Ultra Low NOx Burner Testing

Project Number E23SWG0009

GAS EMERGING TECHOLOGIES (GET) PROGRAM
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Acknowledgements

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Disclaimer

Abbreviations and Acronyms

Abbreviation	Description
BARCT	Best Available Retrofit Control Technology
EE	Energy Efficiency
FGR	Flue Gas Recirculation
M&V	Measurement and Verification
Nitrogen Oxide	NOx
NZN	Near Zero NOx
S9	Sub 9ppm NOx
SCAQMD	South Coast Air Quality Management District
SJVAPCD	San Joaquin Valley Air Pollution Control District
Ultra Low NOx	ULN

Executive Summary

The goal of this GET project was to test and quantify the emissions improvements and efficiency gains for the ClearSign's Core™-Rogue ultra-low-NOx boiler burner compared to conventional (baseline) ultra-low-NOx burners. An industry standard mesh-style burner was selected as a baseline for this study.

The project was completed by ClearSign and Rogue engineers, and the project data and findings was independently verified by a third-party professional engineer. The lab testing took place at the California boiler facility in Santa Ana, California.

An M&V plan and test procedure was developed and followed throughout the testing. There were two main phases of testing with an additional third phase of testing on theClearSign burner (all NO_x values below are corrected to 3% O_2):

- Baseline burner tuned to sub-9 ppm NO_x
- Replacement with ClearSign burner
- ClearSign burner tuned to sub-9 ppm NO_x (S9 mode)
- ClearSign burner tuned to achieve lowest possible NO_x at sub-2.5 ppm (near-zero NO_x or NZN mode)

During each phase, the burner was started up under cold-start conditions and held at low-fire to allow the boiler to warm-up. The burner was ramped up to firing rate levels of 25%, 33%, 66%,84%, and 100% (for the ClearSign burner only), and the output steam flow rate was recorded along with all the other measurement quantities outlined in the M&V Plan to estimate fuel and energy usage as well as boiler efficiency.

The study found that the ClearSign Core-Rogue burner demonstrated higher boiler operating efficiencies, especially at the 66% and 84% firing rates. At the 66% firing rate, the ClearSign-Rogue S9 was more efficient than the baseline mesh burner by 3.5% on average and the NZN was more efficient than the baseline mesh burner by around 2.4%. At the 84% firing rate, these gains for the ClearSign-Rogue burner were 3.2% and 2.8%, respectively.

Compared to the baseline mesh burner, the ClearSign-Rogue burner offers fuel savings at both NOx levels with the savings being greater at sub-9 ppm operation, given the lower operating O2 and higher efficiency gains. At the 66% firing rate, the ClearSign-Rogue S9 had fuel savings of 5.4%, and the NZN had fuel savings of 3.8% compared to the baseline mesh burner. At the 84% firing rate, the ClearSign-Rogue S9 burner had fuel savings of 4.7%, and the ClearSign-Rogue burner at NZN conditions had fuel savings of 3.3% compared to the baseline burner. There were electrical savings that ranged from 7% to 25% at NZN mode and S9 mode, respectively.

Introduction

The State of California has the strictest nitrogen oxide (NOx) emissions standards in the nation. The South Coast Air Quality Management District (SCAQMD) recently updated Rule 1146.2 to require new and existing buildings to transition to zero-emissions NOx standards when replaced. For the first time ever, natural gas-fired pool boilers, larger water heaters, small commercial water heaters, boilers, and process heaters must meet zero-emission NOx standards [1]. Under Rule 1146.2, all residential, commercial, and light industrial equipment rated from 75,000 Btu/hr to 2 million Btu/hr are regulated based on size. This rule is expected to result in the second-largest reduction of NOx emissions in a decade, by nearly 8 tons of NOx per day. San Joaquin Valley Air Pollution Control District (SJVAPCD) Rules 4305–4308, 4320, and 4351 establish NOx emissions limits for process heaters, boilers, and steam generators [2]. The SJVAPCD has also adopted the Best Available Retrofit Control Technology (BARCT) rule. BARCT states that if businesses achieve lower NOx emissions than originally mandated by SJVAPCD, then all new permits must meet this achieved-in-practice limit. This rule establishes a moving target of NOx emissions for businesses since they cannot receive new permits unless they meet the lowest industry standards.

To meet these stricter regulations, manufacturers face the challenge of developing ultra-low NOx (ULN) or near-zero NOx (NZN) technologies for water heaters, boilers, and process heaters. ULN burners can play a crucial role in meeting NOx regulations. By optimizing fuel and air mixing, ULN burner technologies can achieve higher energy efficiency (EE) compared to traditional burners. Improved combustion can help reduce waste and enhance overall system performance through EE and fuel savings.

This project will evaluate the potential energy saving of the ClearSign burner technology compared to the industry standard mesh-style ULN burner. The project will compare the fuel use, energy use, emissions, and boiler operating efficiency before and after retrofitting the test firetube boiler with the ClearSign Core™ burner.

Background

The ClearSign Core™ technology is an innovative gaseous fuel combustion technology designed to significantly reduce environmental emissions of nitrogen oxides (NOx), a highly regulated pollutant, in industrial applications. ClearSign Core™ can meet very low levels of emissions required by the most stringent regulations in the country, while enhancing heat transfer characteristics. The ClearSign Core™ technology consists of air fuel premixing, internal flue gas recirculation (FGR), and their patented distil flame holder technology. They are the only burner company that has this unique combination of those three combustion elements in a fuel burner.

This technology has been successfully implemented across several industrial applications, including once-through-steam-generators (OTSGs), enclosed ground flares, refinery process heaters, gas processing plant transmix heaters, and firetube boilers. Upcoming commercial installations for the technology include midstream oil heaters and boilers for agricultural and recycling industries. The technology has been third-party source tested to achieve as low as sub-2.5 ppm NOx (corrected to 3% O_2) in boiler applications. However, a complete evaluation of efficiency benefits of the technology over conventional NOx reducing technologies has not been previously carried out.

Mesh or surface stabilized burners are commonly used in firetube boiler applications and represent the previous generation of NOx reduction technology. The burners employ lean premixed combustion to achieve single digit NOx emissions and typically operate with high levels of O_2 in the flue gas. One such industry standard mesh-style burner will be selected as a baseline for this study.

Assessment Objectives

The main objectives of this study are the following:

1. Test and measure the efficiency and emissions of an industry standard mesh-style baseline burner
2. Test and quantify the emissions improvements and potential efficiency gains for the ClearSign CORETM Ultra-Low-NOx burner technology.
3. Measure the following: NOx emissions (ppm, corrected to 3% O2), O2 in flue gas (%), CO emissions (ppm), CO2 emissions (%), boiler operating efficiency (%)

Measurement and Verification

Measurement and Verification (M&V) of energy use followed the International Performance Measurement and Verification Protocol (IPMVP) guidelines (ref. M&V Guidelines v4.0, 2015). The retrofit isolation Option A was used which involves isolation of the energy use of the burner + boiler system from the energy use of the rest of the facility. Measurement equipment was used to measure all relevant energy flows in the pre-retrofit baseline burner and the post-retrofit ClearSign burner periods. Energy consumption was determined by direct measurement of key variables that can be reliably used for its calculation.

The quantities measured include the following:

- Direct fuel consumption measured by the utility meter as well as special flow meters installed as part of the isolated system.
- Thermal output of the system through the flow rate and temperature of feed water, flow rate, pressure, and temperature of the outlet system.
- The electrical load and operating hours of the blower on the burner.

Flow meters were utilized in the feed water and steam output lines. Pressure gauges and thermocouples were installed on both lines as well. Boiler operating efficiency is calculated based on the total heat input from the burner and the total thermal output of the boiler. Emissions, including NOx, O_2, CO, and CO_2, was measured in the stack using a portable flue gas analyzer. The emissions analyzer was calibrated with appropriate span gases on a daily basis during the tests. Flue gas temperatures and stack flow rates were also recorded, along with all ambient conditions. Table 1 summarizes all the measured quantities for this experiment, and Table 2 lists all the quantities to be calculated.

Table 1. List of Measured Quantities

Quantity	Unit
Steam Flow	lbs/hr
Steam Pressure	psig
Steam Temperature	°F
Fuel Flow at Burner	scfh
Fuel Flow at Revenue Meter	scfh
Fuel Consumption	scf
Water Flow	lbs/hr
Combustion Air Flow	scfh
Feedwater Pressure	psig
Fuel Pressure	psig
Feedwater Temperature	°F
Fuel Temperature	°F
Combustion Air Temperature	°F
Stack Temperature	°F
Auxiliary Steam Flow	lbs/hr
Auxiliary Steam Temperature	lbs/hr
Auxiliary Steam Pressure	psig
Windbox Pressure	in. w.c.
Furnace Pressure	in. w.c.
Ambient Temperature	°F
Ambient Humidity	%
BMS Electrical Power	W
BMS Electrical Power	W
Feedwater Pump Electrical Power	W
Blower Electrical Power	W
VFD Electrical Power	W
VFD Frequency	Hz
VFD Current	A
VFD Speed	RPM
NOx	ppm (raw and corrected to 3% O2)
CO	ppm
O2	% (dry and/or wet)

Table 2. Quantities to be Calculated

Quantity	Unit
Output Energy	MMBtu/hr
Input Energy	MMBtu/hr
Boiler Operational Efficiency	%
Stack Losses	MMBtu/hr
Electrical Energy Use	W-h
Fuel Energy Use	MMBtu
Natural Gas Energy Savings	MMBtu/hr
Electrical Energy Savings	kW

Testing Approach

There are two main phases of testing with an additional third phase of testing on the ClearSign burner:

1. Baseline burner tuned to sub-9 ppm NOx.
2. Replacement ClearSign burner:
    A. ClearSign burner tuned to sub-9 ppm NOx
    B. ClearSign burner tuned to achieve lowest possible NOx (sub-2.5 ppm)

During each phase, the burner is started up under 'cold-start' conditions and ramped up to high-fire (100% firing rate) following a consistent, preset time at low-fire hold to allow the boiler to warm-up. At high-fire, the output steam flow rate is recorded along with all the other measurement quantities outlined in this document to estimate fuel and energy usage as well as boiler efficiency. The burner is then ramped down to 50% firing rate and the measurements will be repeated. Finally, the burner is set to its low turndown firing rate (25%) for a final set of measurements. At each test condition, the burner is held at the firing rate for 30 minutes to reach steady-state operation. The steam line is fitted with an orifice plate that sets a minimum pressure of 100 psig at 100% firing rate. The test points are repeated over three separate test runs for each phase.

In Phase IIA, the replacement ClearSign burner is de-tuned from its near-zero NOx operation to match the NOx emissions level of the baseline burner. In Phase IIB, the burner will operate in its near-zero NOx mode. In each phase, the burner is fired at fixed rates of 100%, 75%, 50%, and 25%. The fixed fuel flow rates and the steam produced from the boiler will be different in each case. Comparisons of fuel usage and electricity usage are made on a 'per pound of steam produced' basis.

Note that the true firing rates in Phase I and Phase II were different from the selected firing rates due to the boiler design limitations which were only identified during the testing. The calculations are illustrated in the reports for each phase of testing. The approach is shown in a subsequent section below.

'Isolated' Boiler and Burner System

A schematic of the system is shown in Figure 1 below. It details all the flow and energy exchanges into and out of the isolated boiler and burner system as well as the various quantities to be measured. A post-installation verification is performed by the independent engineer assigned to the project to ensure that proper equipment is installed and operating correctly. A detailed list of all installed equipment, and any deviations between proposed and actual equipment are provided to the engineer.

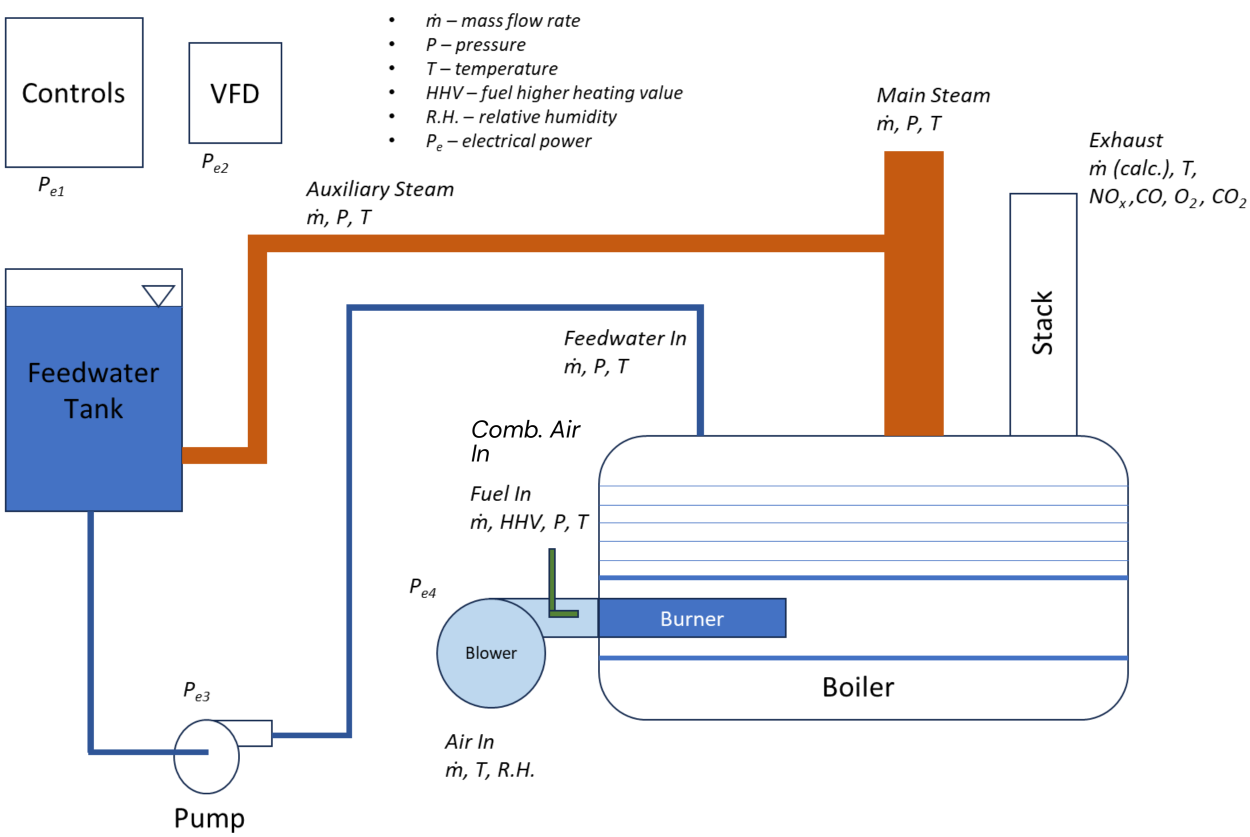

Figure 1. Boiler Burner Schematic

The list of the instruments used for each phase of the testing is summarized below in Table 3.

