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## **CLAUS WASTE HEAT BOILER ECONOMICS – PAY ME NOW OR PAY ME LATER?**

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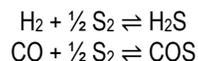
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In a time when uptime metrics and environmental constraints have become ever so more strict, refiners and gas producers have concurrently pushed towards processing higher sulfur feedstocks for margin advantage. These two competing objectives must both be met without failures or economics objectives may not be met. In this paper, the economics of several Claus Waste Heat Boiler (WHB) designs will be benchmarked in terms of:

- Reliability with corrosion and peak heat flux impacts on tube life
- Claus unit hydrogen production and potential savings in TGU make-up hydrogen
- Boiler equipment cost
- Claus unit combustion air blower power and SRU hydraulic capacity

Through a newly developed rate-based heat transfer and chemical reaction model of the Waste Heat Boiler, quantitative behavior of the WHB and how it subtly impacts SRU plant performance can be predicted based upon the recombination reactions that occur at the front of the WHB.



These reactions not only influence sulfur recovery, air demand, and hydrogen production in the SRU, they also impact the heat flux and performance of the WHB. These reactions occur towards the front (inlet) side of the WHB and are exothermic. The “hidden” heat associated with these reactions tends to increase heat flux towards the critical tube-to-tubesheet joint.

Radiative heat transfer, coupled with the exothermic recombination reactions, collectively increase the peak heat flux at the front of the boiler well above predictions from models that ignore or discount these factors. Tube wall temperatures, pressure drop, and heat flux predictions from the model are examined down the length of the tubes for oxygen-enriched vs. air-only operations. Elevated tube wall temperatures well downstream of the area of protection provided by ceramic ferrules for the higher mass velocity cases is demonstrated, backing up documented failures in the industry. The implications

of sulfidic corrosion and the resulting impact on boiler tube life and sulphur plant reliability economics are examined with this new information.

## INTRODUCTION

Today's refiners and gas producers are pushed towards processing higher sulphur feedstocks for margin advantages while uptime metrics and environmental constraints have become increasingly strict. These two competing objectives must both be met reliably without equipment failures, if economic objectives are to be realized. The Claus Waste Heat Boiler (WHB) is one of the most fragile pieces of equipment in the Sulphur Recovery Unit because of its harsh operating conditions and reliability challenges. It provides not only the heat recovery from the thermal section, but also affects the unit's hydrogen balance and COS levels through the recombination reactions. The design of the WHB plays a critical role in determining the extent of these reactions as well as the peak heat flux at the front end of the boiler tubes—all while balancing capital cost and operational reliability.

## IMPORTANT PARAMETERS IN WHB DESIGN

Claus Waste Heat Boilers (WHB) have many parameters that need to be carefully considered in the design phase. Many of the parameters are intertwined with each other where changing one will affect several of the others. In a typical WHB design, the tube size and process-side mass velocity will be chosen to meet a fixed outlet temperature specification. The following case studies look at a typical 125 LTPD Sulphur Plant with two converter stages processing both amine acid gas and sour water acid gas under low-level oxygen enrichment (**Figure 1. Case Study Sulphur Recovery Unit Flowsheet**). **Table 1** shows the conditions of acid gas feed streams. The WHB was sized by fixing the process-side mass velocity, the tube size and the process outlet temperature; tube count and tube length were adjusted to meet the target specifications. A matrix of three tube sizes and four mass velocities was evaluated. The tube sizes were set at 1.5, 2 and 3 inches outside diameter and process-side mass velocities were set at 2, 3, 4, and 5 lb/ft<sup>2</sup>-s. The results were obtained using the kinetic heat transfer and chemical reaction rate-based Sulphur Plant Simulator, ProTreat® Version 6.4.

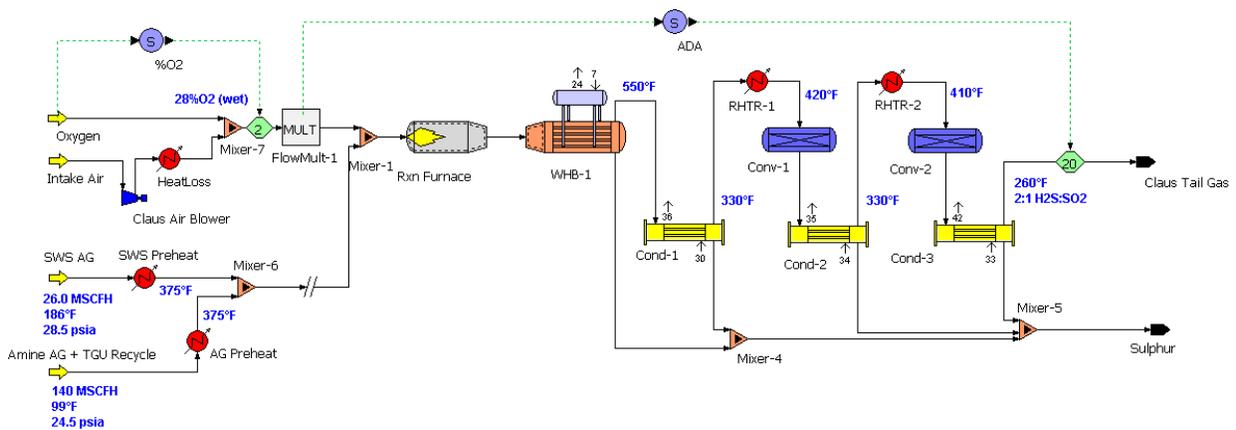
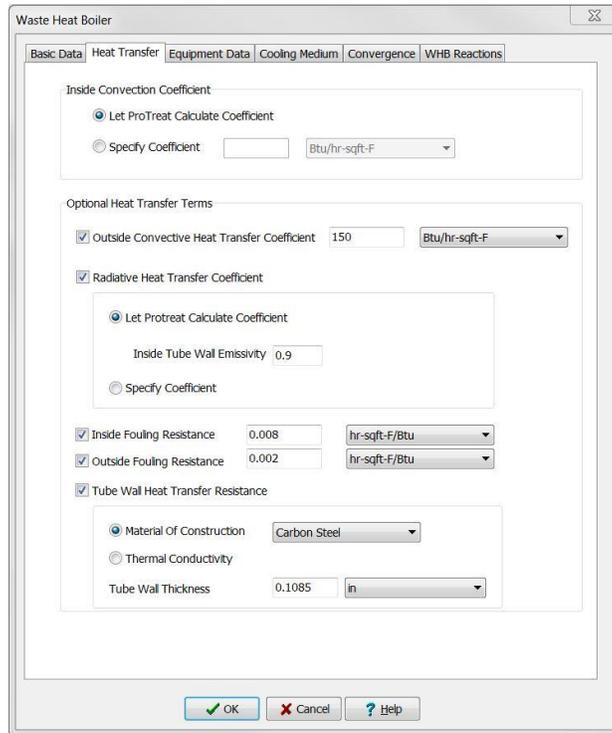


