flux of less than 12.2 kg/m^2-sec (2.5 lb/ft^2-sec) be used to achieve greater reliability of the tube sheet protection system. This helps to maintain acceptable metal temperatures, thus avoiding significant sulfidation corrosion. There is also less potential for Leidenfrost conditions, which results in good WHB reliability. For process gas design temperatures of less than 1315 °C (2400 °F), somewhat increased mass flux rates may be possible; however, sufficient information is not available at this time to provide guidance. Therefore, it is recommended to not exceed 12.2 kg/m^2-sec (2.5 lb/ft^2-sec) unless existing unit operating reliability information is available to provide creditable guidance.

Operating Parameters and Procedures

It is important to have established, formal operating guidelines for routine and non-routine activities established for operating within the design parameters of the WHB. The most robustly designed and fabricated WHB cannot be reliable, as discussed above, if the process gas temperature and/or mass flux is excessive, the boiler drum water of not of satisfactory quality, or the water level is not maintained. To improve the reliability of existing units, the written procedures and non-written best practices should be reviewed and updated periodically to address feedback from root cause and secondary cause analysis results. Non-written best practices and strategies for addressing unusual operations should be reviewed and documented (i.e., they should become *written* best practices). Training for unit operators should be updated to provide the best operating outcomes. As noted above, there are operating conditions affecting the WHB reliability that the unit operators cannot control. These need to be addressed by the units producing the SRU feed gases.

Below are the most important operational items from the authors' viewpoint:

1. Avoid excessive temperatures and mass flux. The maximum continuous service temperature of the industry best practice refractory and tube sheet protection systems is 1540°C (~2800° F). The maximum carbon steel service temperature for sulfidation corrosion is 320 °C (~610 °F).
    a. To protect the thermal protection system from >1540°C (2800°F) conditions, a 100°C (180°F) buffer between the normal and maximum operating temperatures is the minimum that can be used. With this small margin for error, it takes well-designed and calibrated temperature measurement and process control systems, along with vigilant operators, to control the temperature and avoid reducing the reliability of the thermal protection systems.
    b. It should be noted that it is difficult to adequately measure the temperature in the reaction furnace. This has led to instances where these measurements have reported temperatures several hundred degrees less than were indicated by the refractory and ceramic materials during inspections. In these instances it is common for the historical process control system temperature measurement data to not indicate temperatures above 1540°C (2800°F) and sometimes not above 1425°C (2600°F). Since these personnel are unaware of the actual operating temperature, these readings do not provide the unit operators with sufficient information to maintain unit reliability
    c. High temperature unit shutdown should be used and set near the maximum operating temperature limit for the installation (as discussed above). One strategy is to set the shutdown at the maximum operating temperature, for the industry best practice installation with a 5 minute delay before shutdown. That said, the authors caution

that the use of reaction furnace temperature measuring pyrometers for shutdown purposes is not as accurate as the use of specialized hot face themocouples. In addition the authors caution that from their analysis and experience, thermocouples (which measure the hot face of the refractory in the furnace) indicate a lower temperature than the core gas temperature entering the WHB. This differential temperature is typically 110°C (200°F) or more when running at a maximum continuous actual service temperature of 1540°C (2800°F).

   d. Some owners have provided unit operations with guidance on feed rates and associated operating parameters based on bounding graphs similar to Figure J (below) from reference technical paper [3] that addresses Leidenfrost considerations.

