American Flame Research Committee (AFRC) International Combustion Symposium

Sept 18-21, 2011

Next Generation Low NO_x Boiler Burner Retrofits—Field Performance and Considerations

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Abstract

Burner retrofits in industrial boilers are an economical solution to achieving lower NO_x levels with existing fired equipment. However, designing a next generation ultra-low NO_x burner footprint that fits into an existing burner cutout continues to be an industry challenge in many applications. Building a burner with a flame pattern or profile that can operate properly within the existing space and back wall firing length limitations while still achieving significant NO_x reductions has also proven to be a difficult task.

Zeeco has developed a patented next generation ultra-low NO_x free-jet burner technology with a compact mechanical footprint. The GLSF Free-Jet Burner produces a flame profile with very limited flame-to-flame interaction for multiple boiler burner installations, while also achieving shorter flame lengths.

One of the other primary concerns for the end user operating company is the overall cost of ownership for next generation ultra-low NO_x burners. They can have higher maintenance costs versus conventional emission boiler burners. Zeeco provides the lowest maintenance design on the market for similar NO_x emissions results. We will review these design details, specific retrofit installation details and lessons learned during a retrofit of existing boiler burners at Valero's Corpus Christi Refinery in this paper, including tramp air impact, and field emission test results for several of the retrofit applications.

Introduction

In 2006, the Valero Corpus Christi Texas Refining facility purchased Zeeco® GLSF Free-Jet Next Generation Ultra-Low NO_x Burners for two boilers in order to comply with emissions regulations. These boilers were identical in design and operating conditions. The GLSF Free-Jet burner provided the most economical option for meeting the emissions regulations, as they do not require External Flue Gas Recirculation (EFGR). Each boiler is over 70 years old, and retrofitting ultra-low emissions burners without using EFGR to meet strict emissions requirements was challenging. The emissions requirements were:

NO_x emissions.. 0.03 lb/MM Btu (HHV Basis)
CO emissions corrected to 3% dry O_2 .... 50 ppmv
UHC emissions corrected to 3% dry O_2 .... 15 ppmv
Particulate corrected to 3% dry O_2 .... 15 ppmv
VOC corrected to 3% dry O_2.. 15 ppmv

A common issue with boilers of this age is that much of the design information is not readily available and many assumptions must be made during the burner design process. These assumptions are outlined in the Appendix: Design Conditions. After the burners were installed and initially started up, several challenges were identified and the design conditions were revisited and revised. The revised conditions are also detailed in the Appendix: Design Conditions.

This paper will review and examine the parameters of this retrofit and the field solutions created to address the challenges discovered after startup. Factors addressed during the field adjustment phase of the project included: Revising Design Conditions, Revising Gas Tip Sizing, Revising Combustion Air Pressure Drop, Adjusting Forced Draft Boiler Control Practices and Eliminating Air Leakage (Tramp Air) into the Combustion Zone.

Combustion Parameters

Description of Thermal NO_x Creation and Reduction

In order to understand why the Zeeco® GLSF Free-Jet design was selected, formation of thermal NO_x emissions must first be examined. For gaseous fuels with no fuel-bound nitrogen (N_2), thermal NO_x is the primary contributor to overall NO_x production. Thermal NO_x is produced when flame temperatures reach a high enough level to "break" the covalent N_2 bond apart, allowing the "free" nitrogen atoms to bond with oxygen to form NO_x.

Stoichiometric Equation describing typical combustion in a natural gas fired burner