Figure 1. Case Study Sulphur Recovery Unit Flowsheet

	Amine AG + TGU Recycle	SWS AG
Flow Rate (MSCFH)	140	26
H <sub>2</sub> S mole%	88.2	33.1
CO <sub>2</sub> mole%	6.4	-----
NH <sub>3</sub> mole%	-----	40.9

**Table 1. Composition of Acid Gas Streams**

Other design parameters assumed for the model are summarized in **Figure 2**. The boiler produces 350 psig saturated steam from preheated boiler feed water.



**Figure 2. Design Parameters and Assumptions**

**Table 2** illustrates how the overall tube length varies as the mass velocities increase at each tube diameter to meet an outlet temperature specification of 550°F. Because the hot gas is moving faster at the higher mass velocities, less heat is transferred from the gas in a given length, thus the overall length of the tube bundle must be increased to meet the outlet temperature target. Besides the amount of cooling provided by the WHB, another parameter of equal importance is pressure drop through the exchanger. In a Sulphur Plant, pressure drop is at a premium and must be considered in all aspects of the design. Tube size and length have a large effect on pressure drop. Using smaller tubes decreases the overall length of the tube bundle, but it also increases pressure drop per unit length, so a balance must be struck. Neglecting any single factor of the design can lead to design busts and catastrophic operations failures. The driving factors for any project design are meeting the requirements safely and reliably whilst minimizing cost. Sometimes, these factors are at odds with each other and the interaction between design parameters is complex. The base cost of a WHB depends directly on the amount of material needed for construction. Boiler tube length, tube diameter, and tube count all influence the amount of material needed.

	Tube Length (feet)			
	2 lb/ft <sup>2</sup> -s	3 lb/ft <sup>2</sup> -s	4 lb/ft <sup>2</sup> -s	5 lb/ft <sup>2</sup> -s
1.5 inch tube OD	19.2	22.5	25.3	27.9
2 inch tube OD	27.7	32.6	36.9	40.7
3 inch tube OD	44.8	53.3	60.5	66.9

**Table 2. Tube Length at each tube OD and mass velocity**

At each tube size, as the mass velocity in the tubes increases, the overall tube length increases in order to achieve a constant outlet temperature. At the smallest tube size, 1.5 inches, and the lowest mass velocity, 2 lb/ft<sup>2</sup>-s, the boiler tube length is minimized at 19.2 feet. Because the boiler tubes have a smaller diameter, the overall tube count must be adjusted to maintain the specified mass velocity. When tube length is smaller, the tube count increases. Because of the higher tube count and smaller tube diameter, there is a greater amount of total surface area per length of tube bundle available for heat transfer. This requires shorter tubes to obtain the specified outlet temperature.

Pressure drop, on the other hand, increases with increasing mass velocity and decreasing tube diameter. **Table 3** shows the calculated pressure drop through the tube bundle. This does not account for the exchanger effluent nozzle exit loss and assumes clean tubes (no dirt factor).

Calculated Pressure Drop Through the Tube Bundle (psi)				
	2 lb/ft <sup>2</sup> -s	3 lb/ft <sup>2</sup> -s	4 lb/ft <sup>2</sup> -s	5 lb/ft <sup>2</sup> -s
1.5 inch tube OD	0.112	0.282	0.548	0.925
2 inch tube OD	0.105	0.265	0.517	0.875
3 inch tube OD	0.095	0.243	0.476	0.807

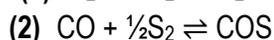
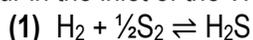
Table 3. Calculated Pressure Drop through Tube Bundle (psi)

The question then becomes: **why would a WHB not always be designed using the lowest mass velocity and smallest tubes possible?** And the answer (at least from a process engineering perspective) involves minimizing the pressure drop, maximizing hydrogen production in the SRU and concurrently maximizing sulphur recovery efficiency. Also of importance is the consideration of protecting the tube-to-tubesheet joint with ceramic ferrules. Allowing for insulation thickness of the ferrules causes the practical limit of the tube size to be 1.5 inch OD tubes. Tubes smaller than this would result in overly severe pressure drop and flow constrictions.