Table 3. Instrumentation List

Instrument	Quantity	Line	Type	Model	Units	Range and Accuracy
Steam Flow Meter	ṁsteam	Main Steam	Vortex	Prowirl F 200	cfh	0.23 to 17000 cfh ±1.0%
Steam Flow Meter	ṁsteam2	Auxiliary Steam	Vortex	Prowirl F 200	cfh	0.23 to 17000 cfh ±1.0%
Fuel Flow Meter	ṁNG	Fuel	Thermal	t-mass F-300	lb/h	1.1 to 8750 lb/h ± 1.0% o.r.
Fuel Consumption Meter – Cumulative	mNG	Fuel Consumption	Real-time/Utility Meter		scf	TBD
Water Flow Meter	ṁH2O	Feedwater		Prowirl F 200	cfh	0.045 to 1300 cfh ±0.75%
Air Flow Meter	ṁair	Combustion Air	Pitot-static	t-mass I-300	lb/h	44 to 1669340 lb/h ± 1.0% o.r.
Pressure Gage	Psteam	Main Steam			psig	±1.6%
Pressure Gage	PH2O	Feedwater			psig	±1.6%
Pressure Gage	PNG	Fuel x 3 (per individual line)			psig	0-5 psig ±1.6%
Pressure Gage	Psteam2	Auxiliary Steam			psig	±1.6%
Thermocouple	Tsteam	Main Steam	K		°F	-454 to 2501 °F ±0.75%
Thermocouple	TH2O	Feedwater	K		°F	-454 to 2501 °F ±0.75%

Instrument	Quantity	Line	Type	Model	Units	Range and Accuracy
Thermocouple	TNG	Fuel	K		°F	-454 to 2501 °F ±0.75%
Thermocouple	Tsteam2	Auxiliary Steam	K		°F	-454 to 2501 °F ±0.75%
Thermocouple	Tair	Combustion Air	K		°F	-454 to 2501 °F ±0.75%
Thermocouple	Texh	Flue Gases	K		°F	-454 to 2501 °F ±0.75%
Electrical Power	Pe1	BMS			W	
Electrical Power	Pe2	VFD			W	
Electrical Power	Pe3	Feedwater Pump			W	
Electrical Power	Pe4	Blower			W	
Ambient Conditions	Tamb, R.H.	Ambient			°F, %	
Emissions	NOx, CO, O2	Flue Gases	Calibrated to appropriate ranges	Testo/ ECOM or equivalent	ppm, ppm, % (vol)	0-500 ppm ±5%, 0-10000 ppm ±2%, 0-21% ±0.2%

Method for Efficiency Measurement and Calculation

The 'Input Output Method' (ref. ASME PTC4, 2013) is used to measure Efficiency of the boiler.

$$Efficiency\ (\%) = \frac{Output}{Input} \times 100 \qquad (1)$$

Efficiency determination by the Input–Output method requires direct and accurate measurement of all output as well as all input. The primary measurements required are the following:

a. Feedwater flow rate entering the steam generator.
b. DE superheating water flow rates (*not applicable*).
c. Flow rates of all secondary output streams such as boiler blowdown (*not applicable*), auxiliary steam, etc.
d. Pressure and temperature of all working fluid streams such as entering feedwater, superheater outlet, reheater inlet and outlets, auxiliary steam, etc.
e. Additional measurements in the turbine cycle as required to determine reheater flows by energy balance methods (*not applicable*).
f. Fuel flow rate.
g. Higher heating value of the fuel.
h. Waste energy input (*not applicable).*

Efficiency Calculation Notations

The variables used for efficiency calculations are denoted in Table 4.

Table 4. Variable Notations for Efficiency Calculations

Variable	Description
$\dot{m}$	mass flow rate
P	Pressure
T	Temperature
HHV	Fuel higher heating value
LHV	Fuel lower heating value
$R.H$	Relative humidity
H	Specific enthalpy (ref. NIST/ASME Steam Properties—STEAM v3.0)
$\dot{Q}$	Energy Flow
η_{comb}*	Modified Combustion Efficiency
Cp	gas component specific heat

* Subscripts indicate the fluid/energy stream considered

Supporting equations are described below:

Main Steam Flow

$$\dot{Q}_{steam} = h_{steam} \times \dot{m}_{steam} \qquad (2)$$

Where h_{steam} will be based on pressure, temperature, and quality of the steam.

Feedwater Flow

Ensure that ṁfeedwater = ṁsteam + ṁaux-steam

$$\dot{Q}_{feedwater} = h_{feedwater} \times \dot{m}_{feedwater} \qquad (3)$$

Where $h_{feedwater}$ is based on saturated liquid properties.

Auxiliary Steam Flow

$$\dot{Q}_{aux-steam} = h_{steam} \times \dot{m}_{aux-steam} \qquad (4)$$

Output Energy

$$\dot{Q}_{out} = \dot{Q}_{steam} + \dot{Q}_{aux-steam} - \dot{Q}_{feedwater} \qquad (5)$$

Input Energy

$$\dot{Q}_{in} = \dot{m}_{NG} \times HHV \times \eta_{comb} \qquad (6)$$

Boiler Operating Efficiency

$$\eta_{boiler}(\%) = \frac{Q_{out}}{Q_{in}} \times 100 \qquad (7)$$

Stack Losses

Stack losses are not used in Input-Output method but used to estimate system losses.

$$\dot{m}_{flue\ gases} = \dot{m}_{NG} + \dot{m}_{comb\ air} \qquad (8)$$

$$\dot{Q}_{flue\ gases} = \dot{m}_{flue\ gases} \times \sum Cp_{CO2,N2,H2O\ ,O2,CO} \times (T_{stack} - T_{ambient}) \qquad (9)$$

Calculations for Energy Use

For energy calculations, the variables referenced are detailed below in Table 5.

Table 5. Variables for Energy Calculations

Variable	Description
$\dot{m}$	mass flow rate
H	Specific enthalpy (ref. NIST/ASME Steam Properties—STEAM v3.0)
$\dot{Q}$	Energy Flow
η_{comb} *	Modified Combustion Efficiency
$\dot{P}$	Electrical Power

* Subscripts indicate the fluid/energy stream considered

Electrical Calculation

$$\dot{P}_{e-total} = \dot{P}_{e-blower} + \dot{P}_{e-VFD} + \dot{P}_{e-BMS} + \dot{P}_{e-pump} \qquad (10)$$

The quantities in equation 10 were measured directly.

$$Total\ Electrical\ Energy\ Use = \dot{P}_{e-total} \times runtime \qquad (11)$$

Fuel Use

$$Fuel\ Energy\ Use = \dot{m}_{NG} \times HHV \times runtime \qquad (12)$$

A cumulative measurement meter was used to verify the fuel usage during each test condition.

The energy savings is calculated by the following equations:

$$Natural\ Gas\ Saving\ \left(\frac{MMBtu}{hr}\right) = (Baseline\ Fuel\ Use - Post\ Retrofit\ Fuel\ Use) \qquad (13)$$

$$Electrical\ Energy\ Savings\ (kW) = (Baseline\ Energy - Post\ Retrofit\ Energy) \qquad (14)$$

Test Set-Up Phase I

The test boiler is a Cleaver-Brooks CB700-125 4-pass steam boiler rated for 125 HP or maximum heat input of 5.23 MMBtu/h. The baseline burner is an industry standard mesh burner with a maximum firing rate of 4998 MMBtu/h with a Siemens LMV3 control system. The steam outlet is connected to a vent system as well as an auxiliary steam line that feeds into a Feedwater Tank. The tank supplies feedwater to the boiler using a feedwater pump. Note that the system does not recycle the condensate and that 100% of the makeup water was used. Figure 2 shows the boiler set up.

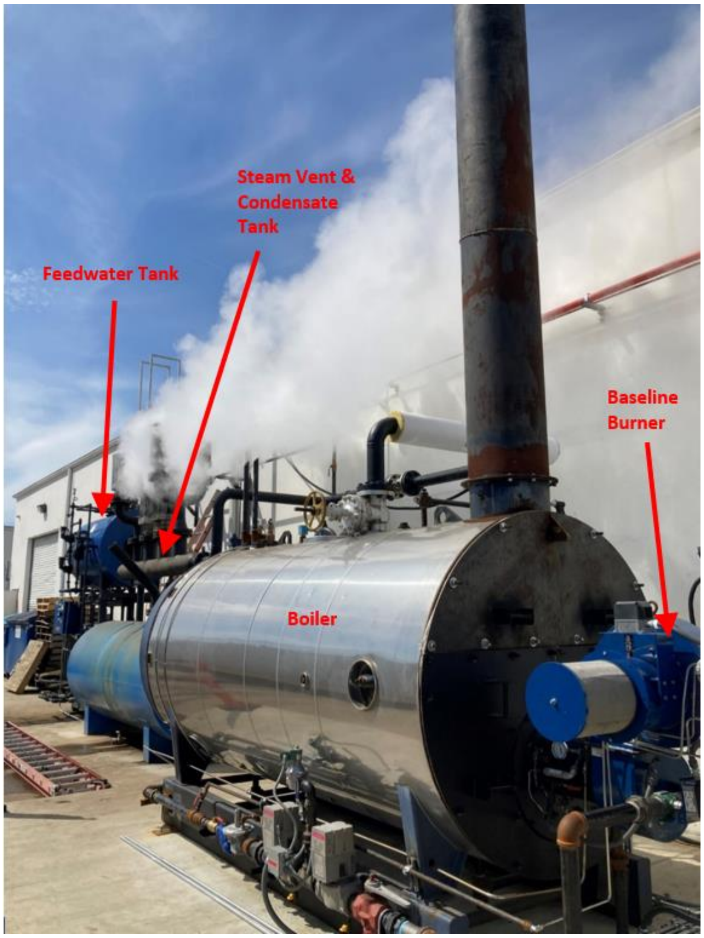

Figure 2. Boiler Test Pad Set-Up

Figures 3-6 show the instruments as installed on the test pad set-up.

Figure 3. Emissions Probe installed in the Stack (left), and ECOM J2KN Analyzer (right)

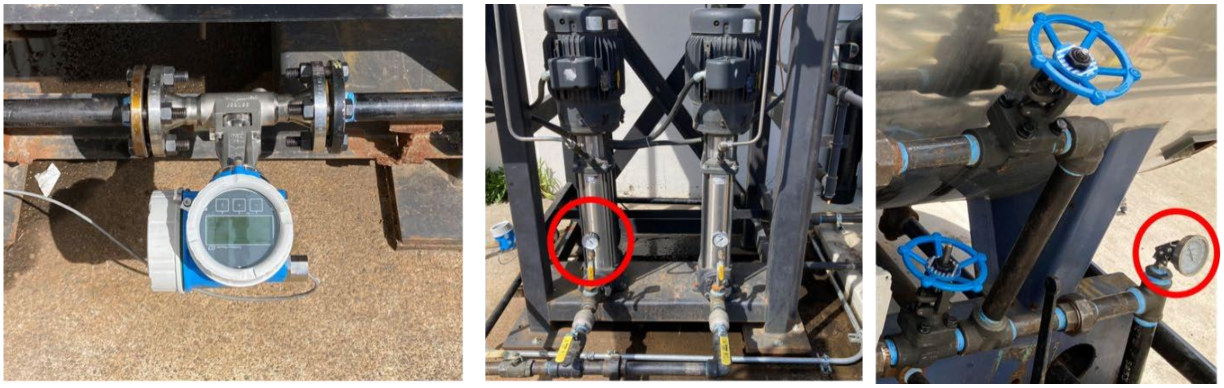

Figure 4. Feedwater Flow, Pressure, and Temperature Measurements

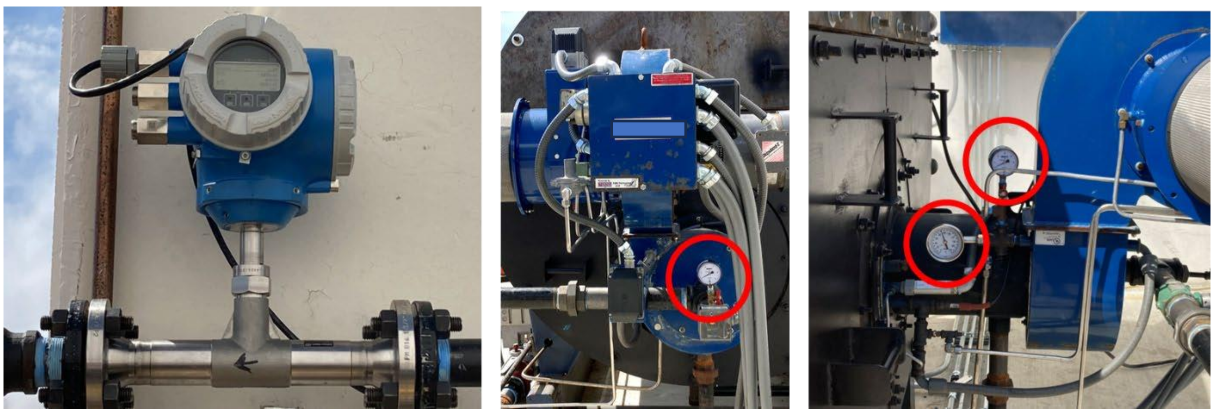

Figure 5. Burner Fuel Flow, Temperature, Pressure, and Combustion Air Pressure and Temperature Measurements.