Methane & Air with Excess Air

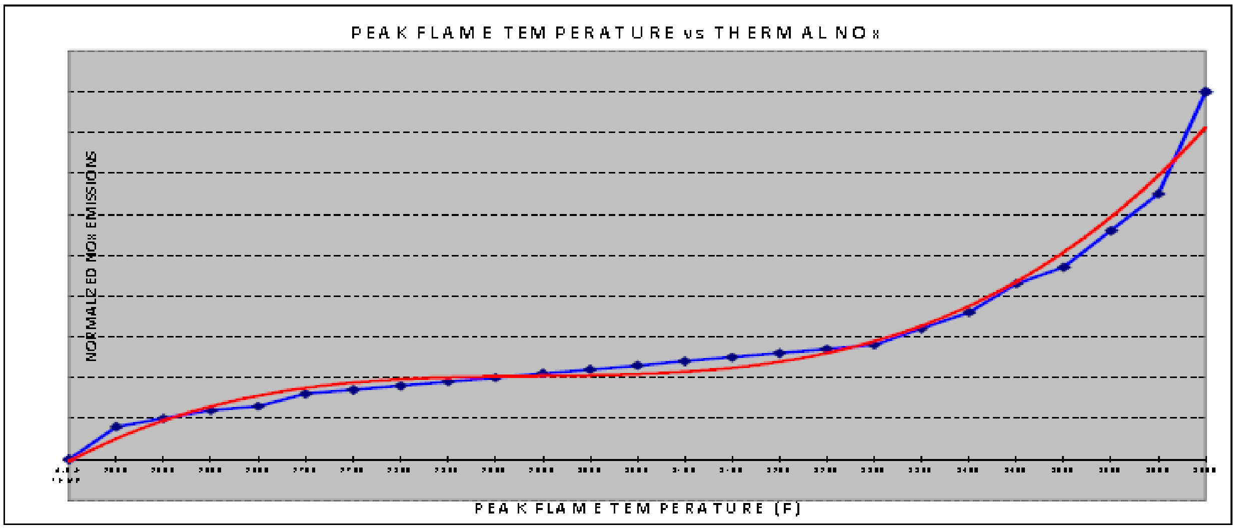
$$2CH_4 + 4\ (XA)\ O_2 + 15\ (XR)\ N_2 \ \text{--->}\ 2CO_2 + 4H_2O + (XA)\ 15N_2 + (XR)\ O_2$$

Natural air is comprised of 21% O_2 and 79% N_2. Combustion occurs when O_2 reacts and combines with fuel (typically hydrocarbon). However, the temperature of combustion is not normally high enough to break all of the N_2 bonds, so a majority of nitrogen in the air stream passes through the combustion process and remains diatomic nitrogen (N_2) in the inert combustion products. Very little N_2 is able to reach high enough temperatures in the high intensity regions of the flame to break apart and form "free" nitrogen. Once the covalent nitrogen bond is broken, the "free" nitrogen is available to bond with other atoms. Basic chemistry dictates that free nitrogen, or nitrogen radicals will react to other atoms or molecules that can accept them to create a more stable atom. Of the possible reactions with the products of combustion, free nitrogen will most likely bond with other free nitrogen to form N_2. However, if a free nitrogen atom is not available, the free nitrogen will react with the oxygen atoms to form thermal NO_x. As the flame temperature increases, the stability of the N_2 covalent bond decreases, allowing the formation of free nitrogen and subsequently increasing thermal NO_x. Burner designers can reduce overall NO_x emissions by decreasing the peak flame temperature, which can reduce the formation of free nitrogen available to form thermal NO_x.

The varied requirements of refining and petrochemical processes entail the use of numerous types and configurations of burners. The method utilized to lower NO_x emissions can differ by application. However, thermal NO_x reduction is generally achieved by delaying the rate of combustion. Since the combustion process is a reaction between oxygen and fuel, the objective of delayed combustion is to reduce the rate at which the fuel and oxygen mix together and burn. The faster the oxygen and the fuel gas mix, the faster the rate of combustion and the higher the peak flame temperature.

Figure 1 plots Peak Flame Temperature against Thermal NO_x created. NO_x emissions increase as the adiabatic flame temperature increases. Slowing the combustion reaction reduces the flame temperature, which results in lower thermal NO_x emissions. The challenge in achieving lower thermal NO_x emissions is not the theory; however, it is in retrofitting the latest burner technologies into older existing boilers without adding expensive external components or processes.

Figure 1: Calculated Peak Flame Temperature vs. Thermal NO_x Production



The industry's standard method to reduce thermal NO_x is to mix the fuel gas together with the inert products of combustion to recondition the fuel before combustion occurs. Since the reconditioned fuel is mainly comprised of inert components, the resulting composition burns at a lower peak temperature. To best utilize the inert products of combustion (flue gas) within the boiler, the fuel gas is introduced along the outside perimeter of the burner tile in an area where flue gas is present while the boiler is in operation. As the fuel gas passes through the inert products of combustion, mixing naturally occurs. This changes the composition of the fuel, and stabilization occurs at the tile exit. Since the reconditioned fuel mixture is 80 to 90% inert in most cases, the resulting flame burns at a lower peak temperature and generates less thermal NO_x.