## RECOMBINATION REACTIONS AND SULPHUR RECOVERY

Although the main purpose of the WHB is to remove the heat generated in the Reaction Furnace and recover it as steam, an unavoidable outcome involves the gas shift reactions, or recombination reactions, that occur in the front of the boiler tubes. These reactions are very fast at high temperatures, but the reaction rates slow to a stop as the process gas is cooled [1]. Accurately predicting the extent of these reactions is an important reason to use a high quality simulator to design the WHB. The approach to modeling the WHB varies from simulator to simulator. Most simulators account only for the heat transfer in the WHB neglecting the important recombination reactions below. These reactions do, however, play a large role in determining how the WHB performs as well as affecting the reliability of the design. The sulphur redistribution (i.e., spontaneous shifts among the allotropes S<sub>2</sub>, S<sub>6</sub>, and S<sub>8</sub>) also has a fairly significant effect on the heat flux through the exchanger. Simulators that do not properly calculate the redistribution and do not account for the recombination reactions will inaccurately calculate the heat flux and thermal performance of the exchanger, especially in the tube inlet region near the critical tube-to-tube sheet joint.

There are two main reactions that occur in the inlet of the WHB tubes:



These are kinetically limited, exothermic reactions that can have a significant effect on the peak heat flux at the front end of the exchanger. Since the rates of the reactions are kinetically determined, they depend on two factors: residence time and temperature, with residence time determined by the mass velocity through the tubes. Temperature also plays a role in the residence time through its effect on gas density and therefore velocity. As the mass velocity in the tubes increases, the gas flows faster, providing less residence time in the

boiler tubes. Less residence time works to offset the faster reaction kinetics at higher temperature. **Figure 3**, **Figure 4**, and **Figure 5** illustrate the effect of mass velocity on the two recombination reactions under the same matrix of tube diameters already outlined in **Table 2**. The *Percentage of Inlet H<sub>2</sub> Reacted* shows how much hydrogen is converted back to H<sub>2</sub>S. The *COS Formed Ratio* shows the ratio of COS at that point in the boiler tubes to the COS present in the inlet gas to the boiler.

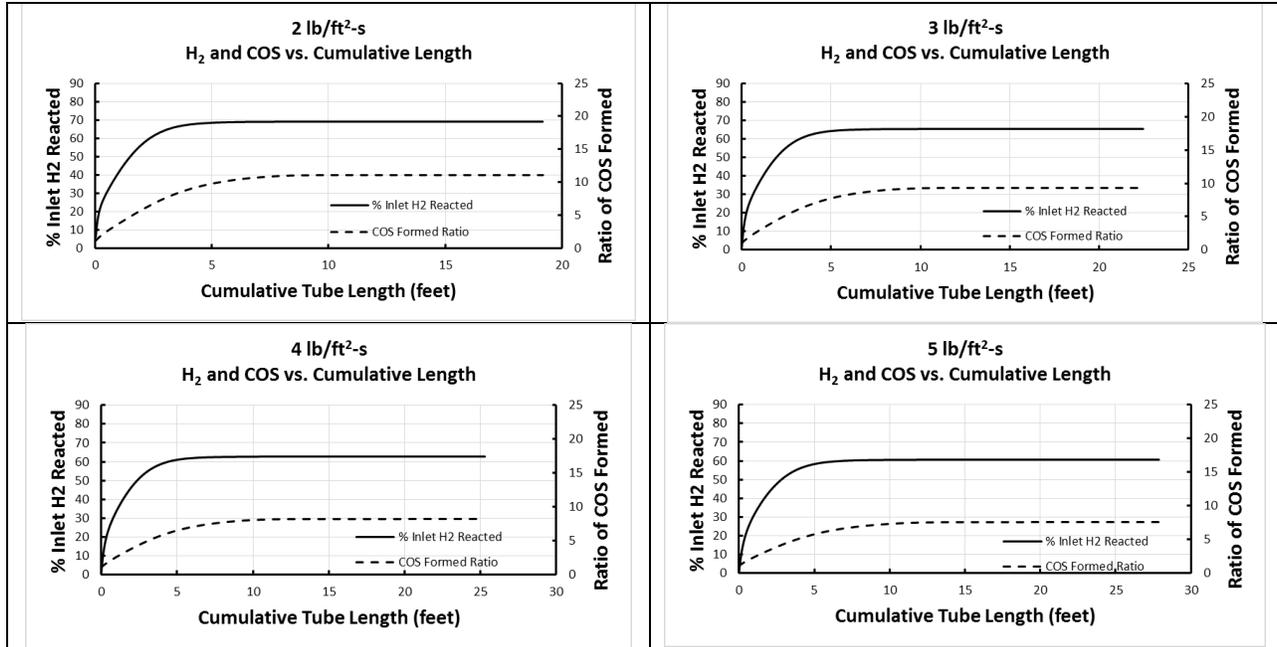


Figure 3. Reactions of H<sub>2</sub> and CO through the boiler tubes at 1.5 inch tube OD