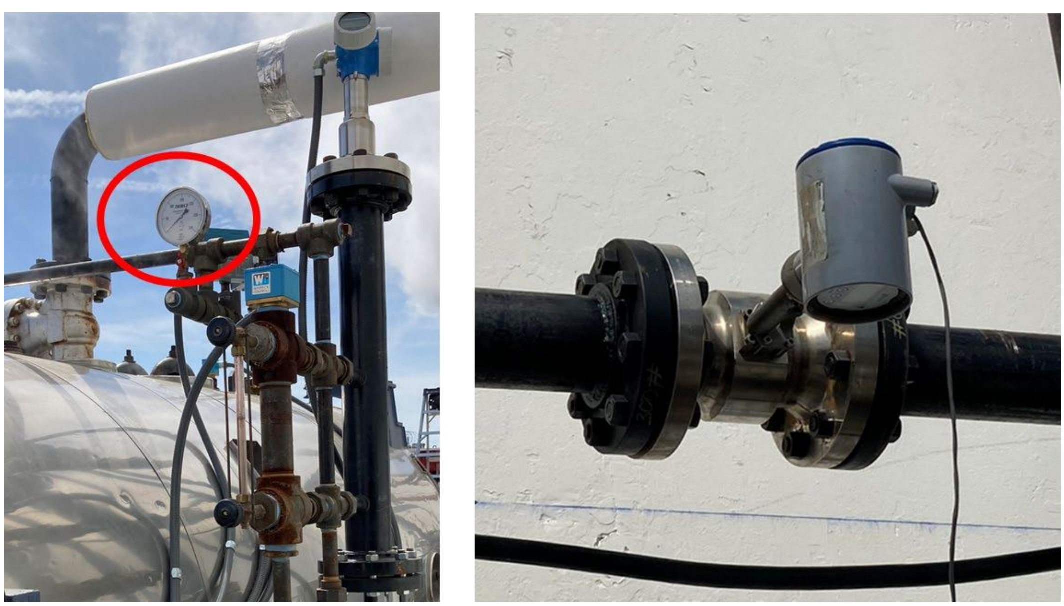

Figure 6. Steam Pressure, Flow, and Temperature Measurements

The steam flow meter was installed upstream of where the steam flow split into the 'main' and 'auxiliary' lines i.e. the steam mass flow rate was the total of the main and auxiliary steam flows. Note that fuel usage could not be measured from the utility meter to verify the flow meter readings as the display was locked out and there was no measurement of the supply pressure. The baseline burner did not have a VFD, therefore no VFD power was recorded. The Building Management System (BMS) electrical power could not be recorded due to limited access, but this value is expected to be negligible compared to other components and similar for the ClearSign burner BMS as well.

Phase I Testing

Prior to the start of testing, the baseline burner was tuned to achieve sub-9 ppm NOx with a target NOx of 7-8 ppm (corrected to 3% O_2). The burner wasn't readjusted or tuned once testing commenced to set exact O_2 or NO_x levels. As expected, during operation, due to variations in ambient conditions and boiler operating conditions, repeatability of control valves, and analyzer uncertainties, the actual NOx fell in the 6 to 8.5 ppm range. Similar variability will be expected during testing of the ClearSign burner.

The testing followed the M&V Plan detailed in the previous section. Four firing rates were initially selected for the test conditions – 25%, 50%, 75% and 100%. However, the burner was limited to around 85% of its design rate due to its combustion air blower capacity, thus the firing rates ended up being – 25%, 33%, 66%, and 84%. At each firing rate, the system was allowed to stabilize until the steam flow rate and stack temperature reached steady values. Then data were collected at 10-minute intervals for a total duration of 30 minutes. The steam, feedwater, and fuel flow rates were totalized readings over the 30-minute period. All remaining quantities were averages of four readings. Each firing rate condition was repeated three times – twice while the burner firing rate was increased and once while it was decreased. The baseline burner did not have a VFD, therefore no VFD power was recorded. All the recorded raw data are presented in Appendix 1.0.

Phase I Results

The calculated values including the mass flow rate, volumetric flow rates, energy and enthalpy of the various fluid streams are shown in Table 6 below.

Table 6. Phase I Calculated Flow and Energy Quantities

		RUN 1				RUN 2				RUN 3				
Stream														
Steam	Mass Flow Rate	988	1254	2456	3004	3024	2500	1266	978	994	1200	2426	2962	lb/h
	Specific Enthalpy	1153.6	1154.9	1161	1163.7	1164	1161.2	1155.1	1154.1	1153.5	1154.7	1161	1163.6	Btu/lbm
	Total Enthalpy	1.14	1.45	2.85	3.50	3.52	2.90	1.46	1.13	1.15	1.39	2.82	3.45	MMBtu/h
Fuel	Volume Flow Rate	1312.72	1650.14	3343.72	4055.76	4056	3292.52	1640.78	1266.1	1354.92	1654.98	3301.7	4036.6	Scfh
	Heat Input	1.36	1.71	3.49	4.25	4.24	3.43	1.70	1.31	1.40	1.71	3.43	4.16	MMBtu/h
	Heat Input	397.34	500.56	1013.95	1229.77	1230.25	998.71	497.66	383.90	409.62	500.91	999.76	1219.68	kW
	Rate	27%	34%	69%	84%	84%	68%	34%	26%	28%	34%	68%	83%	
Feedwater	Mass Flow Rate	777.56	1041.48	2343.02	3016.44	3146.78	2587.02	945.62	696.94	929.8	946.52	2298.54	2999.86	lb/h
	Specific Enthalpy	80.289	66.117	88.895	118.28	121.07	113.47	88.895	73.203	47.896	47.896	83.073	106.88	Btu/lbm
	Total Enthalpy – 1 (feedwater flow)	0.06	0.07	0.21	0.36	0.38	0.29	0.08	0.05	0.05	0.05	0.19	0.32	MMBtu/h
	Total Enthalpy -2 (steam flow)	0.08	0.08	0.22	0.36	0.37	0.28	0.11	0.07	0.05	0.06	0.20	0.32	MMBtu/h
Combustion Air	Flow Rate	20097.36	24891.55	47979.74	59969.22	59439.55	47995.20	24436.45	18822.20	20070.13	24692.64	49172.85	59578.96	Scfh
	Flow Rate	20805.83	25886.46	50785.16	64710.66	63709.59	50589.87	25651.33	19741.31	20445.22	25294.96	51021.55	62866.30	Acfh
	Sensible Enthalpy	0.00	0.00	0.01	0.01	0.02	0.01	0.01	0.00	0.00	0.00	0.01	0.01	MMBtu/h
Energy	Heat Output	1.06	1.37	2.63	3.14	3.15	2.62	1.35	1.06	1.10	1.33	2.62	3.13	MMBtu/h
	Boiler Op Efficiency	**78.2%**	**80.0%**	**76.1%**	**74.8%**	**75.1%**	**76.9%**	**79.5%**	**80.7%**	**78.6%**	**77.7%**	**76.7%**	**75.2%**	
Electrical	Blower Electrical Power	3.41	3.35	3.99	4.50	4.50	3.98	3.37	3.34	3.40	3.38	4.04	4.52	HP
	Blower Electrical Power	2.54	2.50	2.98	3.36	3.36	2.97	2.51	2.49	2.54	2.52	3.01	3.37	kW
	Estimated Flow Energy	0.11	0.23	1.47	2.71	2.66	1.48	0.22	0.11	0.13	0.22	1.54	2.65	HP

		RUN 1				RUN 2				RUN 3				
	Estimated Blower Efficiency	3.28%	6.88%	36.86%	60.20%	59.04%	37.05%	6.63%	3.37%	3.70%	6.52%	38.14%	58.66%	
	Pump Electrical Power	3.96	3.91	3.81	3.93	4.07	3.96	3.91	3.88	3.93	3.91	3.81	3.97	HP
	Pump Electrical Power	2.95	2.92	2.84	2.93	3.04	2.95	2.92	2.89	2.93	2.92	2.84	2.96	kW
Exhaust	Energy in Stack Exhaust	0.211	0.272	0.606	0.779	0.775	0.600	0.267	0.199	0.217	0.270	0.614	0.782	MMBtu/h
Energy Use	Fuel Energy Use	0.68	0.85	1.72	2.09	2.09	1.70	0.85	0.65	0.70	0.85	1.70	2.08	MMBtu
	Electrical Energy Use	5.50	5.42	5.82	6.29	6.39	5.92	5.43	5.38	5.47	5.44	5.86	6.33	kW-h
	Fuel Energy Used/lb of Steam	1372.24	1360.67	1408.69	1396.86	1388.17	1363.11	1341.30	1339.40	1406.12	1424.32	1406.15	1450.04	Btu/lb-steam
	Electrical Energy Used/lb of Steam	5.56	4.32	2.37	2.09	2.11	2.37	4.29	5.50	5.50	4.53	2.41	2.14	W-h/lb-steam

Notes:

i) On the baseline mesh burner, the combustion air temperature was measured downstream of the blower whereas on the ClearSign-Rogue burner, it was measured upstream. Therefore, for consistency, the calculations for the baseline mesh burner were changed to use the Ambient temperature as the combustion air temperature so that it is consistent with the ClearSign-Rogue burner. This resulted in the Mesh burner efficiencies improving slightly.

ii) In the Phase I calculations, the feedwater pump electrical power was incorrectly calculated using the Blower current instead of the pump current which is why the Blower and Pump power results were identical. A correction was made to use the Feedwater Pump current (Amps).

Fluid Properties used in the calculations are summarized in Table 7.

Table 7. Fluid Properties References for Calculations and Analysis

Natural gas Higher Heating Value (HHV)	1,031 Btu/scf
Natural gas Higher Heating Value (HHV)	21,000 Btu/lbm
Standard Temperature and Pressure	60 °F, 14.696 psia
Gas Specific Heats (CO2, H2O, O2, N2)	NIST Chemistry Webbook
Saturated Steam and Water Properties	NIST Chemistry Webbook

There are some differences between the mass flow rate of the feedwater coming into the boiler and that of the steam leaving the boiler, especially at low firing rates. The differences ranged from as high as 29% at low fire down to 0% at high fire. Under steady state conditions, these rates are expected to match each other within measurement uncertainty. However, given that the feedwater valve to the boiler opens intermittently at low fire based on the water level inside, the feedwater pump does not run continuously but turns on and off based on feedwater valve control. Thus, the instantaneous readings taken every 10-minutes are not representative of the true average flow rate of feedwater over 30 minutes. Since the pump ran continuously at high fire to keep up with the rate of steam flow, the flow rate measurements matched better, within uncertainty, at high fire. On the other hand, steam flow out of the boiler is steady at all firing rates. Steam mass flow rate is used for the final calculations of efficiency.

Since CO emissions were zero, combustion efficiency was assumed to be at 100%. Boiler operating efficiency of the boiler with the baseline burner ranged from 80.4% at minimum firing rate. to 73.9% at maximum firing rate, i.e. the efficiency reduced as the burner fired harder. These efficiency numbers are lower than the typical 80% boiler efficiency rating for burner-boiler systems. The lower efficiency is a result of the burner being operated at around 8% O_2 in the stack to comply with sub-9 ppm NOx emissions (corrected to 3% O_2). Fuel and energy use are represented on a 'per pound of steam produced' basis. This representation will allow for normalized comparisons after the second phase of testing**.** On average, the baseline burner used 1,392 Btu/lb-steam of thermal energy across all firing rates**.** The electrical energy use, which included the blower and feedwater pump, was around 3.45 W-h/lb-steam at low fire to 1.49 W- h/lb-steam at high fire. The electrical energy use was lower at high fire because the blower operated closer to its design point where it is most efficient, as summarized in Table 6.

For Phase I, **the baseline burner boiler operating efficiency at maximum rate was 74.1% on average**. The average **fuel energy use was 1,392 Btu/lb- steam** produced while the **electrical energy use ranged from 1.49 to 3.45 W-h/lb-steam** produced.