The mixing of the fuel gas with flue gas prior to combustion is called Internal Flue Gas Recirculation (IFGR). When IFGR is too aggressive, it can result in an increased blower power usage, decreased burner turndown, and increased flame destabilization. Through Free-Jet Theory, maximizing IFGR while maintaining flame stability and flame length can become a challenge.

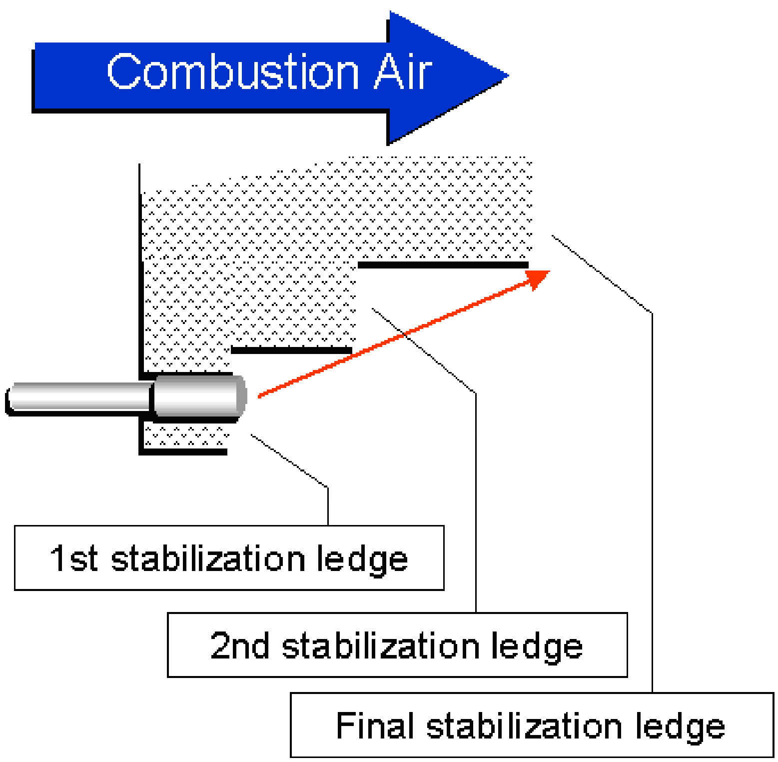
Flame Stabilization

In order to fully utilize the Free-Jet Theory, Zeeco devised a method to stabilize the burner flame with a highly inert fuel gas/flue gas mixture. This type of combustion is achieved when the flame is stabilized in a low-pressure area created on a series of specially designed hot refractory ledges. As combustion occurs, the refractory ledge retains heat and flame stability is enhanced. Thus, to achieve improved stability and extreme Thermal NO_x reduction, the Free-Jet Technology:

1. Mixes inert flue gas through free-jet methods with all of the fuel gas before combustion occurs, lowering flame temperature.
2. Stabilizes the flame on a refractory ledge, improving flame characteristics

Before combustion is initiated, a furnace is typically filled with normal air, which contains 21% oxygen. Once the burner is ignited, the oxygen content inside the furnace decreases until the burner achieves maximum duty. At this point, the oxygen content in the firebox is normally 2 to 3%. To keep the burner stable throughout the transition from start-up with 21% oxygen to maximum duty with 2 to 3% oxygen, Zeeco developed a series of stabilization ledges as shown in **Figure 2**. These ledges are a design feature of the Zeeco® GLSF Free-Jet Burner chosen for the Valero Burner Retrofit.