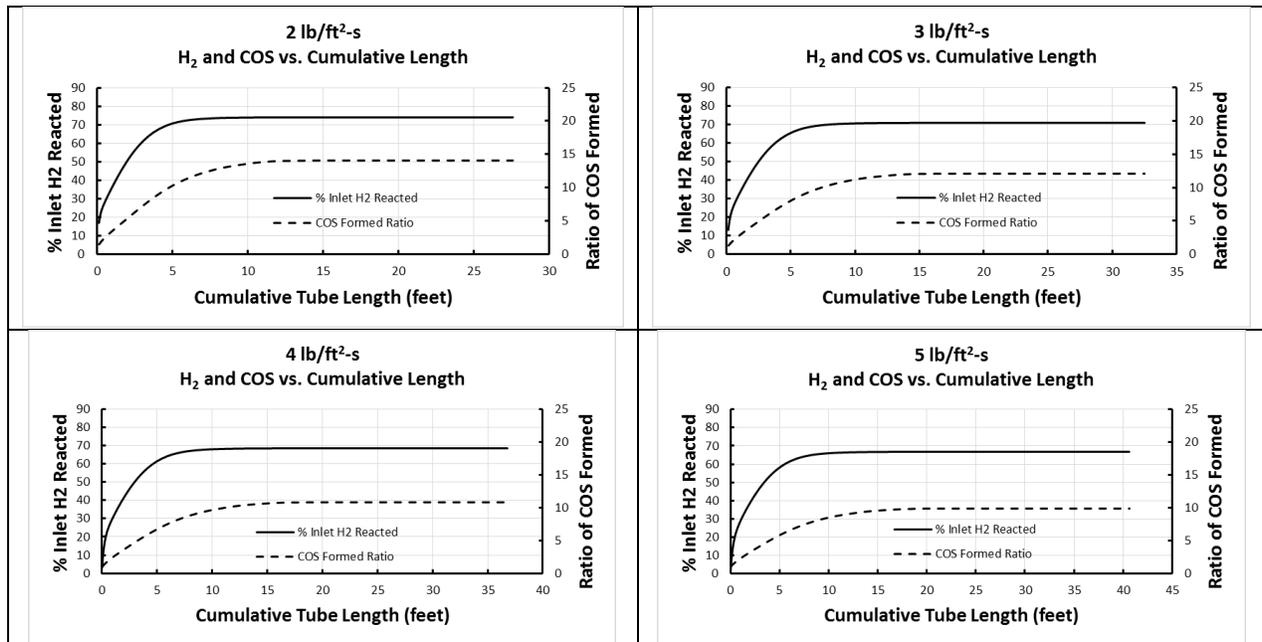


Figure 4. Reactions of H<sub>2</sub> and CO through the boiler tubes at 2 inch tube OD

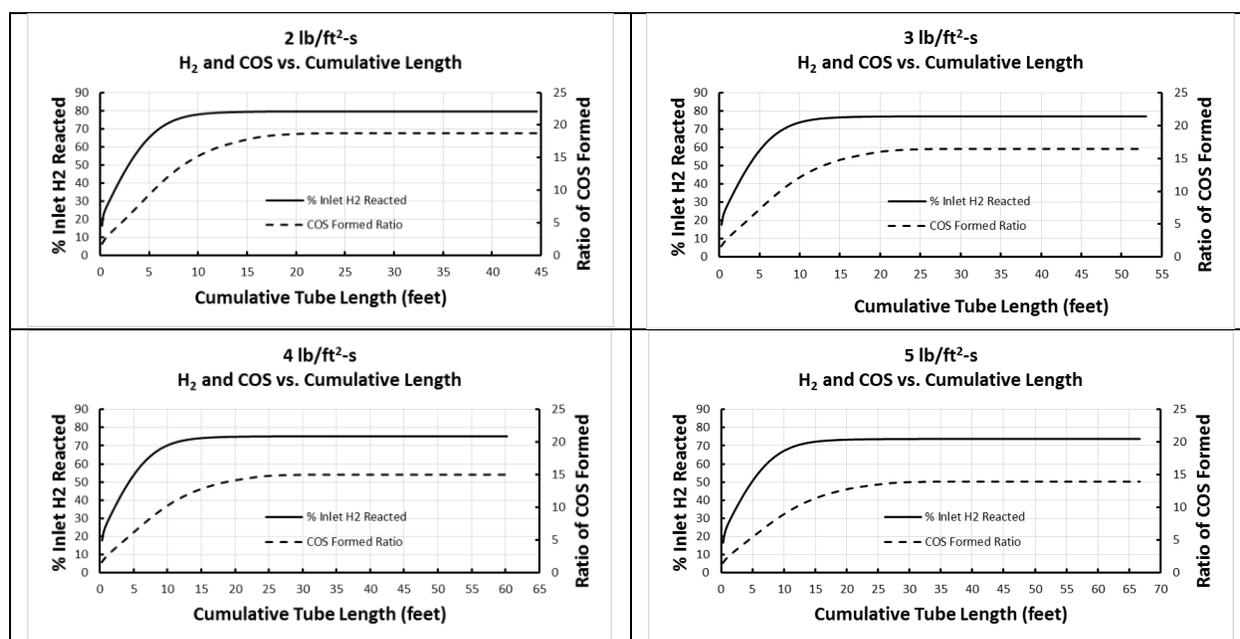


Figure 5. Reactions of H<sub>2</sub> and CO through the boiler tubes at 3 inch tube OD

As shown in the charts of Figure 3, Figure 4, and Figure 5, the reactions occur fairly rapidly, typically completing in the first quarter of the boiler tube length. These reactions are still occurring well beyond the protective area provided by the ferrules. As the mass velocity in the tubes increases, the reactions tend to be quenched more rapidly, leaving more hydrogen and sulphur in the boiler effluent. Additionally, less COS is made, increasing the Sulphur conversion. These factors collectively translate to higher thermal sulphur conversion and hydrogen make. In the case of hydrogen, having more available is beneficial to the TGU from either a reliability perspective (added protection from SO<sub>2</sub> breakthroughs) or reducing OpEx generated by external hydrogen consumption. Table 4 illustrates how the mass velocity and the extent that the reactions affect both sulphur recovery and available tail gas hydrogen.