Test Set-Up Phase II

For Phase II, the same test boiler, the Cleaver- Brooks CB700-125 4-pass steam boiler rated for 125 HP or maximum heat input of 5.23 MMBtu/h is used. The steam outlet system, feedwater tank supplies, and feedwater system are the same as well. The Phase II burner represents the emerging technology is a Rogue CF-125 HP burner with ClearSign Core™ technology. The Phase II set up is shown below in Figure 7.

Figure 7. Phase II Boiler Test Pad

Figure 8 shows the instrumentation schematic per the M&V Plan. Figures 9-12 show all the instruments as installed on the test set-up. One change was made to the instrumentation set-up from Phase I: The fuel flow meter was moved to the burner fuel skid since it is an integral part of the burner controls – however, the necessary inlet and outlet diameters/distances were maintained as specified by the flow meter manufacturer.

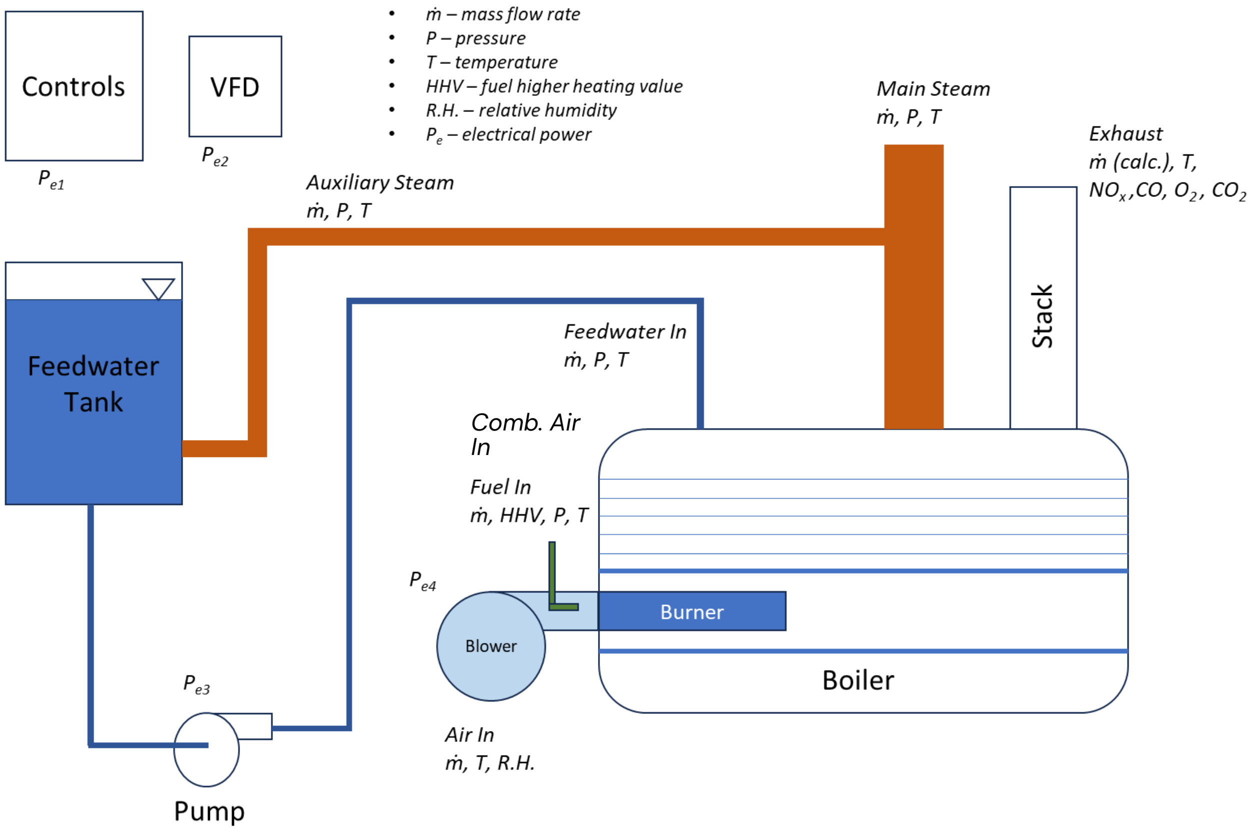

Figure 8. Phase II Test Instrumentation Layout (From M&V)

Figure 9. Emissions Probe Installed in the Stack (left), ECOM J2KN Analyzer (right)

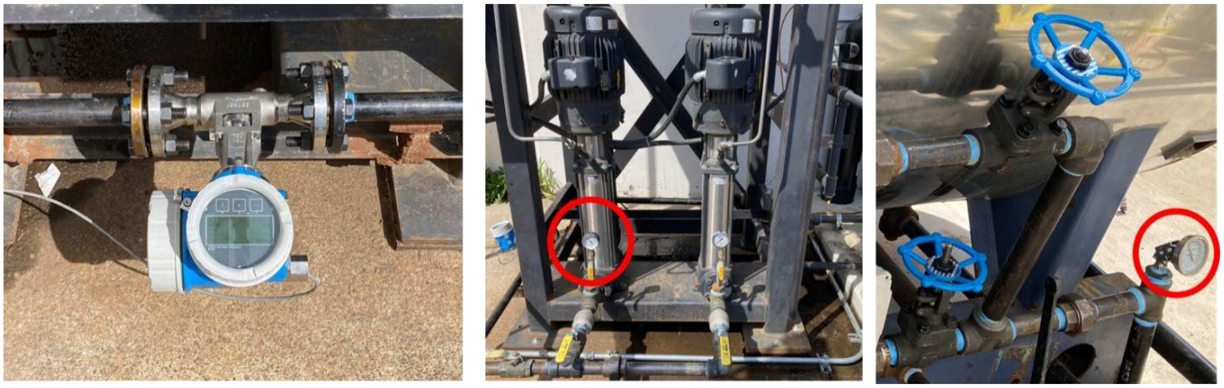

Figure 10. Feedwater Flow, Pressure, and Temperature Measurements

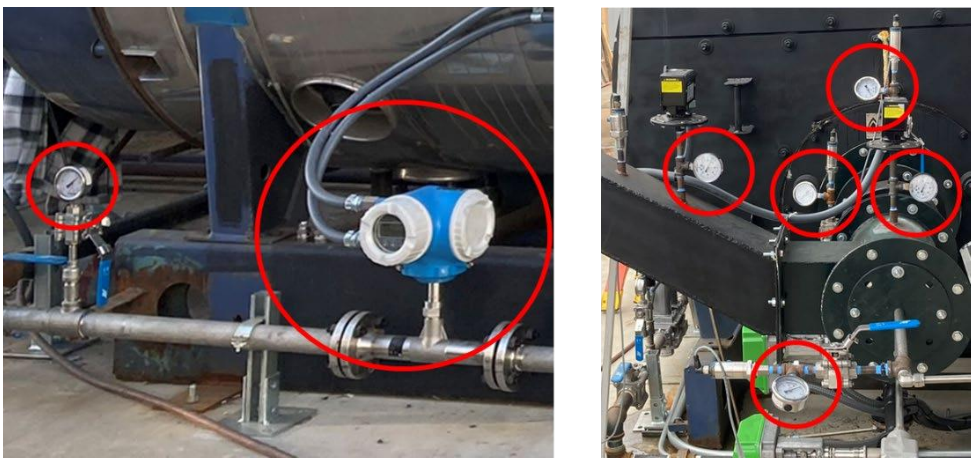

Figure 11. Burner Fuel Flow, Temperature, Pressure, and Combustion Air Pressure and Temperature Measurements

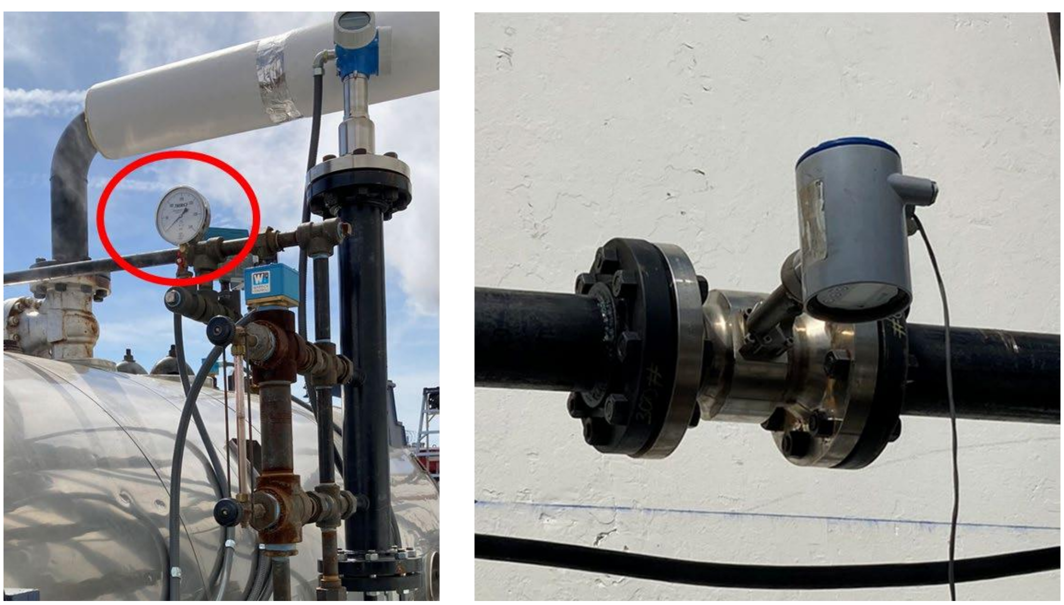

Figure 12. Steam Pressure, Flow, and Temperature Measurements

Similar to Phase I, the BMS electrical power could not be recorded to limited access, but the value is expected to be negligible compared to the power used by other components for the ClearSign burner BMS.

Phase II Testing

As described in the M&V section, Phase II of the testing consists of:

A. ClearSign burner turned to sub-9 ppm NOx ('S9' mode)
B. ClearSign burner tuned to achieve the lowest possible NOx at sub 2.5ppm (near-zero NOx or 'NZN' mode)

During each phase, the burner is started up under 'cold-start' conditions and held at low-fire to allow the boiler to warm-up. The burner is ramped up to firing rate levels of 25%, 33%, 66%, 84%, and 100% (for the ClearSign burner only), and the output steam flow rate is recorded along with all the other measurement quantities outlined in the M&V Plan to estimate fuel and energy usage as well as boiler efficiency. Prior to each day of testing, the sensors were calibrated with the following span gases: CO – 44.9 ppm and 80.8 ppm; NO – 37.0 ppm, 12.7 ppm, and 7.48 ppm; O_2 – 3% and 21%.

At each test condition, once the steam flow, steam pressure, stack temperature, leveled out, and the system reached steady-state, the burner is held at the firing rate for 30 minutes. Data are recorded every 10 minutes during the 30-minute period with the flow rates (steam, fuel, feedwater) being recorded as totalized readings. The test points are repeated over three separate test runs at each firing rate. In the NZN mode, only two repeat runs are possible due to time constraints and the increased number of firing rate conditions compared to the original plan laid out in the M&V document.

In Phase IIA, the replacement ClearSign burner is de-tuned from its near-zero NO_x operation to match the NO_x emissions level of the baseline burner. In Phase IIB, the burner operated in its near-zero NO_x mode. Phase IIA-B Raw Data can be found in Appendix 2.

Phase II Results

The calculated values from Phase II testing are shown below in Table 8. Referenced properties from Table 7 were used in the calculations.