Figure 2: Free-Jet Flame Stabilization Method Illustration

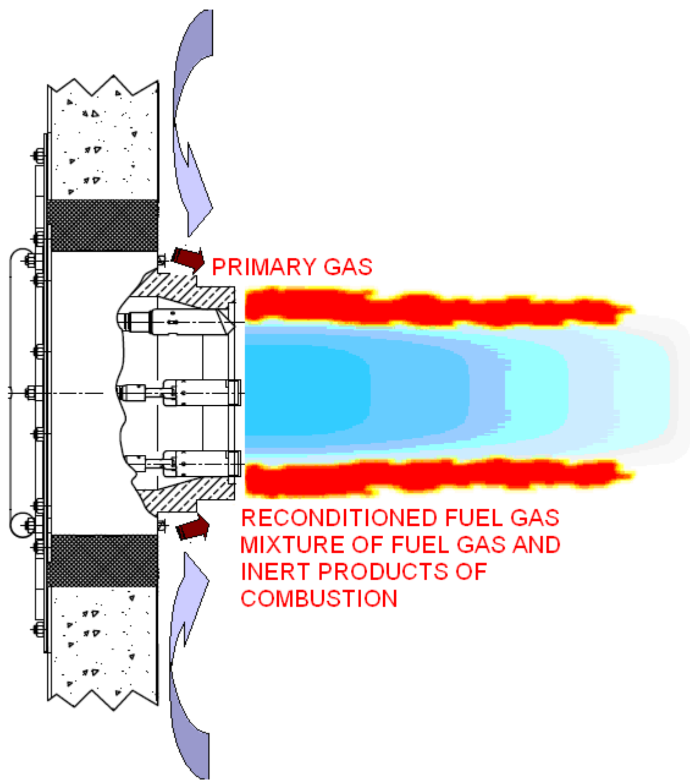


Burner Technology Description

Introduction to Free-Jet Technology

The Zeeco GLSF Free-Jet burner series was designed with the specific purpose of maximizing the amount of IFGR to reduce thermal NO_x emissions without sacrificing burner performance with respect to flame length, turndown, and stability. The maximization of IFGR means many of the problems associated with using high levels of EFGR to achieve low emissions can be reduced or eliminated. Specifically, Zeeco's Free-Jet design dramatically reduces or eliminates the need for EFGR by reducing blower power usage, increasing turndown, reducing maintenance and improving flame quality.

Inert Products of Combustion (Flue Gas)



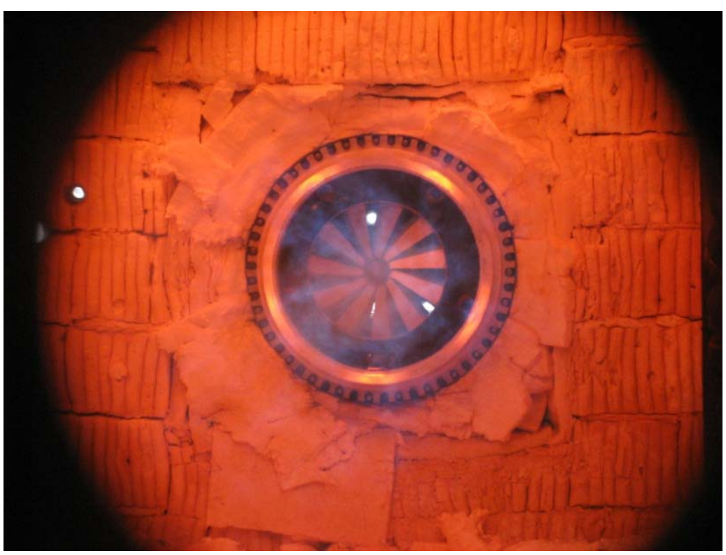
Original Design Conditions

The compact boilers were originally designed for service on a ship. Later, the boilers were removed from the ship and installed at what is now the Valero Corpus Christi Refinery. The boiler firebox dimensions are 14 feet deep*, 20 feet tall, and 10.8 feet wide.

Each boiler was equipped with two conventional burners. Information on the boilers was limited due to age of the installation, and many of the details in regards to next generation burner retrofits were not important 70 years ago and were therefore not clearly documented. Additionally, some original design documentation was missing. Zeeco replaced each of the existing conventional burners with a Zeeco GLSF Free-Jet burner. The heat release design of the new burners was set at 77.4 MM Btu/hr per burner. The combustion air pressure drop was set at 3.25" W.C. at 15% excess air with an air temperature of 100° F.

The new burners were designed to use 0.3 lb steam/lb fuel gas injected into the fuel gas stream for increased NO_x reduction if needed since EFGR was not planned for this application. The use of a small amount of steam was less expensive than reworking the boiler to add approximately 14% EFGR to achieve the required NO_x emissions level of 0.03 lb/MM Btu (HHV).

The new burners were installed in the existing burner wind-box configuration. The new burner footprint was approximately the same size as the existing burners, so boiler modifications for burner installation were minimized to reduce the overall installation cost of the retrofit.



*this dimension was not apparent during the application development phase. It was left as "to be determined".

The fuel gas compositions for the original burner design are as follows. Note: The burner was designed to have up to 0.3 lb steam/lb fuel gas mixed with the fuel gas, below in Table B are listed the fuel compositions with 0.1, 0.2 and 0.3 lb steam/lb fuel gas mixed with the fuel gas.