Mass Velocity (lb/ft <sup>2</sup> -s)	1.5 inch Boiler Tubes				2 inch Boiler Tubes				3 inch Boiler Tubes			
	2	3	4	5	2	3	4	5	2	3	4	5
Tail Gas H <sub>2</sub> (mol% dry)	4.24	4.73	5.09	5.37	3.55	4.00	4.31	4.55	2.82	3.16	3.41	3.61
Net Excess H <sub>2</sub> in Tail Gas (mol% dry)	3.50	4.11	4.54	4.88	2.63	3.18	3.58	3.88	1.59	2.06	2.41	2.67
% Sulphur Recovery	96.16	96.26	96.32	96.38	95.98	96.09	96.15	96.21	95.76	95.84	95.93	95.99

Table 4. Hydrogen in Claus Tail Gas and Sulphur Recovery

From a hydrogen and sulphur recovery standpoint, it is evident that smaller diameter boiler tubes and a higher mass velocity would be more desirable. When considering operational flexibility, it is important to account for the fact that at turndown conditions, an operating unit will tend to make less hydrogen due to the slower mass velocity in the tubes. This is a characteristic that can **only** be seen with a truly rate-based simulator.

Beyond process chemistry considerations, we still need to consider other important aspects of the WHB design. To minimize capital cost, we must optimize the overall tube length and tube count. To ensure that the unit has sufficient hydraulic capacity we must consider pressure drop through the WHB. In addition to these, we must still take into account another parameter of equal, or even greater, importance, namely the heat flux.

## HEAT FLUX, TUBE WALL TEMPERATURE, AND CORROSION IMPLICATIONS

Heat flux is a very important factor in the reliability, life cycle cost, and the safe long-term operation of the WHB. Heat flux varies greatly along the tube length; it is highest at the process inlet and decreases as the process gas cools. In terms of reliability, it is the author's experience that failures tend to become more common with heat fluxes exceeding 50,000 Btu/hr-ft<sup>2</sup>. At elevated heat flux, problems with steam blanketing on the utility side are more common. Local high heat flux values can result in local steam blanketing which, in turn, can result in locally higher tube wall temperatures and increased corrosion rates. A host of other factors also play into the likelihood of steam blanketing, such as the pitch and orientation of the tubes; these will not be discussed here [2]. The life cycle cost of a WHB depends greatly on the corrosion rate of the boiler tubes due to high heat flux and high tube wall temperature. Tube wall temperature together with the concentration of H<sub>2</sub>S present correlate directly into the sulfidic corrosion rate [2]. **Figure 6, Figure 7, and Figure 8** show the heat flux and process temperature through the exchanger with a range of mass velocities at each boiler tube size.