Table 8. Phase II Calculated Flow and Energy Quantities

Stream																
Steam	Mass Flow Rate	1030	1226	2636	3132	3106	3126	3706	3716	3660	2610	2608	1006	1086	1248	1252
	Specific Enthalpy	1153.8	1155	1161.9	1164.4	1164.3	1164.3	1167.4	1167.3	1167.1	1161.9	1161.9	1153.6	1154.1	1154.9	1154.9
	Total Enthalpy	1.19	1.42	3.06	3.65	3.62	3.64	4.33	4.34	4.27	3.03	3.03	1.16	1.25	1.44	1.45
Fuel	Volume Flow Rate	1382.72	1596	3438	4020	3998.2	4040.6	4844.2	4750.2	4726.8	3287.6	3287.6	1315.2	1399.4	1635	1636.6
	Heat Input	1.43	1.65	3.55	4.15	4.13	4.18	5.01	4.91	4.89	3.40	3.40	1.36	1.45	1.69	1.69
	Heat Input	417.94	483.10	1041.56	1217.61	1211.30	1223.71	1467.53	1439.04	1431.98	995.42	995.22	398.51	423.92	495.14	495.55
	Rate	29%	33%	71%	83%	83%	84%	100%	98%	98%	68%	68%	27%	29%	34%	34%
Feedwater	Mass Flow Rate	775.76	1596.8	2559.22	3196	3132	3124	4078	4132	4030	2548	2570	844	894	1182	1034
	Specific Enthalpy	54.983	60.297	87.629	119.8	122.59	123.86	119.3	127.41	126.65	117.01	118.54	68.395	67.888	68.141	64.599
	Total Enthalpy-1 (feedwater flow)	0.04	0.10	0.22	0.38	0.38	0.39	0.49	0.53	0.51	0.30	0.30	0.06	0.06	0.08	0.07
	Total Enthalpy-2 (steam flow)	0.06	0.07	0.23	0.38	0.38	0.39	0.44	0.47	0.46	0.31	0.31	0.07	0.07	0.09	0.08
Combustion Air	Flow Rate	16151.15	18744.74	41229.43	48276.88	48424.96	47917.06	58923.24	58196.54	58246.28	38772.04	38718.63	14703.38	15726.18	18445.92	18684.31
	Flow Rate	16160.20	19061.17	41367.75	48048.56	48132.58	47699.04	57730.62	57032.06	56913.23	38665.18	38540.27	15063.75	16057.39	18750.82	18939.35
	Sensible Enthalpy	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
Energy	Heat Output	1.13	1.34	2.83	3.27	3.24	3.25	3.88	3.86	3.81	2.73	2.72	1.09	1.18	1.36	1.37
	Thermal Efficiency	79.4%	81.4%	79.7%	78.7%	78.3%	77.9%	77.6%	78.7%	77.9%	80.3%	80.1%	80.3%	81.6%	80.3%	80.7%
Electrical	Blower Electrical Power	1.00	0.60	1.70	2.64	2.60	2.50	4.45	4.45	4.46	1.46	1.46	0.95	1.10	0.63	0.64
	Blower Electrical Power	0.75	0.45	1.26	1.97	1.94	1.86	3.32	3.32	3.33	1.09	1.09	0.71	0.82	0.47	0.48
	Estimated Air Flow Energy	0.06	0.10	0.89	1.46	1.45	1.39	2.59	2.55	2.56	0.76	0.74	0.05	0.06	0.09	0.10
	Estimated Blower Efficiency	5.78%	17.29%	52.48%	55.24%	55.76%	55.71%	58.22%	57.25%	57.39%	52.08%	50.79%	5.52%	5.67%	14.38%	15.78%
	Pump Electrical Power	3.79	3.83	4.08	4.08	4.08	4.10	4.14	4.11	4.12	4.07	4.08	4.00	3.98	4.00	3.99
	Pump Electrical Power	2.83	2.85	3.04	3.04	3.05	3.06	3.09	3.06	3.08	3.04	3.04	2.98	2.97	2.98	2.98
Exhaust	Energy in Stack Exhaust	0.205	0.239	0.586	0.713	0.710	0.713	0.900	0.886	0.883	0.558	0.558	0.188	0.202	0.240	0.242
Energy Use	Fuel Energy Use	**0.71**	**0.82**	**1.77**	**2.07**	**2.06**	**2.08**	**2.50**	**2.45**	**2.44**	**1.69**	**1.69**	**0.68**	**0.72**	**0.84**	**0.84**
	Fuel Energy Used / lb of Steam	**1384.55**	**1344.55**	**1348.24**	**1326.53**	**1330.70**	**1335.72**	**1351.17**	**1321.37**	**1335.01**	**1301.35**	**1302.09**	**1351.67**	**1331.93**	**1353.77**	**1350.56**
	Electrical Energy Use	3.58	3.30	4.31	5.01	4.98	4.92	6.41	6.38	6.40	4.12	4.13	3.69	3.78	3.45	3.45
	Electrical Energy Used / lb of Steam	3.47	2.69	1.63	1.60	1.60	1.57	1.73	1.72	1.75	1.58	1.58	3.66	3.48	2.77	2.76

Stream										
Steam	Mass Flow Rate	3728	3724	3038	3008	2518	2538	1296	1304	lb/h
	Specific Enthalpy	1167.5	1167.5	1164	1163.8	1161.3	1161.5	1155.2	1155.2	Btu/lbm
	Total Enthalpy	4.35	4.35	3.54	3.50	2.92	2.95	1.50	1.51	MMBtu/h
Fuel	Volume Flow Rate	4846	4815.4	3938.8	3968.8	3279.6	3275.6	1706.8	1713.4	scfh
	Heat Input	5.02	4.98	4.07	4.10	3.39	3.38	1.76	1.77	MMBtu/h
	Heat Input	1470.01	1460.06	1191.59	1200.73	992.80	992.01	516.70	518.59	kW
	Rate	100%	100%	81%	82%	68%	68%	35%	35%	
Feedwater	Mass Flow Rate	4550	4530	3028.38	2966.56	2440	2462	1024	1274	lb/h
	Specific Enthalpy	122.85	124.88	118.79	106.88	101.81	106.62	56.754	54.223	Btu/lbm
	Total Enthalpy-1 (feedwater flow)	0.56	0.57	0.36	0.32	0.25	0.26	0.06	0.07	MMBtu/h
	Total Enthalpy-2 (steam flow)	0.46	0.47	0.36	0.32	0.26	0.27	0.07	0.07	MMBtu/h
Combustion Air	Flow Rate	66435.75	66564.31	54719.73	55228.81	44594.65	44540.26	21961.04	22012.32	scfh
	Flow Rate	64616.97	64661.90	53056.33	53493.59	43903.21	44040.54	22106.03	22123.49	acfh
	Sensible Enthalpy	0.02	0.02	0.00	0.01	0.01	0.01	0.00	0.00	MMBtu/h
Energy	Heat Output	3.89	3.88	3.18	3.18	2.67	2.68	1.42	1.44	MMBtu/h
	Thermal Efficiency	77.6%	77.9%	78.1%	77.6%	78.8%	79.1%	80.7%	81.1%	
Electrical	Blower Electrical Power	6.78	6.78	3.90	4.02	2.26	2.23	1.21	1.21	HP
	Blower Electrical Power	5.06	5.06	2.91	3.00	1.68	1.66	0.90	0.90	kW
	Estimated Air Flow Energy	3.85	3.89	2.14	2.22	1.21	1.21	0.16	0.16	HP
	Estimated Blower Efficiency	56.71%	57.37%	54.90%	55.18%	53.60%	54.25%	13.56%	13.28%	
	Pump Electrical Power	4.14	4.10	4.28	3.81	4.04	3.99	3.91	4.05	HP
	Pump Electrical Power	3.09	3.05	3.19	2.84	3.01	2.97	2.91	3.02	kW
Exhaust	Energy in Stack Exhaust	0.952	0.953	0.755	0.759	0.595	0.594	0.266	0.268	MMBtu/h
Energy Use	Fuel Energy Use	**2.50**	**2.48**	**2.03**	**2.05**	**1.69**	**1.69**	**0.88**	**0.88**	MMBtu
	Fuel Energy Used / lb of Steam	**1345.46**	**1337.80**	**1338.35**	**1362.06**	**1345.35**	**1333.68**	**1360.39**	**1357.00**	Btu/lb-steam
	Electrical Energy Use	8.15	8.11	6.10	5.84	4.69	4.64	3.81	3.92	kW
	Electrical Energy Used / lb of Steam	2.18	2.18	2.01	1.94	1.86	1.83	2.94	3.01	W-h/lb-steam

Discussion

Photographs of the Baseline Mesh burner and the ClearSign Core™ – Rogue burner flames are shown in Figure 13 below.

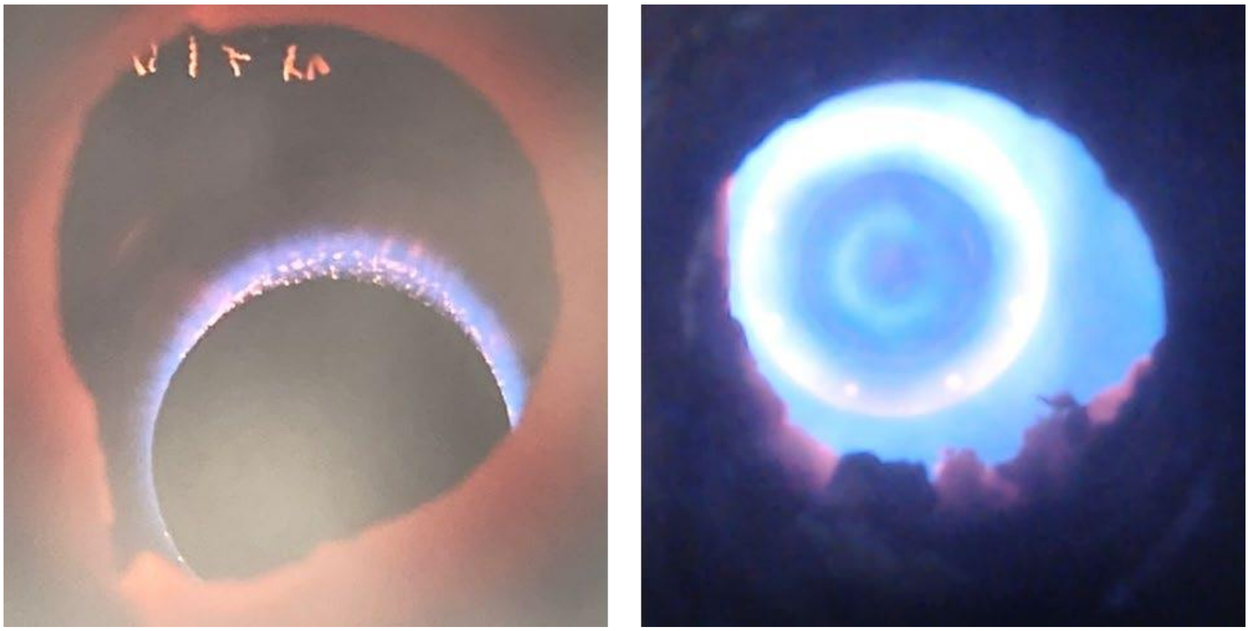

Figure 13. Photographs of the burner flames – Baseline Mesh burner (left), ClearSign Core™-Rogue Burner (right)

There were some differences between the mass flow rate of the feedwater coming into the boilerand that of the steam leaving the boiler, especially at low firing rates. Under steady state conditions, these rates are expected to match each other within measurement uncertainty. However, given that the feedwater valve to the boiler opens intermittently at low fire based on the water level inside, the feedwater pump did not run continuously but turned on and off basedon feedwater valve control. Since the pump ran continuously at high fire to keep up with the rateof steam flow, the flow rate measurements matched better, within uncertainty, at high fire. On the other hand, steam flow out of the boiler was steady at all firing rates. Hence, steam mass flow rate is used for all the final calculations of efficiency.

Measured steam flows for the baseline mesh burner and the ClearSign Core-Rogue burner are presented in Figure 14 at different rates of fuel flow.

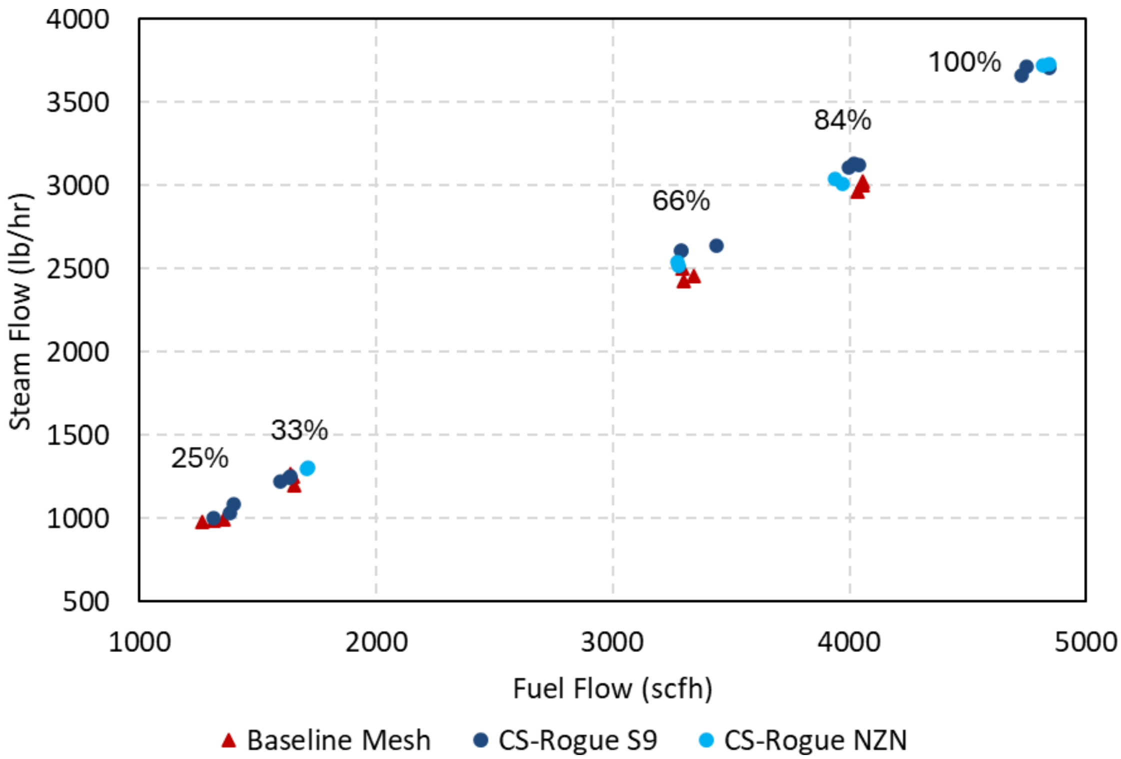

Figure 14. Steam Flow Rate Measured at Different Firing Rates

The ClearSign-Rogue burner produces higher rates of steam flow compared to the baseline mesh burner, which indicates increased thermal output to the boiler. Between the two operating modes for the ClearSign Rogue burner, i.e. at the sub-9 ppm NO_x (S9) or sub-2.5 ppm NO_x (NZN), the steam flow was slightly higher in the S9 mode. As described earlier, the baseline mesh burner could not be run at 100% rate, hence onlythe ClearSign-Rogue burner data are shown at this rate.

