Why do waste heat boilers fail?

D. Martens and **M. Porter** of Porter McGuffie, Inc. and **L. Stern** of Stern Treating & Sulphur Recovery Consulting, Inc. examine the main causes of waste heat boiler failures in Claus sulphur recovery units and discuss what lessons can be learned from past WHB failures.

Why do waste heat boilers in sulphur plants fail? We can look to the auto racing industry to find the answer. Engine size in Formula 1 race cars has continually reduced over the years as engineers have found ways to make the cars go faster and faster with a given engine size. On its super speedways, NASCAR places restrictor plates below the carburettor to limit engine output. Similar efforts take place in almost all types of racing. Why? Because the limiting factor is the ability of the driver to react quickly enough to safely control the car. Waste heat boilers fail because we try to operate them at levels beyond which we can adequately design and safely control them to provide reliable operation.

Typically waste heat boilers (WHBs) fail due to three factors: excessive temperature, excessive mass flux rate and excessive water-side fouling[1]. Similar to the racing industry, the sulphur industry has increased temperatures and mass flux (process flow) rates to obtain greater unit capacity. However, this push has exceeded reasonable bounds, to the extent that reliability of a unit can be and has been compromised. To maintain acceptable discharge environmental criteria, often the sulphur recovery units (SRUs) must operate with significant variance in acid gas flow rates – variances that are not controllable by the SRU operators. Water-side fouling is potentially affected by these same parameters and becomes a significant factor for reduced reliability.

Excessive temperature

Reaction furnaces (e.g., in refinery service) were originally operated with a combination of amine acid gas and sour water acid gas burning in a sub-stoichiometric combustion environment using atmospheric air as the oxygen source. As plants were debottlenecked for needed increased sulphur capacity, it was determined that increasing the oxygen content to the burner would allow increased capacity with the same furnace and boiler. Improved burner technology allowed even greater increases in oxygen enrichment and, consequently, more sulphur was produced by the same plant. This added oxygen technology has become a standard offering for new SRU units. However, the higher temperatures encountered with oxygen enriched operations has resulted in cases where we are bumping up against the sulphur plant's "speed limit".

The continuous operating temperature limit for modern, well-designed and installed thermal protection systems (both refractory and ferrule systems) is approximately 1,540°C. A well designed system (please note the emphasis on the word system) can operate successfully for brief periods of time at temperatures above 1,540°C, but only by sacrificing reliability. If a 3-4 year life is desired for the thermal protection systems, the design operating temperature should be somewhat less than 1,540°C. A 100°C buffer between the normal and maximum operating temperature is about the minimum that can be used to protect the thermal protection system from negative (i.e., >1,540°C) conditions. With this small margin for error, it takes a well-designed and calibrated temperature measurement system, a process control system, and vigilant operators to control the temperature and avoid reducing the reliability of these thermal protection systems. Increased temperatures affect the reliability of the WHB by increasing the temperature of the metal parts, which can increase corrosion. It also increases the heat flux through the tubes, which can result in a Leidenfrost steam blanketing condition that usually occurs at the end of the ferrules[2,3].

The ability to accurately simulate and monitor the furnace core gas temperatures is often a problem that can result in excessive operating temperatures. It is common to use both pyrometers and thermocouples to provide the best possible temperature measurements. However, during shutdown inspections the refractory and ferrule materials will often indicate that the operational temperatures were actually above 1,650°C. At the same time, the process control system temperature measurement historical data often does not indicate temperatures above 1,540°C and sometimes not above 1,425°C.

One strategy for high temperature shutdown protection is to use thermocouples in the furnace with the shutdown set at 1,540°C for five minutes. The 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 or more.