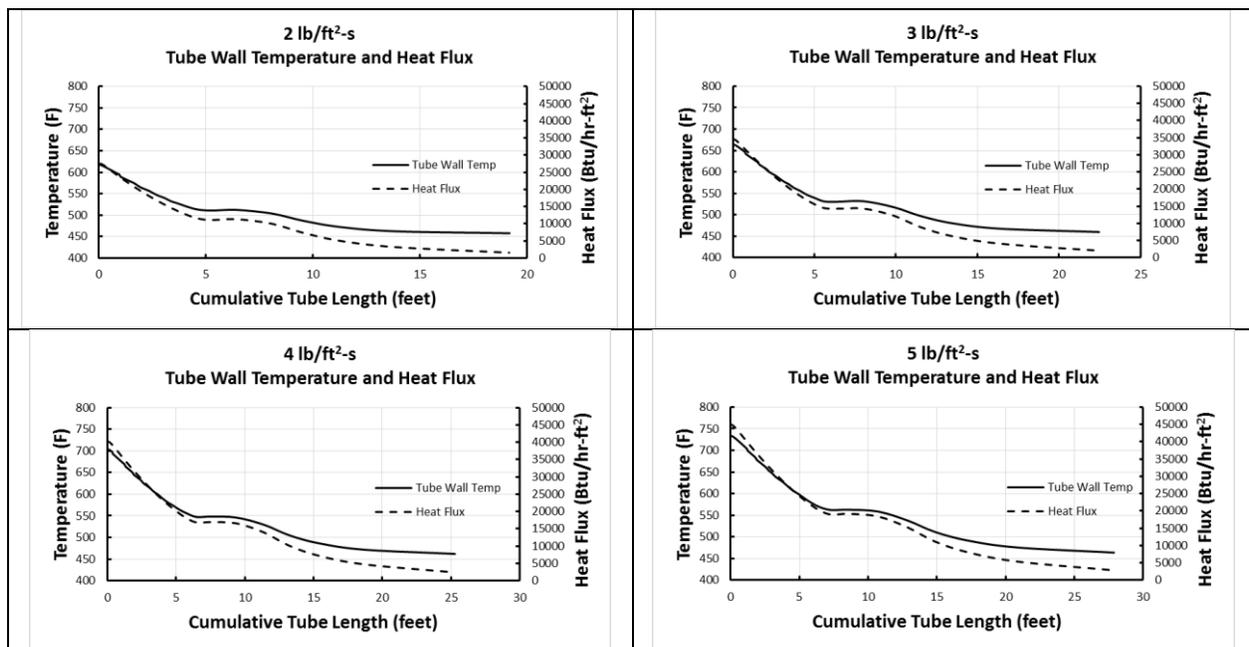


Figure 6. Heat Flux and Tube Wall Temperature through 1.5 inch OD boiler tubes

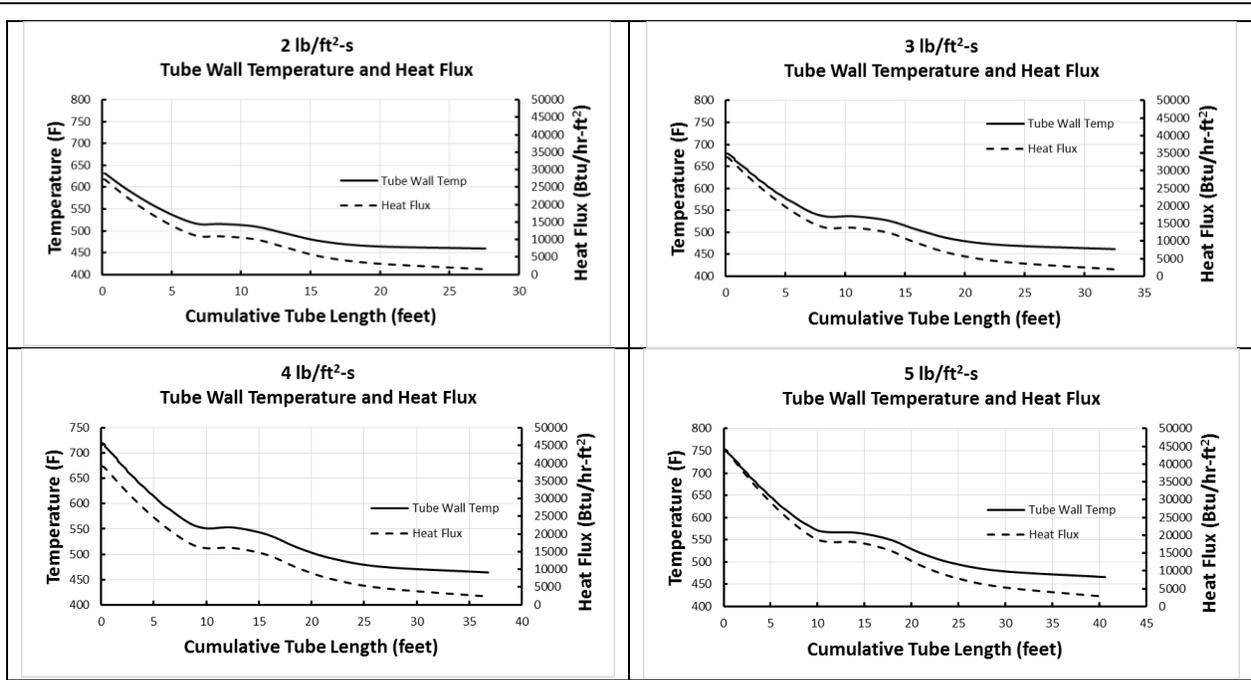


Figure 7. Heat Flux and Tube Wall Temperature through 2 inch OD boiler tubes

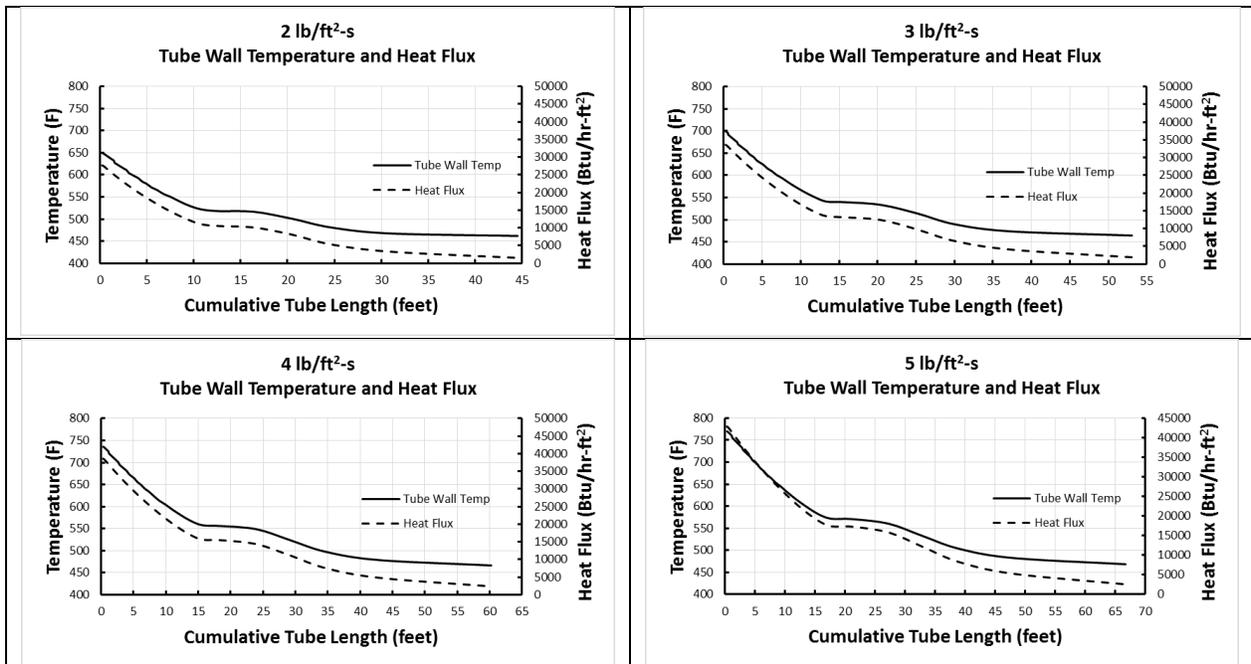
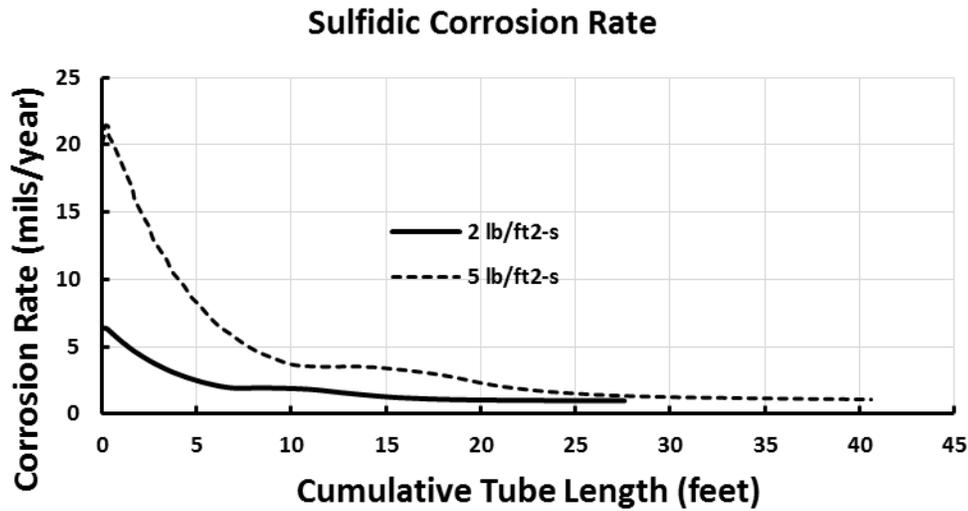