Table B: Original Fuel Gas Compositions

Composition	Fuel Gas % vol	Fuel Gas with 0.1lb Steam/lb Fuel % vol	Fuel Gas with 0.2lb Steam/lb Fuel % vol	Fuel Gas with 0.3lb Steam/lb Fuel % vol
CH_4 (methane)	77.49%	70.31%	64.36%	59.34%
C_2H_6 (ethane)	3.96%	3.59%	3.29%	3.03%
C_3H_8 (propane)	1.58%	1.43%	1.31%	1.21%
C_4H_{10} (butane)	1.04%	0.94%	0.86%	0.80%
C_5H_{12} (pentane)	1.29%	1.17%	1.07%	0.99%
C_6H_{14} (hexane)	0.33%	0.30%	0.27%	0.25%
C_5H_{10} (cyclopen)	0.20%	0.18%	0.17%	0.15%
C_6H_{12} (cyclohex)	0.00%			
C_2H_4 (ethene)	1.15%	1.04%	0.96%	0.88%
C_3H_6 (propene)	0.25%	0.23%	0.21%	0.19%
C_4H_8 (butene)	0.04%	0.04%	0.03%	0.03%
C_5H_{10} (pentene)	0.04%	0.03%	0.03%	0.02%
C_6H_6 (benzene)				
C_5H_8 (isoprene)				
CO_2	0.94%	0.85%	0.78%	0.72%
H_2O		9.24%	16.92%	23.40%
O_2	0.07%	0.06%	0.06%	0.05%
N_2	3.56%	3.23%	2.96%	2.73%
SO_2				
H_2S				
CO				
NH_3				
H_2	8.10%	7.35%	6.73%	6.20%
AR				
Total (vol%)	100.0%	100.0%	100.0%	100.0%

Challenges

After the burners were installed and started, it was apparent that the flames were longer and lazier than expected, especially at low rates. At higher firing rates, CO emission limits could not be met.

Troubleshooting

The flame appearance indicated the gas and air mixture was not thoroughly mixed. To understand what was occurring, Zeeco and Valero probed the boiler, sampled the flue gas and conducted air and flue gas system pressure surveys. The following challenges and solutions were identified:

1. Boiler Leakage

a. **Challenge**: Boilers had air leakage issues, causing air to enter the boiler through locations other than through the burner throat. Not all of the air was being used to help mix the gas and air together, resulting in longer flames.

b. **Solution**: Boilers were thoroughly sealed. Combustion air entered through the burner and not through the leakage in the boiler.

2. Boiler Forced Draft Blower Control

c. **Challenge:** The existing Forced Draft (FD) blower control mechanism contained older technology and lacked fine adjustments. Therefore, it was difficult to maintain the desired airflow rate through the burner. The Induced Draft (ID) fan was instead used to control the airflow, affecting the draft within the boiler, which increased tramp air leakage.

d. **Solution:** Mechanism on the Forced Draft blower was adjusted to allow for better excess air control. This allowed the boiler to be operated in a more traditional balanced draft configuration, reducing tramp air and NO_x.

The above changes helped but did not fully resolve all performance issues. Further investigation would detect another issue—the firebox was only 14 feet deep. This was identified through much speculation, drawing reviews, and field measurements. Not obtaining key information throughout the original burner design phase resulted in the burners producing a 26 foot-long flame at design firing rate.
Zeeco and Valero brainstormed options to address this issue and settled on the two most viable strategies for shortening the flame without creating any other performance issues. These strategies are listed as items 3 and 4 on the following page.

3. Change Gas Port Sizing:

e. Original GLSF burner design incorporated steam injection into the fuel gas. Steam injection into the fuel stream proved unnecessary for NO_x reduction. When operating with zero steam injection, the gas pressure was very low which resulted in less energy for mixing air and fuel gas.

f. The size of the ports were altered to operate at a maximum fuel gas pressure of 32 psig as opposed to the original 25 psig. In addition, the steam injection was removed from the gas tips so the burner could operate at high fuel gas pressure. The high gas pressure provided more energy to mix the fuel and air together, resulting in a shorter flame and reduced emissions. The burner was also redesigned to mix the steam directly with the air stream prior to entering the boiler. The new rate for the steam was revised to 0.5 lb.