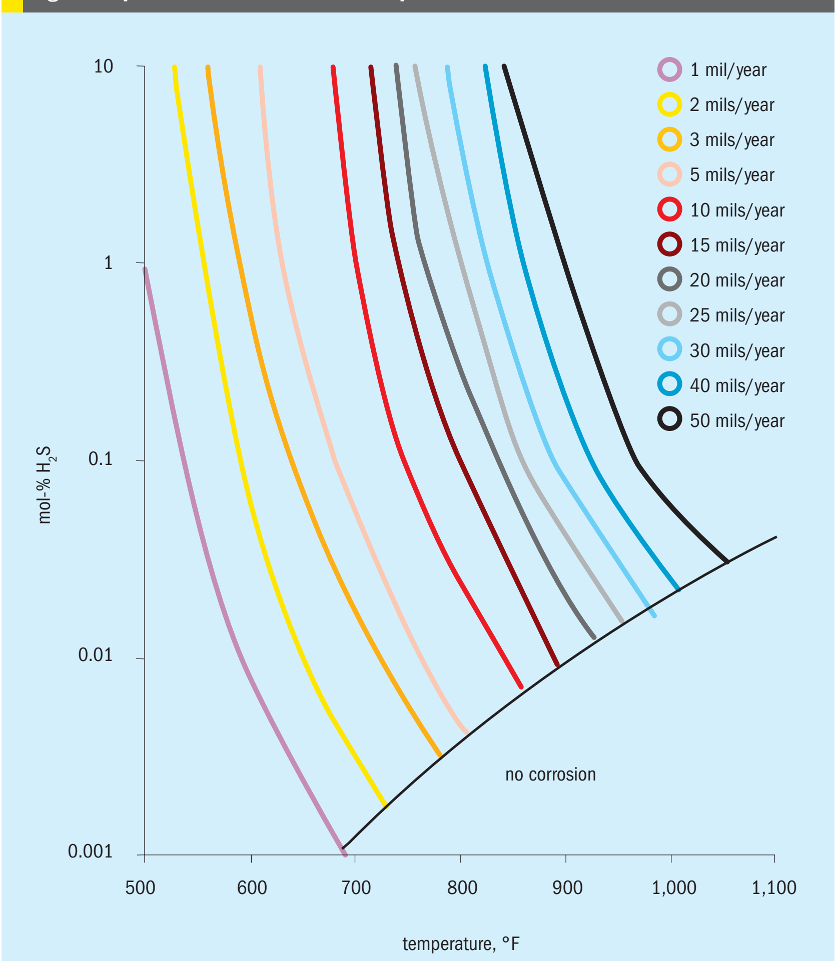
It should be noted that pyrometer temperature measurements may be highly influenced by the process gas analysis change (such as occurs with oxygen enrichment). Pyrometers set for air only will normally read low by as much as several hundred degrees. As a caution, we would suggest that there are inherent inaccuracies of all temperature measurement devices due to installation, location, calibration, interference, maintenance, etc., issues. Therefore, any specific plant reading can be off by as much several hundred degrees C. This discrepancy is normally lower than the actual temperature.

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 much less than an hour without adequate tempering can significantly impact the reliability of the refractory and ferrule systems. Temperatures in excess of 1,650°C can occur without adequate tempering. A stoichiometric high temperature can result in significant ferrule system failure and/or reduced reliability.

Sudden changes in process temperature can be detrimental to the WHB tube sheet protection system, resulting in a loss of system reliability and increased corrosion potential for the tube sheet and tube welds. Significant changes of the WHB steam pressure 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 the tube-to-tube sheet welds that were already thinned due to corrosion.

Fig 1: **Severely corroded and non-corroded tube sheets**

Fig 2: **Proposed Claus SRU service sulphidation corrosion curve for carbon steel**



Mass flux rates

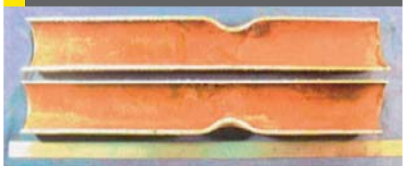
Mass flux refers to the mass flow rate through the tube set. It is the total mass flow through the unit divided by the open area of all the tubes. As with temperatures, common practice has been to increase the mass flux rate as a means of achieving increased capacity without increasing the tube area. It is common to have design and operating mass flux rates today that are twice the design and operating mass fluxes from two to three decades ago. Excessive mass flux will result in a significantly increased pressure drop at the entrance to the ferrules. This pressure drop can be expected to increase the gas bypass of an individual ferrule, leading to significant Increases in the metal temperature and resulting corrosion[4].

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 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 is almost all across the paper.

This higher temperature results in accelerated sulphidation corrosion of the tube sheet and tube welds. Thus, the increased mass flux rate adversely affects the WHB tube sheet protection system's reliability. This is true for both removable ferrule and non-removable ferrule systems. Figure 1 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 been corroded away and some are leaking. After five years in the same service, the replacement WHB tube sheet on the right looks almost pristine[5,6]. The difference is that the tube sheet on the left has seen much higher temperatures in operation than the one on the right although the normal process operating temperature was essentially the same. However, the mass flux was reduced significantly.

The rate of corrosion in a waste heat boiler is a function of the metal temperature. 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 environments. It has been the authors' experience that these Couper-Gorman curves are somewhat conservative for the SRU environment. For a number of

Fig 3: **Tube partial collapse at end of ferrule due to steam blanketing conditions**



years, therefore, a modified Couper-Gorman curve has been used that correlates better to the actual experience in SRUs. Figure 2 illustrates this modified Couper-Groman curve for SRU service.

The increased mass flux rate also raises the heat flux through the tubes, which can result in a Leidenfrost steam blanketing or tube dry-out condition that usually occurs at the end of the ferrules. When this happens, the tube metal temperature can go up by 300°C or more in a matter of minutes. This can result in short term creep, as illustrated in Fig. 3. This condition occurs more frequently in kettle type boilers but can occur in those with a separate steam drum.

There is no universally agreed upon limit for the mass flux rate to achieve reliability in a waste heat boiler. However, experience has shown that boilers operating at a mass flux of less than 12.2 kg/m^2-sec have runs exceeding eight years without failure. Units operating at 25 kg/m^2-sec or above have often exhibited failures within two years or less. Based on information collected, the closer the unit can be operated at a mass flux of 12.2 kg/m^2-sec, the greater the reliability of the tube sheet protection system to maintain acceptable metal temperatures and less potential for Leidenfrost conditions.