Boiler operating efficiency results are presented in Figure 15. Across all the phases, the efficiency appears to decrease at higher firing rates, likely due to increased heat losses from theboiler to the surroundings. The overall efficiency of 75-80% are typical for firetube boilers. Compared to the baseline mesh burner, the ClearSign Core-Rogue burner demonstrateshigher operating efficiencies, especially at the 66% and 84% firing rates. Between the two operating modes,i.e. the sub-9 ppm (S9) and the sub-2.5 ppm NO_x (NZN), the efficiency was higher in the S9 mode. At the 66% firing rate, the ClearSign-Rogue S9 is more efficient than the baseline mesh burner by 3.5% on average and the NZN was more efficient than the baseline mesh burnerby around 2.4%. At the 84% firing rate, these gains for the ClearSign-Rogue burner were 3.2% and 2.8% respectively. These effects are primarily caused by the different levels of operating O_2 as evident in Figure 16. There is a slight drop-off in efficiency from the ClearSign- Rogue burner operating in S9 mode to the NZN mode where the oxygen increases from 4-5% range to around 7%. There is a more significant decrease in efficiency for the baseline mesh burner that operates at around 8% O_2. Figure 17 presents the efficiency at different levels of NO_x emissions. Note that all NO_x emissions are corrected to 3% O_2.

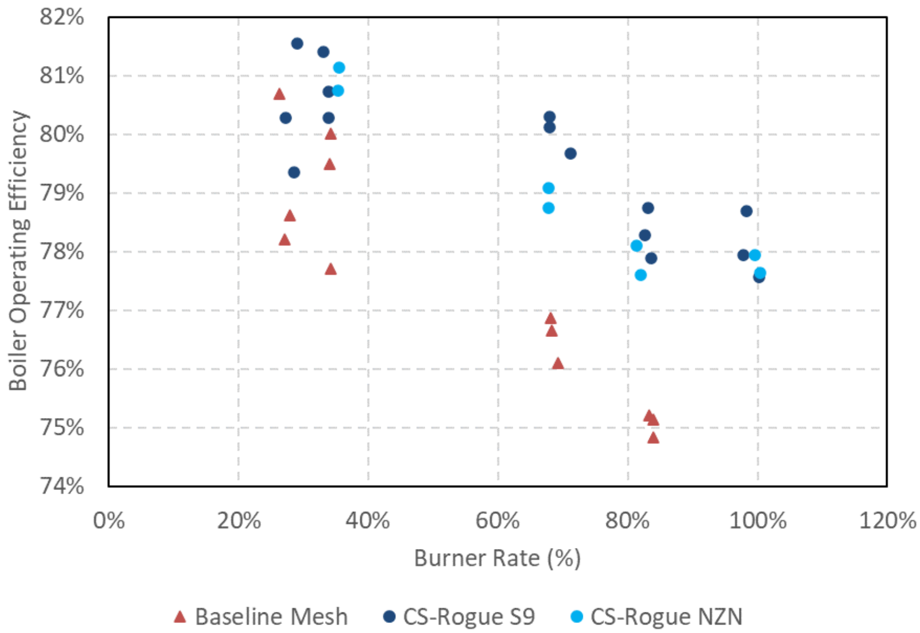

Figure 15. Boiler Operating Efficiency at Different Firing Rates

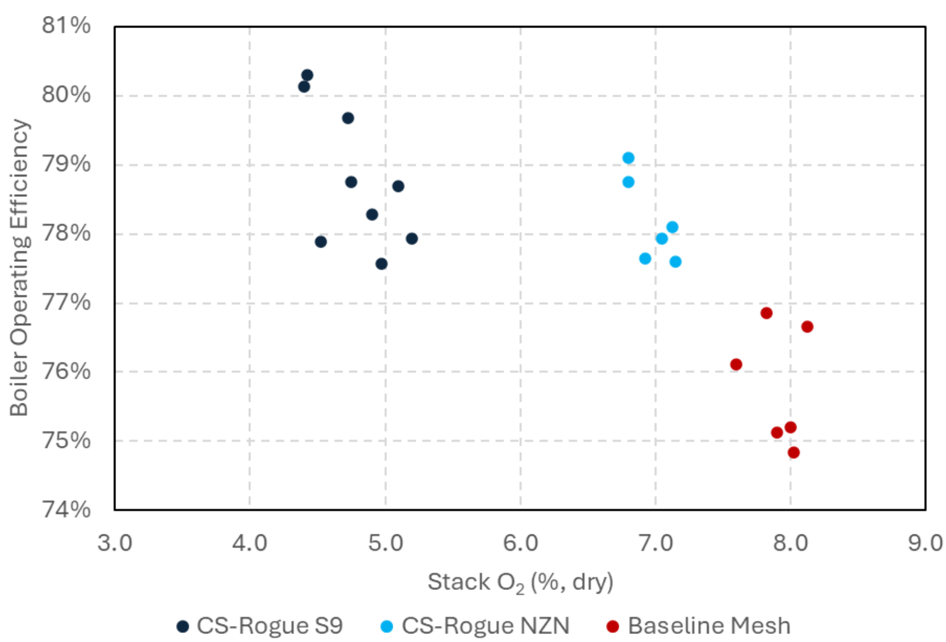

Figure 16. Boiler Operating Efficiency Dependence on Operating Oxygen

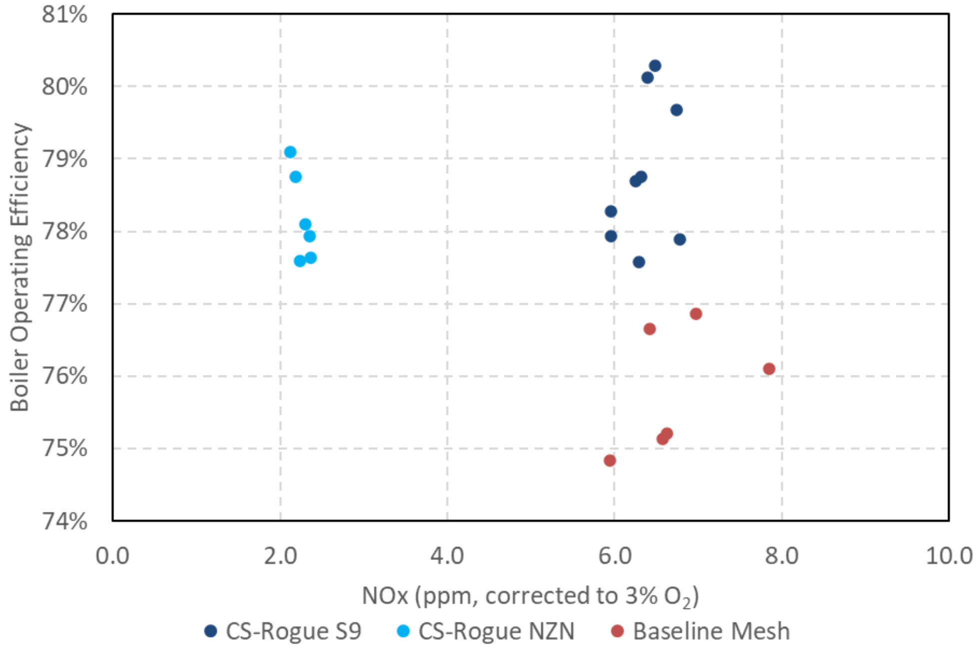

Figure 17. Boiler Operating Efficiency vs. NOx emissions

Stack outlet temperature is plotted in Figure 18 while stack energy losses, expressed as a percentage of the burner heat release, are shown in Figure 19. Note that the baseline mesh burner has a lower stack outlet temperatures but still results in more energy lostthrough the stack. This effect was a result of the higher excess air levels at which the baseline mesh burner operated, as the stack losses are a function of the mass flow rate of the flue gases as well as the flue gas temperature. The ClearSign-Rogue burner in S9 mode had the least stack losses as it operated at the lowest excess air or O_2 levels.

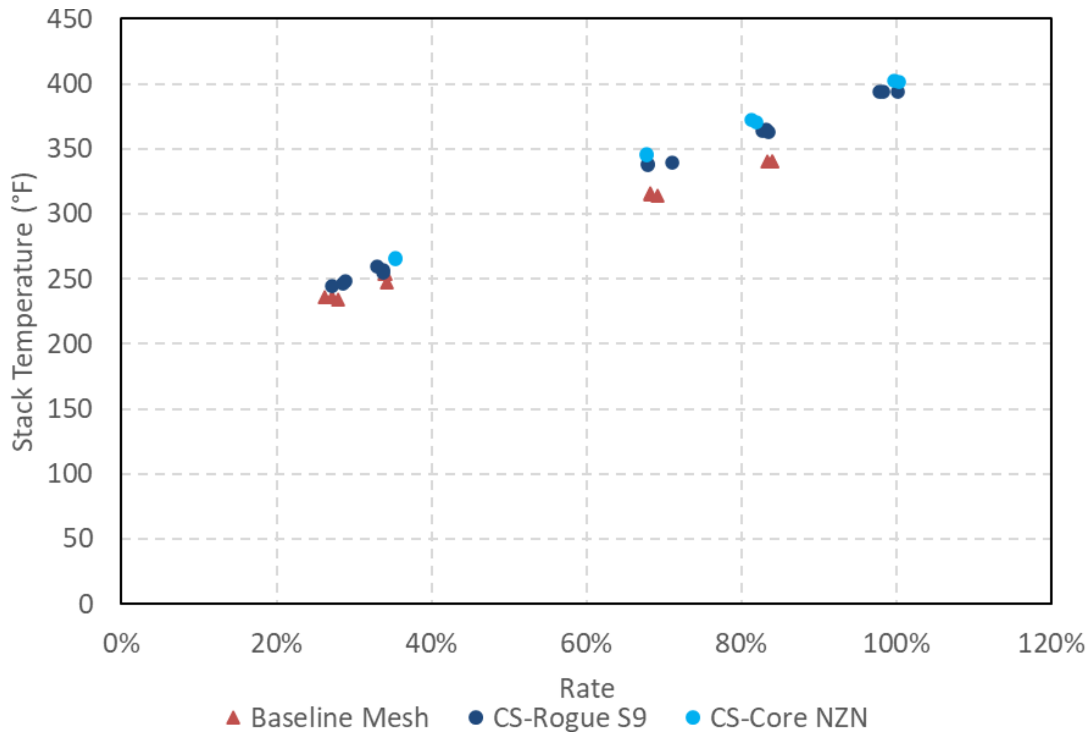

Figure 18. Stack Outlet Temperature

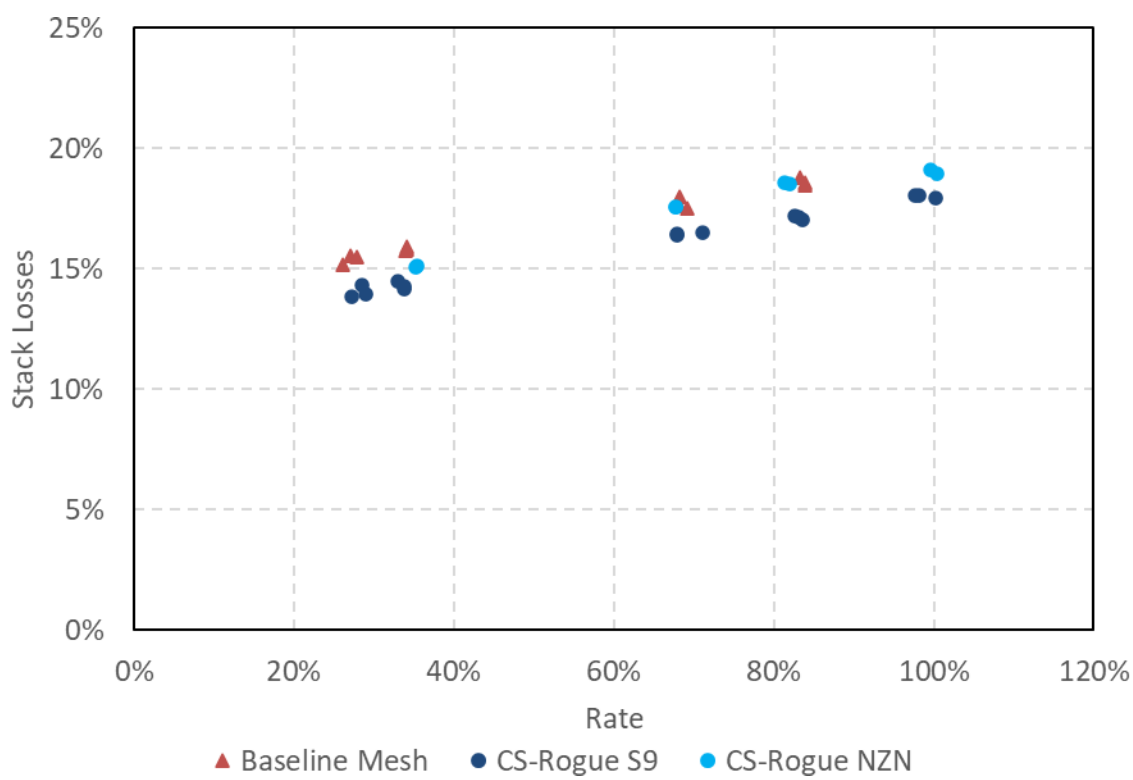

Figure 19. Stack Energy Losses (% of burner heat release)

During each phase, the burner was fired at fixed rates of 100%, 84%, 66%, 33% and 25%, i.e. at fixed fuel flow rates. The steam produced from the boiler was different in each case with comparisons of fuel usage and electricity usage made using a normalized 'per pound of steam produced' basis. These results are presented in Figures 20 and 21. Averaged fueland electrical energy savings are presented in Tables 9 and 10.