4. Increase Air Pressure Drop and Add Air Spin

g. Original GLSF design was based upon maximum combustion air pressure drop of 3.25" W.C. with no air spin. Field testing confirmed there was a slightly higher air pressure drop available to help with the mixing of the air and gas. A spin diffuser in the throat of the burner was employed to improve mixing of the air and fuel and change the flame shape from long and narrow to shorter and bushy. Airside pressure drop increased to 3.5" W.C.

Field Results

After the burners and boilers were modified as described in the Challenges and Solutions section of this paper, the following emissions were achieved:

NO_x emissions .... 0.03 lb/MM Btu (HHV Basis)
CO emissions, corrected to 3% dry O_2 .... 50 ppmv

After initial startup, evaluation and redesign, the burners were able to operate from low firing rates with good flame characteristics. The burners utilize approximately 0.3 to 0.4 lb steam injected into the combustion air stream and are currently operating at or below the target NO_x emissions requirements.

Considerations

When taking on projects of this magnitude, it is important to consider the following:

1. **Burner Design Conditions**: It is necessary to receive all of the design information at the beginning of the project. This task was very difficult due to the age of the boilers and the limited amount of information that was available. Small changes in conditions can have a large effect on performance. It is essential to develop and maintain a clear line of communication with all parties involved.

2. **Gas Port Sizing**: It is crucial to maximize the mixing energy of the gas and the air stream, especially at low rates to increase flame quality (shorter length).

3. **Air Pressure Drop:** It is critical to maximize the mixing energy of the gas and the air stream, especially at low rates to keep flame lengths short.

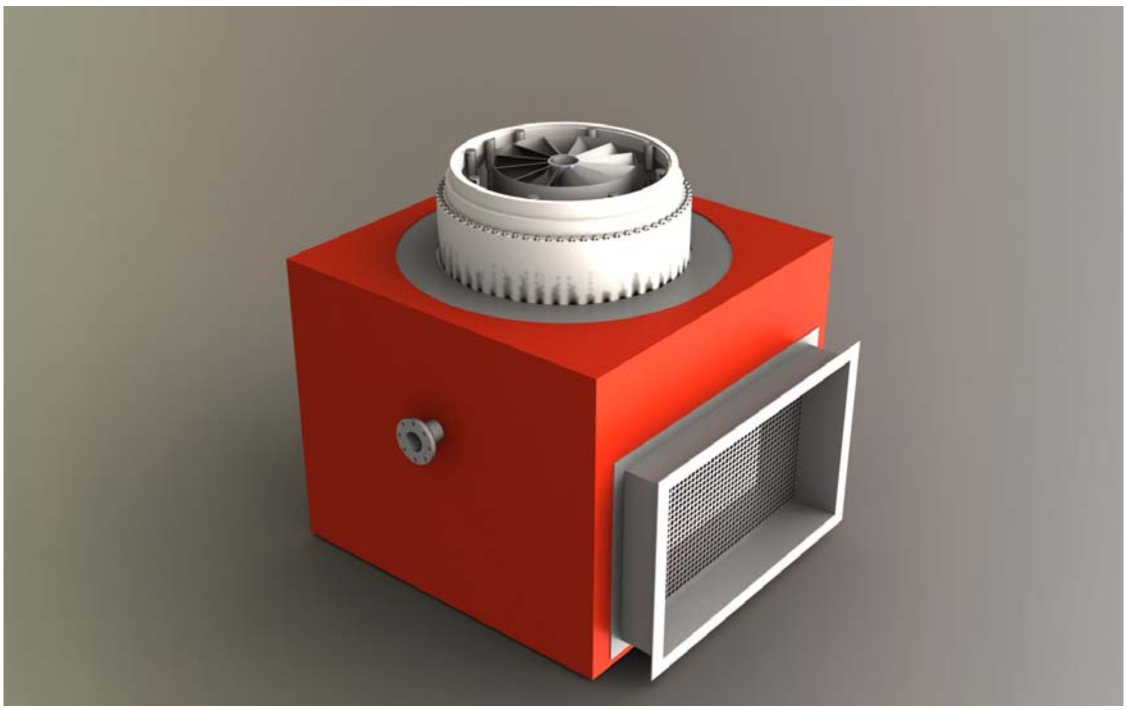
4. **Boiler Forced Draft Blower Control**: It is very important to be able to control the combustion air with both the Forced Draft blower (FD) and the Induced Draft (ID) blower in a FD/ID system to keep tramp air from affecting performance.