Figure 8. Heat Flux and Tube Wall Temperature through 3 inch OD boiler tubes

Note that the inflection in the curves approximately  $\frac{1}{3}$  of the way along the boiler tubes is caused by the sulphur species shifting from S<sub>2</sub> to S<sub>6</sub> and S<sub>8</sub> (sulphur redistribution). Furthermore, the heat flux considered here does not account for thermal protection provided by ferrules nor for the eddy effects at the ferrule exits. Eddies in the process gas flow as it exits the ferrules can cause the heat flux to be amplified several times for a short distance [2]. As the mass velocity is increased at a constant boiler tube size, the peak heat flux and tube wall temperature both increase at the front of the tubes. This is where almost all failures from sulfidic corrosion occur. The tube wall temperature, as mentioned previously, ties directly into the sulfidic corrosion rate. As the mass velocity through the boiler tubes increases, the tube wall temperature increases by

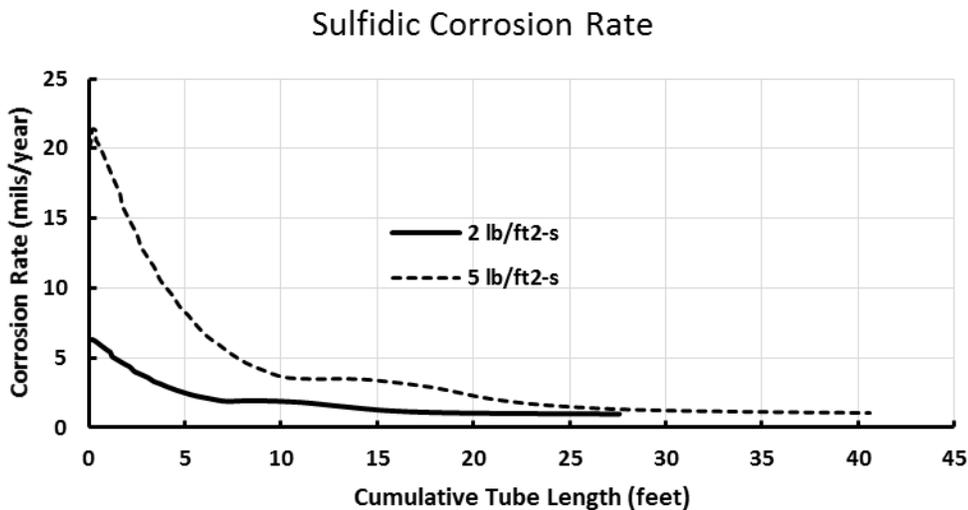
approximately 150°F. This increase in tube wall temperature translates directly into higher sulfidic corrosion rates as illustrated in **Figure 9**.



**Figure 9. Sulfidic Corrosion (mils/year) at front end vs. Mass Velocity (lb/ft²-s)**

At a constant mass velocity, the larger boiler tubes tend to produce higher tube wall temperatures. Corrosion concerns tend to increase at tube wall temperatures greater than 600-650°F. For this study, the tube wall temperature at the front of the boiler tubes is generally approaching this operation for a mass velocity between 2 and 3 lb/ft²-s. The service life of the exchanger is directly determined by the corrosion rate, and the life cycle cost is strongly influenced by service life.

Looking at how sulfidic corrosion occurs through the length of the exchanger, the higher mass velocity case has significant corrosion rates through the first 5 feet or so of the tubes. **Figure 10** shows how the corrosion trends through a 2 inch outside diameter tube at 2 and 5 lb/ft²-s. Corrosion rate jumps by nearly a factor of 4x at the higher mass velocity!



**Figure 10. Sulfidic Corrosion Rate vs. Cumulative Boiler Tube Length at 2 inch OD boiler tubes**

## LIFE CYCLE COST AND ECONOMICS

As the title to this paper implies, there are two ways that Claus Waste Heat Boilers cost the operator:

- Capital cost incurred when the plant is built - “pay me now”, and
- Operating and maintenance costs that are incurred - “pay me later”.

Capital cost is relatively straight forward to estimate. For purposes of this paper, the capital costs were calculated based upon ratioed in-house budgetary equipment quotes and then applying an overall installation factor of approximately 5 to place the estimates on a US Gulf Coast battery limits installed cost basis. Consideration of a steam drum was included in the cost estimate.