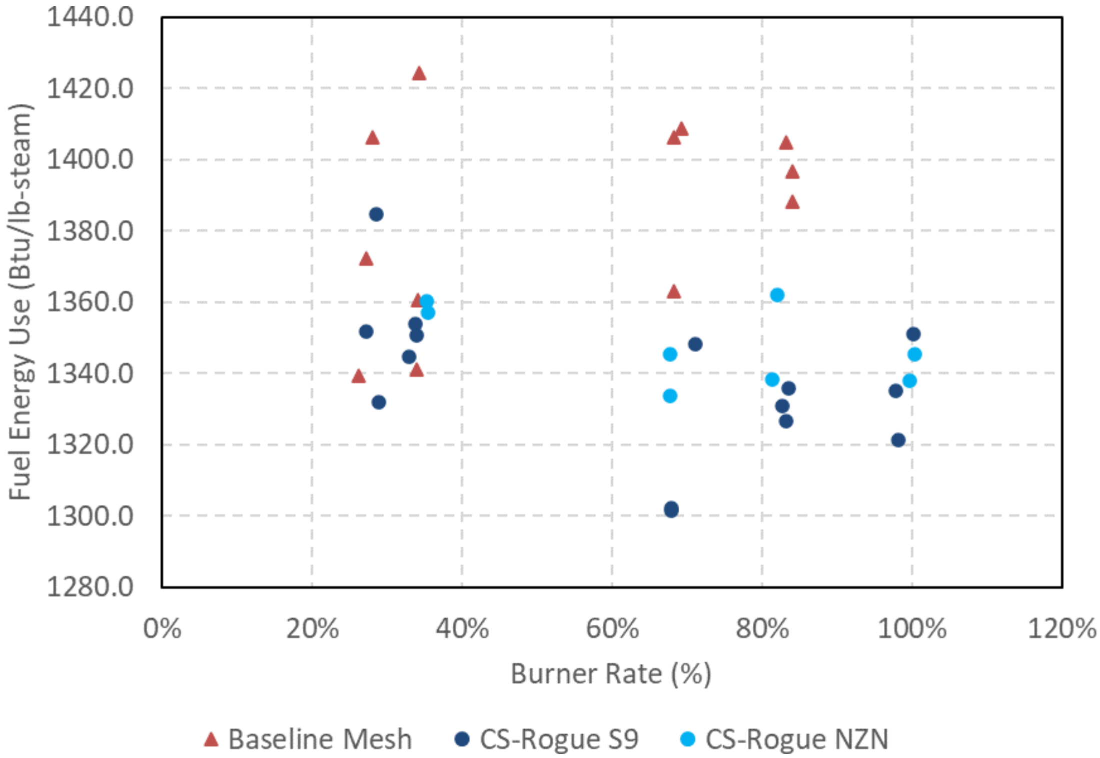

Figure 20. Fuel Energy Used per lb of Steam Produced

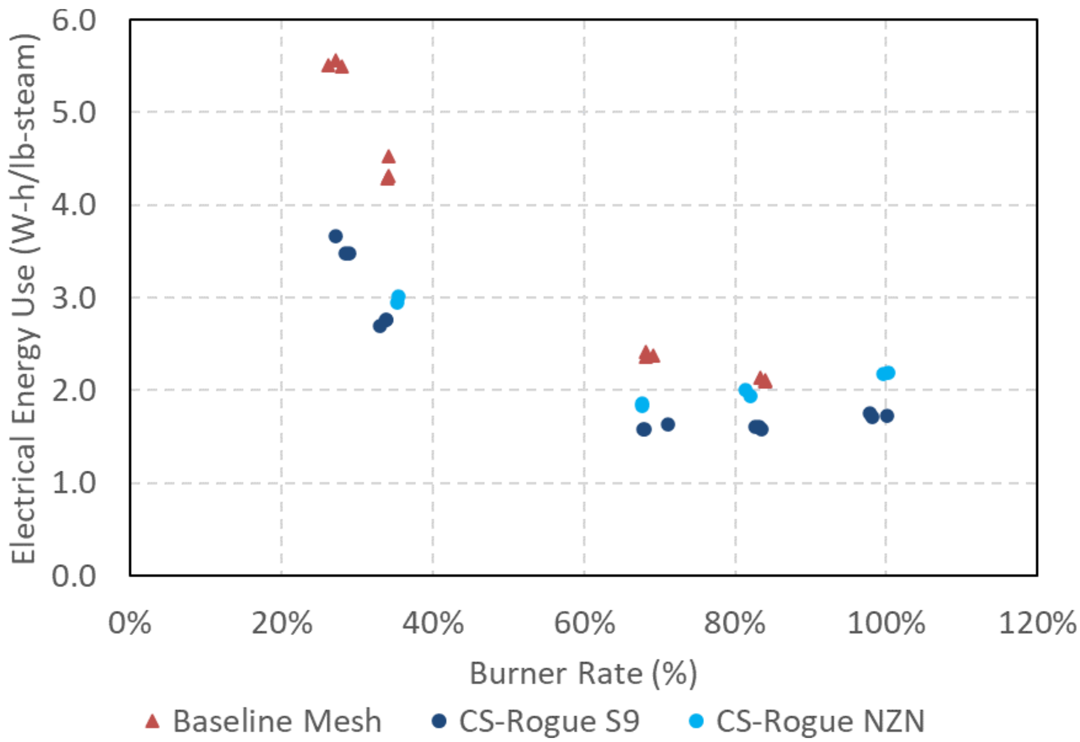

Figure 21. Electrical Energy Used per lb of Steam Produced

Table 9. Fuel and Electrical Energy Used per lb of Steam Produced at 66% Firing Rate

Burner	Fuel Energy/lb-steam	Savings	Electrical Energy/lb-steam	Savings
	Btu/lb-steam	*%*	*W-h/lb-steam*	*%*
Baseline Mesh	1392.65		2.38	
CS-Rogue S9	1317.23	5.4%	1.60	33%
CS-Rogue NZN	1339.52	3.8%	1.85	25%

Table 10. Fuel and Electrical Energy Used per lb of Steam Produced at 84% Firing Rate

Burner	Fuel Energy/lb-Steam	Savings against baseline	Electrical Energy/lb-steam	Savings against baseline
	Btu/lb-steam	%	W-h/lb-steam	%
Baseline Mesh	1396.69		2.11	
CS-Rogue S9	1330.98	4.7%	1.59	25%
CS-Rogue NZN	1350.20	3.3%	1.98	7%

Compared to the baseline mesh burner, the ClearSign-Rogue burner offers fuel savings at both NO_x levels with the savings beinggreater at sub-9 ppm operation, given the lower operating O_2 and higher efficiency gains. Similarsavings were observed in electrical energy use as well with gains being greater at the S9 levels. Figures 22 and 23 show the Feedwater pump Electrical Energy and the Blower Electrical Energy.

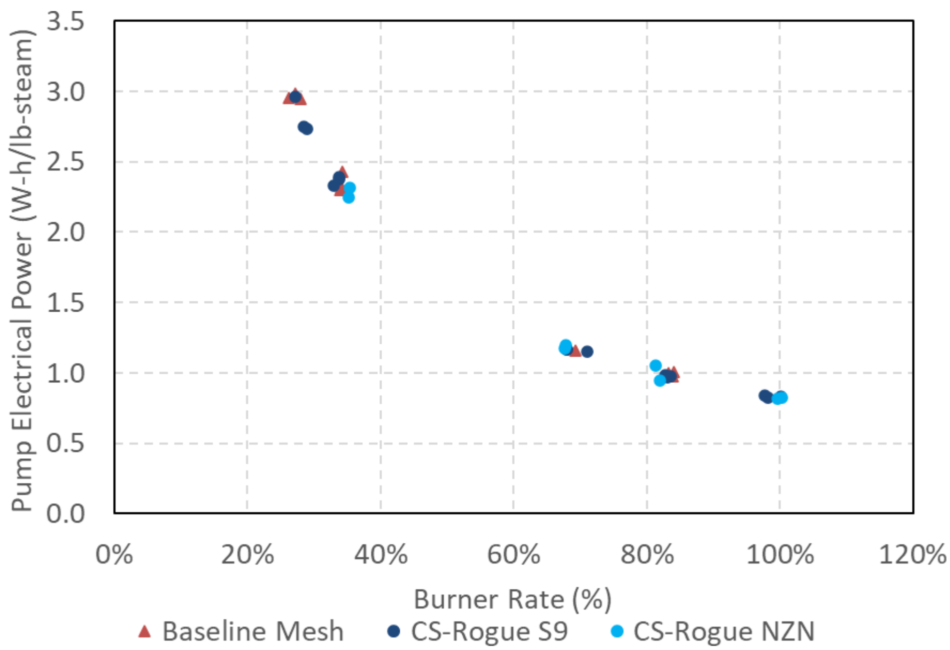

Figure 22. Feedwater pump Electrical Energy use per lb of Steam Produced

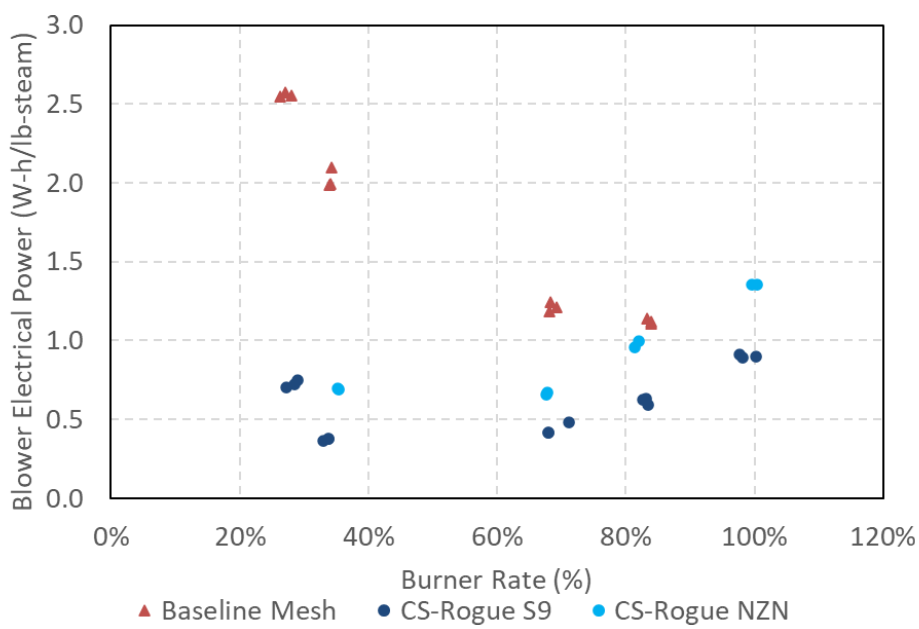

Figure 23. Blower Electrical Energy use per lb of Steam Produced

From Figure 22, it is clear that the feedwater pump power consumption is quite similar for both the baseline and ClearSign-Rogue burners. The electrical savings are mainly from the blower, due to the use of a VFD (variablefrequency drive) on the ClearSign-Rogue burner. The benefit of the VFD is evident in Figure 23. Since the baseline mesh burner uses a constant speed blower, its energy use is highest at low firing rates since the air damper is mostly closed. On the ClearSign burner, the VFD lowers the operating frequency at the low firing rates thereby reducing the energy use. The usage goes up as the firing rate increases. The blower energy use is higher in the NZN mode as the burner utilizesa higher air flow, i.e. a higher O_2 ratio to achieve sub-2.5 ppm NO_x emissions.

Conclusions

To conclude, the main objective of this study was to test and quantify the emissions improvements and efficiency gains for the ClearSign's Core™-Rogue ultra-low-NOx boiler burner compared to conventional (baseline) ultra-low-NOx burners.

A comprehensive study of emissions, efficiency, fuel and energy use for a conventional ultra-low- NO_x mesh burner and the emerging, near-zero-NO_x capable Rogue burner powered by ClearSignCore™ technology was completed. The ClearSign-Rogue burner demonstrated higher boiler operating efficiency, fuel savings, as well as electricity savings not only at comparable NO_x levels as the baseline mesh burner but also when operating at sub-2.5 ppm NO_x. The ClearSign-Rogue burner in S9 mode had the least stack losses as it operated at the lowest excess air or O_2 levels. The fuel savings ranged from 3.3% when the ClearSign-Rogue burner was operating at sub-2.5 ppm NO_x to 4.7% at sub-9 ppm NO_x at high fire. Savings in electricity ranged from 7% at sub-2.5 ppm NO_x to 25% at sub-9 ppm NO_x compared to the baseline mesh burner.