5. **Boiler Leakage**: Small leaks allowing tramp air into the boiler or combustion air leakage can result in less air entering through the burner throat in a FD/ID type application, resulting in poor mixing of air and fuel and increased NO_x.

6. **Placement of Steam Injection**: To maximize the mixing energy of the gas and the air when not using steam injection, a steam lance inserted into the air steam was used. With the steam lance, the addition or subtraction of steam will not affect gas pressure or the mixing energy of the fuel and air.

Conclusion

The retrofit of the boilers was very challenging due to the age of the boilers and the amount of information available for the application. However, after the challenges were identified and addressed, the boilers were able to achieve the required 0.03 lb/MM Btu NO_x emissions and 50 ppmv CO emissions without the use of EFGR. Using Free-Jet mixing technology with flame stabilization ledges and careful field assessments and adjustments reduced the initial retrofit costs and the long-term maintenance and operation costs.

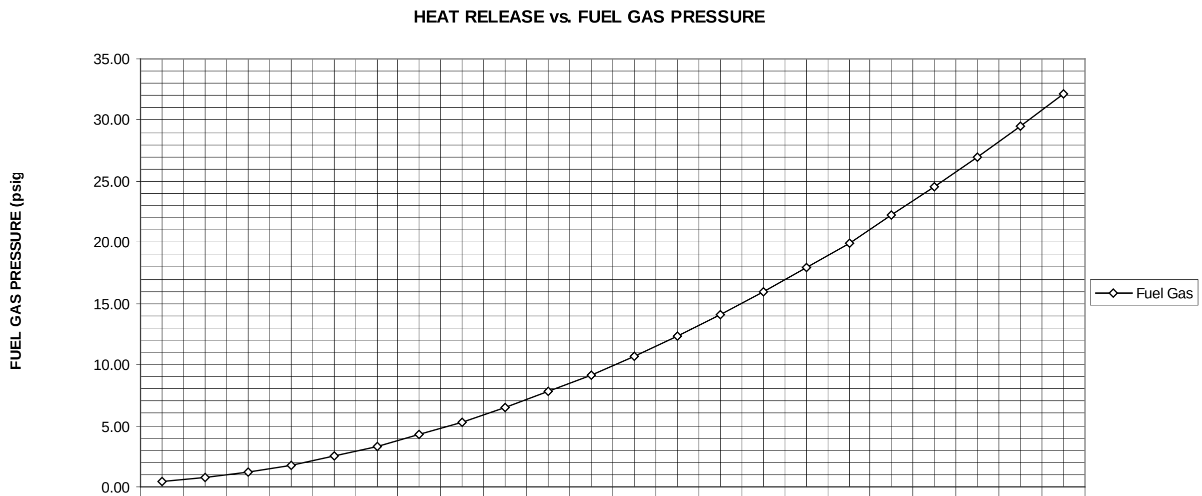


The Zeeco GLSF Free-Jet Burner

Appendix: Design Conditions

	Original	Revised
Boiler Tag #	132-B-1&2	132-B-1&2
Type of Boiler	Boiler	Boiler
Basic Flame Shape	Round Flame	Round Flame
Predicted Flame Length (feet)	25.9	13
Predicted Flame Diameter (feet)	3.44	4
Firing Direction	Horizontal	Horizontal
Mounting Direction	Sidewall	Sidewall
Refractory Thickness (in)	14.625	14.625
Boiler Steel Thickness (in)	0.25	0.25
Boiler Depth (ft)	TBD	14
Boiler Width (ft)	10.8	10.8
Boiler Height (ft)	20	20
Quantity of Burners per boiler	2	2
Max HR Gas (MMBtu/hr)	77.4	75
Norm HR Gas (MMBtu/hr)	63.75	63.75
Min HR Gas (MMBtu/hr)	7.74	7.5
Fuel Gas Pressure (psig)	25	32
Type of Draft	Forced	Forced
Pressure Drop @ Burner (H2O)	3.250	3.500
Air Temperature (°F)	100	100
% Excess Air Gas	10%	10%
Predicted Boiler Temperature at front wall (°F)	2305.00	2293.00
Ignition Type	Electric Ignition	Electric Ignition
Pilot	JM-1S-EF	JM-1S-EF
Approximate Boiler Volume, (ft3) =	TBD	3033
Approximate Boiler Front Wall Area, (ft2) =	216.67	216.67
Total Heat Release of Boiler, (MM Btu/hr (LHV)) =	154.80	150.00
Volumetric Heat Released, (Btu/ft3 (LHV)) =	TBD	49451
Heat Rel. per Wall Area at Max. H.R., (Btu/ft2 (LHV)) =	TBD	692308
Approx. Front Wall Temp. at Max H.R. (Degrees F) =	2305.00	2293.00
Main Gas line size, (inch)	4	4
Maximum Heat Release of Burner	77.4	75
Velocity of main gas line, ft/sec	139.1	132.3
Burner Size	20	20
% Floor Refractory	100	100
% Roof Refractory	0	0
% Front Wall Refractory	15	15
% Backwall Refractory	0	0
% Sidewall Refractory	0	0
Baseline NO_x (Standard Low NO_x Boiler Burner), Predicted ppmv	54.6	52.4
Baseline NO_x Boiler Burner, Guaranteed ppmv	61.3	59.1
CO Emissions Requirement	50	50
H2 Percentage in Baseline Fuel	8.1%	8.1%
NO_x Emissions Requirement	26	26
Standard External Flue Gas Recirculation Required, %	14%	13%