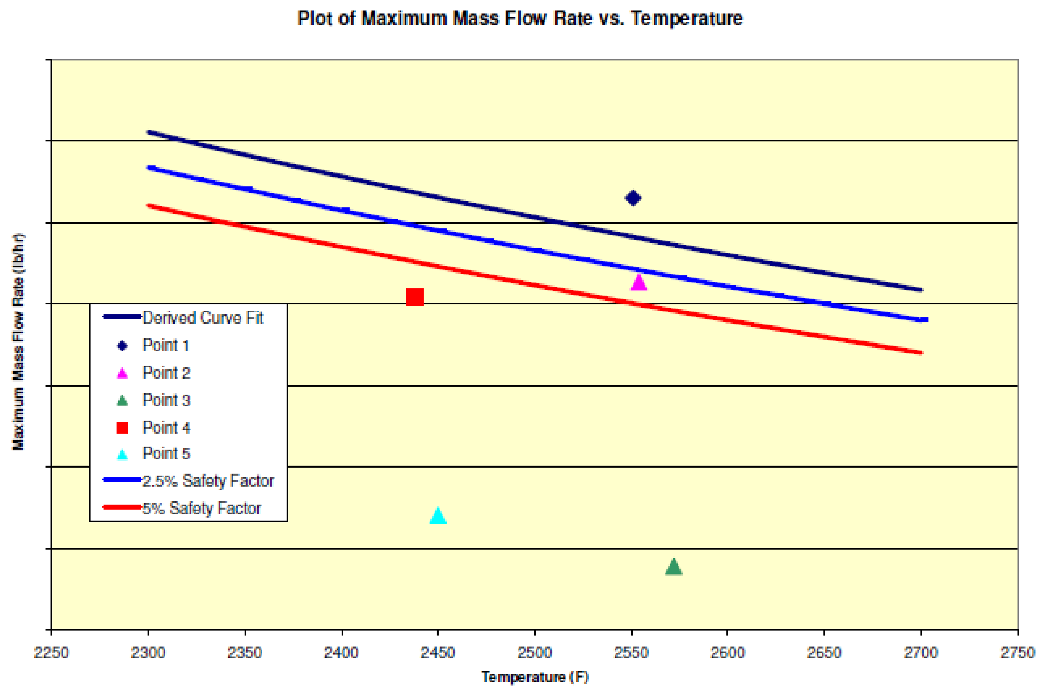

Figure J - Example of Operational Parameters for Avoiding Leidenfrost Conditions

2. The use of tempering steam is necessary for fuel gas firing during heating up, shutting down, and hot standby operations [1].
   a. Tempering steam flow indication and flow control loop should be provided, including consideration for steam to the fuel gas flow ratio control.
   b. It should be noted that the heating up, shutting down and hot standby operating temperatures, even with tempering steam, can exceed normal operating temperatures. For this reason it is common practice to use the industry best practice materials for the refractory and tube sheet protection systems, providing for maximum continuous service temperature of 1540°C (2800°F) to support the tempering effort, even though the normal operating temperature is less.

3. The boiler water quality must be adequately maintained and should be monitored effectively.

   a. As noted above, tube water-side fouling can result in tube failures. Operating procedures should include the effective use of continuous and intermittent blow-downs and water quality sampling.
   b. For example, a water sampling point on the continuous blow down may not represent the boiler drum water quality in the lower part of a kettle boiler or in an external steam drum. If the continuous blow down location is near or above the normal water level or after the flow control valve, the sample cooler may actually be condensing steam along with cooling the water if a two phase flow condition occurs. This could indicate better water quality than actually exists within the boiler.

4. Every effort should be made to reduce unit trips because each hot restart has the potential to damage the tube sheet protection system.
   a. For example, the use of 2 out of 3 type voting instrumentation for low boiler water level shutdowns will help avoid superfluous trips.
5. Avoid deflagrations, including “lighting off the wall” for hot restarts, as these have the potential to damage the tube sheet protection system.
6. If there is new or repaired castable refractory, use a suitable refractory dry-out procedure and do not rush the heating up and dry out operation.

References:

[1] Top Five Fundamental Integrity Issues for SRU Waste Heat Exchanger (Boiler), panel discussion presented at Brimstone 2011 Conference. Panel included the following technical papers:

- Burner Flame Temperature During Warm Up and Hot Standby by Alan_Mosher (KPS Technology & Engineering LLC)
- Ferrule Design and Installation for SRU Tube sheets by Domenica Misale (Industrial Ceramics Limited)
- Boiler Water Level Safety Considerations and Tube Collapse by Lon Stern (Stern Treating & Sulfur Recovery Consulting, Inc.)
- Tube and Tube Weld Corrosion and Tube Collapse by Dennis Martens (Porter McGuffie, Inc.)
- SRU Overpressure In A Waste Heat Boiler Failure by Justin Lamar (Black & Veatch, Inc.)

[2] A Means of Avoiding Sulfur Recovery Furnace Fired Tube Boiler Failures, presented at Brimstone 2009 Conference by Mike Porter, Dennis Martens and Sean McGuffie (Porter McGuffie, Inc.) and John Wheeler (Motiva Enterprises)

[3] 2009 ASME PVP paper number 78073, A Means of Avoiding Sulfur Recovery Reaction Furnace Fired Tube Boiler Failures, by Mike Porter, Dennis Martens, Sean McGuffie (Porter McGuffie, Inc.), John Wheeler (Motiva Convent)

[4] 2005 ASME PVP paper number 71143 “Computational Fluid Dynamics Investigation of a High Temperature Waste Heat Exchanger Tube Sheet Assembly”, by Mike Porter, Dennis Martens, Sean McGuffie (Porter McGuffie Inc.), Tom Duffy (Motiva Convent)

[5] Robust SRU Waste Heat Boiler Design, presented at Brimstone 2012 conference by Sean McGuffie and Dennis Martens (Porter McGuffie Inc.), Mike Demskie (Flint Hills Resources)

[6] 2011 ASME PVP paper number 57625 “Combining CFD Derived Information and Thermodynamic Analysis to Investigate Waste Heat Boiler Characteristics”, by Sean McGuffie, Mike Porter, Dennis Martens (Porter McGuffie Inc.), Mike Demskie (Flint Hills Resources)

[7] Metals Handbook Ninth Edition Volume 13 Corrosion, Copyright 1987, ASM International

[8] 2012 ASME PVP Conference Tutorial “Use of CFD in Design”, by Sean McGuffie, Mike Porter, Thomas Hirst (Porter McGuffie Inc.).

[9] Mechanisms of Ammonia Destruction in the Claus Furnace, by Peter D. Clark, Norman I. Dowling and Minming Huang (Alberta Sulfur Research LTD) presented at 2001 Laurance Reid Gas Conditioning Conference