Recommendations

The ClearSign-Rogue Burner powered by the ClearSign Core™ technology has demonstrated emissions and efficiency benefits at S9 and NZN levels. This study has identified an interest in Hydrogen blending and its impact on burner emissions and efficiency. The study recommends further testing to determine how various Hydrogen and Natural Gas blends impact burner efficiency and NOx levels. The study also recommends a technoeconomic analysis to identify customer savings and the payback period for retrofitting existing burners with the ClearSign-Rogue burner technology.

Appendices

Appendix 1.0 Phase I Raw Data

Stream	Quantity	RUN 1				RUN 2				RUN 3				Unit
Time	Measurement Start Time	9:22	10:42	11:51	13:00	13:40	15:04	15:59	16:40	8:33	9:32	10:51	11:58	
	Measurement End Time	9:53	11:13	12:22	13:31	14:11	15:35	16:30	17:11	9:04	10:03	11:22	12:29	
Steam	Flow Rate (totalized)	494	627	1228	1502	1512	1250	633	489	497	600	1213	1481	lb/30 mins
	Pressure	2.125	3.25	9.9375	13.5625	13.9375	10.125	3.5	2.5625	2	3.0625	9.9375	13.4375	psig
	Temperature	218.575	222.35	238.725	246.4325	246.825	239.5175	222.575	218.25	218.575	221.25	238.375	246.1775	°F
Fuel	Flow Rate (totalized)	656.36	825.07	1671.86	2027.88	2028	1646.26	820.39	633.05	677.46	827.49	1650.85	2018.3	SCF/30 mins
	Consumption													
	Pressure	1	1.9	8.65	13.2	13.2	8.575	1.85	0.8	0.95	1.9	9	13.25	in. H2O
	Temperature	63.15	74.8	81.375	71.45	69.825	72.05	72.825	72	59.425	62.525	72.9	78.55	°F
Feedwater	Flow Rate (totalized)	388.78	520.74	1171.51	1508.22	1573.39	1293.51	472.81	348.47	464.9	473.26	1149.27	1499.93	lb/30 mins
	Pressure	217.5	220	210	202.5	202.5	208.75	217.5	220	220	222.5	210	212.5	psig
	Temperature	112.375	98	121	150.25	153	145.5	121	105.25	80	80	115	139	°F
Combustion Air	Pressure	2.05	3.4	11.05	15.975	15.9	11.125	3.325	2.175	2.35	3.325	11.525	16.075	in. H2O
	Temperature	80	84.25	104.25	122	118	102	89.25	87.25	71.75	76	93.75	109.25	°F
Emissions	O2	8.5	8.3	7.6	8.025	7.9	7.825	8.125	8.1	8.05	8.15	8.125	8	%, dry
	NO	6.65	6.1	7.275	5.35	5.925	6.175	6.575	7.825	7.925	6.7	5.625	5.85	ppm
	NO2	0.1	0.4	0.575	0.6	0.65	0.8	0.65	0.6	0.6	0.625	0.8	0.775	ppm

Stream	Quantity	RUN 1				RUN 2				RUN 3				Unit
	NO_x (corrected to 3% O_2)	6.8	6.5	7.9	6.0	6.6	7.0	7.2	8.4	8.5	7.3	6.4	6.6	ppm
	CO	1	0.5	0	0	0	1	1	1	0	0	0	0	ppm
Electrical	VFD/Blower Power/Current	5.3	5.21	6.2025	6.995	6.99	6.1875	5.2375	5.1875	5.2875	5.2525	6.28	7.0175	Amps
	FdWtr Pump Power/Current	6.15	6.075	5.925	6.1	6.325	6.15	6.075	6.025	6.1	6.075	5.925	6.175	Amps
	VFD Speed													RPM
	VFD Frequency													Hz
	BMS Power/Current													W
Furnace/ Stack	Furnace Pressure	0.1375	0.2125	0.9125	1.4	1.4	0.8875	0.2	0.125	0.1	0.2	0.9375	1.4	in. H2O
	Stack Temperature	236.2	253.65	314.55	340.325	340.25	315.95	254.4	235.7	233.825	247.4	315.125	340.9	°F
	Stack Temperature	386.6	396.3	430.1	444.4	444.4	430.9	396.7	386.3	385.3	392.8	430.4	444.8	K
Ambient	Temperature	66.48	71.03	74.20	73.48	74.90	75.13	74.53	73.43	62.08	66.48	68.15	69.50	°F
	Temperature	292.29	294.82	296.58	296.18	296.97	297.10	296.77	296.15	289.85	292.29	293.22	293.97	
	Humidity	70	62	58	60	60	58	58	58	67	59	58	46	%

Appendix 2.0 Phase II Raw Data

Stream	Quantity															
	Run#	1	1	1	1	2	3	1	2	3	2	3	2	3	2	3
	Load %	25	33	66	84	84	84	100	100	100	66	66	25	25	33	33
	NOx Level	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
	Date	5/29/2024	5/29/2024	5/29/2024	5/29/2024	5/29/2024	5/29/2024	5/29/2024	5/29/2024	5/29/2024	5/29/2024	5/29/2024	5/30/2024	5/30/2024	5/30/2024	5/30/2024
Time	Measurement Start Time	8:10	11:13	12:24	13:19	13:59	14:38	15:51	16:37	17:12	18:13	18:44	15:16	15:47	16:56	17:27
	Measurement End Time	8:40	11:44	12:55	13:50	14:30	15:09	16:22	17:08	17:43	18:44	19:14	15:47	16:17	17:27	17:57
Steam	Flow Rate (totalized)	515	613	1318	1566	1553	1563	1853	1858	1830	1305	1304	503	543	624	626
	Pressure	2.325	3.35	11.025	14.55	14.35	14.425	19.25	19.1	18.9	11.125	11.1	2.15	2.55	3.325	3.25
	Temperature	218.865	221.75	241.2	248.085	247.615	247.815	256.0825	255.635	255.41	240.6625	240.62	218.7875	220.315	222.4675	221.8875
Fuel	Flow Rate (totalized)	691.36	798	1719	2010	1999.1	2020.3	2422.1	2375.1	2363.4	1643.8	1643.8	657.6	699.7	817.5	818.3
	Consumption															
	Pressure															
	Temperature	67.225	92.25	90.825	88.3	87.15	85.475	80.625	79.175	76.825	73.8	72.325	94.2	92.275	79.5	76.55
Feedwater	Flow Rate (totalized)	387.88	798.4	1279.61	1598	1566	1562	2039	2066	2015	1274	1285	422	447	591	517
	Pressure	225	225	220	217.5	212.5	212.5	212.5	211.25	207.5	216.25	215	223.75	222.5	223.75	222.5
	Temperature	87	92.25	119.75	151.75	154.5	156	151.25	159.5	158.75	149	150.5	100.5	100	100.25	96.5
Combustion Air	Pressure	1.36666667	2.075	8.2	11.575	11.475	11.125	17.125	17.025	17.15	7.5	7.325	1.325	1.475	1.85	2.025
	Temperature	61.0333333	70.45	71.225	71.225	70.4	70.75	69.875	69.875	68.475	67.1	65.9	73.45	71.85	69.975	68.7
Emissions	O2	4.25	4.35	4.725	4.75	4.9	4.525	4.975	5.1	5.2	4.425	4.4	3.425	3.525	3.6	3.825
	NO	5.425	5.35	5.125	4.75	4.45	5.15	4.6	4.475	4.225	4.8	4.7	6	6	5.8	5.6
	NO2	0.6	0.725	0.975	0.95	0.875	1.05	1	1.05	1	1.175	1.2	0.9	0.85	0.9	0.9
	NO_x (corrected to 3% O_2)	6.5	6.6	6.7	6.3	6.0	6.8	6.3	6.3	6.0	6.5	6.4	7.1	7.1	6.9	6.8
	CO	3.75	0	0.25	1	1	1	1	1	1	1	1	2	1.5	1	1
Electrical	VFD/Blower Power/Current	7.16	6.84	8.01	9.09	9.02	9.02	11.06	11.03	11.09	7.75	7.75	7.05	7.21	6.81	6.84
	FdWtr Pump Power/Current	5.8925	5.9425	6.3375	6.3375	6.345	6.3725	6.4275	6.38	6.4075	6.325	6.3325	6.2075	6.18	6.2125	6.205
	VFD Voltage	211.6	155.6	219.8	259	257	257	313.2	313.3	313.4	206.9	206.9	206	222.4	159.8	163.4
	VFD Frequency	27.4666667		28.4	33.3	33.1	32.8	40.1	40.1	40.1	26.775	26.8	27.25	28.9	20.825	21.2
	VFD Power	1.0025	0.6	1.695	2.64	2.5975	2.4975	4.4525	4.4475	4.46	1.46	1.4575	0.9475	1.095	0.6325	0.6375
Furnace/Stack	Furnace Pressure	0.3	0.3125	0.65	0.925	0.875	0.875	1.5	1.375	1.4375	0.6	0.6	0.2	0.25	0.275	0.3
	Stack Temperature	246.35	259.35	339.475	364.475	363.95	363.425	394.3	394.15	393.675	338.125	337.4	244.4	248.15	255.333333	256.825
	Stack Temperature	392.2	399.4	444.0	457.8	457.6	457.3	474.4	474.3	474.1	443.2	442.8	391.1	393.2	397.2	398.0
Ambient	Temperature	61.70	68.65	72.55	71.48	72.53	71.05	72.23	72.08	72.10	69.95	69.00	74.28	72.95	71.40	70.50
	Temperature	289.64	293.50	295.67	295.07	295.65	294.83	295.49	295.40	295.42	294.22	293.70	296.63	295.89	295.03	294.53
	Humidity															

Stream	Quantity									Unit
	Run#	1	2	2	1	1	2	1	2	
	Load %	100	100	84	84	66	66	33	33	
	NOx Level	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	
	Date	5/30/2024	5/30/2024	5/31/2024	5/31/2024	5/30/2024	5/30/2024	5/30/2024	5/30/2024	
Time	Measurement Start Time	13:17	13:51	8:40	8:09	9:51	10:22	18:35	19:06	
	Measurement End Time	13:48	14:22	9:10	8:40	10:22	10:52	19:06	19:36	
Steam	Flow Rate (totalized)	1864	1862	1519	1504	1259	1269	648	652	lb/30 mins
	Pressure	19.5	19.4666667	13.925	13.675	10.35	10.5	3.55	3.575	psig
	Temperature	256.535	256.4125	246.6125	246.005	239.35	240.1	222.1875	223.0975	°F
Fuel	Flow Rate (totalized)	2423	2407.7	1969.4	1984.4	1639.8	1637.8	853.4	856.7	SCF/30 mins
	Consumption									
	Pressure									in. H2O
	Temperature	87.0333333	85.825	68.95	67.45	75.15	80.175	71.225	69.775	°F
Feedwater	Flow Rate (totalized)	2275	2265	1514.19	1483.28	1220	1231	512	637	lb/30 mins
	Pressure	203.75	207.5	220	217.5	217.5	216.25	227.5	221.25	psig
	Temperature	154.75	157	150.75	139	133.75	138.75	88.75	86.25	°F
Combustion Air	Pressure	22.7	22.95	15.4	15.825	10.5	10.475	2.825	2.775	in. H2O
	Temperature	72.925	72.575	62.25	62.225	64.125	66.375	66.05	65.175	°F
Emissions	O2	6.925	7.05	7.125	7.15	6.8	6.8	5.925	5.9	%, dry
	NO	1.5	1.5	1.4	1.4	1.35	1.25	0.9	1.05	ppm
	NO2	0.35	0.325	0.375	0.325	0.375	0.425	0.9	0.875	ppm
	NO_x (corrected to 3% O_2)	2.4	2.4	2.3	2.2	2.2	2.1	2.1	2.3	ppm
	CO	1	0	2.25	2.75	3.75	3	21	20.5	ppm
Electrical	VFD/Blower Power/Current	13.38	13.55	10.38	10.65	8.6	8.61	7.35	7.34	Amps
	FdWtr Pump Power/Current	6.4325	6.3625	6.6475	5.92	6.2775	6.1975	6.0675	6.2875	Amps
	VFD Voltage	362.2	364.8	296.2	302.9	243.6	244.2	216.4	216.4	V
	VFD Frequency	46.425	46.5	38.4	38.8	31.475	31.5	28.1	28.1	Hz
	VFD Power	6.7825	6.7825	3.9025	4.0225	2.255	2.23	1.2075	1.2125	kW
Furnace/Stack	Furnace Pressure	2.1	2.1	1.75	1.81666667	1.4375	1.4375	0.625	0.6875	in. H2O
	Stack Temperature	401.55	402.766667	372.425	370.9	345.15	346.35	265.425	266.575	°F
	Stack Temperature	478.4	479.1	462.3	461.4	447.1	447.8	402.8	403.5	K
Ambient	Temperature	76.30	74.30	65.03	65.23	67.83	69.58	68.40	67.53	°F
	Temperature	297.75	296.64	291.49	291.60	293.04	294.02	293.36	292.88	
	Humidity									%

References

[1] South Coast Air Quality Management District (June 7, 2024), South Coast AQMD Approves Rule to Accelerate the Transition to Zero-Emission for Building Water Heater. https://www.aqmd.gov/docs/default-source/news-archive/2024/1146-2-June-7-2024.pdf

[2] SJVAPCD, (2020) Rule 4306: Boilers, Steam Generators, and Process Heaters. https://www.valleyair.org/rules/currntrules/r4306.pdf