Normal operating and maintenance (O&M) costs that run day-to-day were assumed to even out across the various cases. The main distinguishing parameter that impacts O&M costs is replacement frequency and whether a planned or unplanned outage was taken. For purposes of this paper, the replacement cost was estimated to be a new exchanger purchase in the future year of the purchase plus a variable “outage” cost component. If a particular hydrocarbon producing plant happens to be sulfur constrained, then an outage can result in quite significant lost profit opportunity (LPO) based upon an advantaged feedstock margin. In many cases, the O&M cost may be considerably less if, for example, only refractory work or retubing were conducted. The results of this work are intended to be illustrative, and it is the relative difference between the lifecycle costs that is important vs. the absolute value.

**Table 5** below summarizes the assumed cost parameters.

Corrosion Allowance (inches)	0.125
Production Advantage (\$/LT)	1000
Outage Duration (days)	14
Sulphur Production (LTPD)	125 (Design Rate)
CEPCI Basis (Year)	2016

**Table 5. Assumed Cost Parameters**

The base case used for estimating the relative comparisons was chosen with 1.5 inch OD boiler tubes at a mass velocity of 2 lb/ft<sup>2</sup>-s. Each design in the previous design matrix was evaluated on cost based on the assumptions described in **Table 5**. The cost calculations included the initial installed cost, annualized LPO for downtime, equipment replacement cost, O&M annualized cost, O&M relative cost vs. the base case, TIC (Total Installed Cost) savings vs. the base case, and the number of years it would take for the base case to payback. **Table 6** shows the O&M Cost vs. Base Case and **Table 7** shows the TIC savings vs. Base Case.

At each tube size, as the mass velocity increases, the initial installed cost decreases (see **Table 7**) due to the surface area required with 1.5 inch tubes being the least expensive of the three groups. Since the replacement cost was assumed to be the cost of a new exchanger, this also decreases with increasing mass velocity. The annualized LPO for downtime is directly dependent on the corrosion rate, and looking back at **Figure 9**, we know that the corrosion rate increases with mass velocity and tube size which ties directly into the service life of the exchanger. As the mass velocity through the exchanger increases, the LPO for downtime increases due to the higher corrosion rates. This ties into the O&M annualized cost per **Table 6**.

So would you like to “pay me now” with a Waste Heat Boiler design that has a higher up front cost or “pay me later” with a design that has higher cost over time? In reality, the answer to this question is usually not so black and white and one must look at both the O&M Cost and the Total Installed Cost (TIC). An accurate simulation tool quantifies the effects of all aspects of WHB design so that you will know up front what the full implications of your decisions will be.

	2 lb/ft <sup>2</sup> -s	3 lb/ft <sup>2</sup> -s	4 lb/ft <sup>2</sup> -s	5 lb/ft <sup>2</sup> -s
1.5 inch OD	BASE CASE	\$10,992	\$54,945	\$119,418
2 inch OD	\$26,467	\$50,591	\$100,243	\$203,692
3 inch OD	\$58,241	\$92,336	\$176,744	\$276,918

Table 6. Annualized O&M Relative Cost vs. Base Case (\$)

	2 lb/ft <sup>2</sup> -s	3 lb/ft <sup>2</sup> -s	4 lb/ft <sup>2</sup> -s	5 lb/ft <sup>2</sup> -s
1.5 inch OD	BASE CASE	\$93,962	\$131,038	\$142,055
2 inch OD	-\$226,934	-\$164,145	-\$152,986	-\$162,824
3 inch OD	-\$623,465	-\$624,944	-\$661,103	-\$712,166

Table 7. Total Installed Cost (TIC) Savings vs. Base Case (\$)

From **Table 6**, as the mass velocity increases, the O&M cost increases due to the higher corrosion rates and shorter life cycle of the exchanger. From **Table 7**, we can see that the 1.5 inch tubes are the most economical choice based on the TIC savings. As the mass velocity increases, the TIC savings increase because less material is required to manufacture the tube bundle. For 2 and 3 inch tube sizes, we can see that the TIC savings are negative, meaning that these exchangers are more expensive option for upfront cost.

There are many other factors that play into the cost analysis, and one of those is the number of exchanger passes. Waste Heat Boilers with a tube length greater than 35 feet are typically built with two passes due to structural support issues and plot layout considerations. Looking back at **Table 2**, we can see that half of the 2 inch tube cases and all of the 3 inch tube cases would probably require two passes. This influences both the initial installation cost as well as the O&M annualized cost of the exchanger. Scaling cost for two pass exchangers introduces a level of complexity in the cost analysis that was not explored for this paper.

Another factor that was not fully explored was the pressure drop through the ferrules. Although the 1.5 inch tube sizes appear to be the best choice not only from an economic standpoint, but also for hydrogen production and sulphur recovery, introducing the ferrules and pressure drop calculations may show that the smaller tube sizes have a higher than ideal pressure drop and as such may outweigh the benefits strictly based on this.

## CONCLUSIONS

The intelligent and economic design of a Waste Heat Boiler is quite challenging. As we've seen, there are many (often opposing) factors that go into not only the performance and reliability of the exchanger, but the economic feasibility as well. If a Waste Heat Boiler is designed without the proper considerations for all of the factors, the design could fall flat in one or more aspects. ProTreat accounts for all the factors. We've shown that Waste Heat Boilers designed with small tubes and lower mass velocity favor heat flux, tube wall temperature and corrosion rate. All of these factor into the LPO for downtime of the exchanger favorably. However, it would be at the expense of optimized hydrogen production, sulphur production, and the initial installed cost of the exchanger. In consideration of all of the aforementioned factors, a balance would have to be struck depending on the specific plant's economic objectives and performance requirements.

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