Water-side tube fouling

The increase in both operating temperature and mass flux increase the tube heat flux, which can increase the potential for water-side fouling with the same quality boiler feed water. The boiler water quality can also become compromised by inadequate blow down and chemical treatment additions for increased steaming rate with the same tube surface area[6]. The tube OD fouling reduces the heat flux on the outside of the tube by insulating it from the water, resulting in higher tube temperatures. The higher temperatures, in turn, promote sulphidation in the tube as illustrated in Fig. 4.

Process-side tube fouling

Fouling on the process side often occurs first in the hot pass tubes which reduces the heat transfer. This duty is passed on to the next pass or exchanger often with increased potential of sulphidation of unprotected channels and tube sheets at the “cold end” of the first pass. The fouling of the hot pass tubes has been observed to cause failure of the downstream pass or exchanger.

Learning from WHB failures

When a WHB does not provide reasonable reliability, it is imperative to understand the root cause(s) of the failure. The principle inputs for evaluation are the inspection observations, the actual operating conditions and procedures, installed materials and installation procedures.

Inspection activities are critical to information gathering for reliability considerations and failure analysis. All too often, the inspection activities do not gather critical information necessary for further review and root cause analysis During an unscheduled or scheduled unit shutdown, the unit inspection is often conducted quickly to determine the scope of possible necessary repairs before returning to service. This cursory examination does not provide sufficient input for a root cause analysis. As already described, if inspection indicates ferrule and refractory glazing, the unit has been operated at high temperatures. Corrosion characteristics observed during inspection may indicate a local problem or a general problem that may have differing root causes. For example, inspection should be conducted after a thorough removal of all scale including the I.D. of the tubes within the ferrule length to assist in determining the apparent corrosion rate and support the remaining life and root cause analysis.

Review of historical operating data is one of the most effective tools for input into root cause analysis of WHB failures. Such reviews often confirm operating conditions that are distinctly different from those the plant personnel understood was occurring. For example:

- Was the unit started up 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?
- Comparison of WHB steam production to the mass flux and temperature to confirm data is reasonable.
- Reported process temperatures as compared to inspection observations.

The 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

Fig 4: **Corrosion at end of ferrule due to water side fouling**

that an SRU unit has been subjected to, such as a short duration high mass flux required due to facility operational conditions, or hydrocarbon carry-over in the acid gas feed stream. 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 for rates and multiple unit load sharing requirements. In addition to the measurement accuracy of the instrumentation, the response time of the process control systems and analyser feed back to the control system for these feed variations is critical to achieving a reliable WHB service result.

A thorough engineering analysis of a WHB using state-of-the-art tools can provide the insight as to root cause of a failure mechanism. These analysis tools, such as computational fluid dynamics (CFD)[8], can also assist in determining the actual metal temperatures and mass flux operating conditions for a specific WHB to provide reliable service. The limitations of heat flux in the turbulent area at the end of the ferrule and the 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 resulting refractory and ferrule temperatures can also be studied with these engineering tools and help verify the true temperatures reached. The CFD analysis[2,3] can indicate what physical and process parameters changes could be possible to improve the reliability of the WHB and can include both the process and water services of a WHB.

New and replacement WHB specifications

There is no industry consensus document that an owner and operator can refer to 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[5]. When combined with your existing unit's reliability and operating parameter experience, this guidance information can provide the foundation for establishing the physical and operational criteria and specifications for the detailed design of a reliable and robust waste heat boiler. ■

References

1. Brimstone 2011 "Top five fundamental integrity issues for SRU wasteheat exchanger (boiler) panel discussion" and technical papers: Mosher A.: "Burner flame temperature during warm up and hot standby"; Misale D.: "Ferrule design and installation for SRU tubesheets"; Stern L.: "Boiler water level safety considerations & tube collapse"; Martens D. "Tube and tube weld corrosion and tube collapse"; Lamar J.: "SRU overpressure in a waste heat boiler failure".
2. Porter M.: "A means of avoiding sulphur recovery furnace fired tube boiler failures", Brimstone 2009.
3. Porter M.: "A means of avoiding sulfur recovery reaction furnace fired tube boiler failures", ASME PVP paper number 78073 (2009).
4. Porter M.: "Computational fluid dynamics investigation of a high temperature waste heat exchanger tube sheet assembly", ASME paper number PVP 2005-71143 (2005).
5. Martens D.: "Robust SRU waste heat boiler design", Brimstone 2012
6. "Combining CFD derived information and thermodyamic analysis to investigate waste heat boiler characteristics", ASME paper number PVP 2011-57625 (2011).
7. Metals Handbook Ninth Edition Volume 13 Corrosion Copyright 1987 ASM International
8. McGuffie S.: ASME PVP Conference Tutorial "Use of CFD in design" (2012).