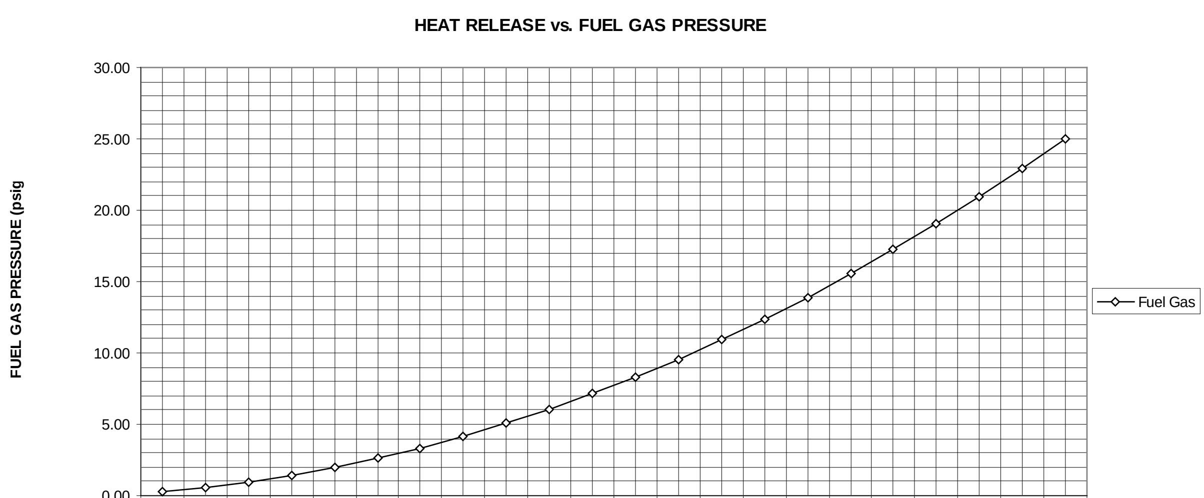
Heat Release vs. Fuel Gas Pressure Curve



	7.74	10.70	13.67	16.63	19.60	22.56	25.53	28.49	31.46	34.42	37.39	40.35	43.32	46.28	49.25	52.21	55.18	58.14	61.11	64.07	67.04	70.00
Fuel Gas	0.39	0.75	1.23	1.82	2.52	3.34	4.28	5.33	6.49	7.77	9.17	10.68	12.31	14.05	15.91	17.89	19.98	22.18	24.50	26.93	29.48	32.15

HEAT RELEASE (MM btu/hr)

Original Heat Release vs. Fuel Gas Pressure Curve



	7.74	10.70	13.67	16.63	19.60	22.56	25.53	28.49	31.46	34.42	37.39	40.35	43.32	46.28	49.25	52.21	55.18	58.14	61.11	64.07	67.04	70.00
Fuel Gas	0.31	0.58	0.95	1.41	1.96	2.60	3.33	4.14	5.05	6.05	7.13	8.31	9.57	10.93	12.37	13.91	15.53	17.25	19.05	20.94	22.93	25.00

HEAT RELEASE (MM btu/hr)