

Multi-Burner Demonstration Test Report ClearSign Core[™] Burner Technology

Customer: Confidential - CA Refinery

Burner Type: ClearSign Core-8 Test Date: February 27-28, 2023

CONFIDENTIAL

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Executive Summary

ClearSign has been awarded a project to provide our ClearSign Core technology process burners for a confidential client. The project includes two different up-fired natural draft vertical cylindrical furnaces. ClearSign has selected our ClearSign Core 8 burner for both furnaces. Furnace # 1 has 12 burners rated at 9.75 MMBtu/hr for a total maximum heat release of 117 MMBtu/hr. Furnace # 2 has 8 burners rated at 8.38 MMBtu/hr for a total maximum heat release of 67.04 MMBtu/hr. A witnessed, two-burner, performance test was conducted February 27th and 28th, 2023. The test was conducted at Zeeco's test facility in their furnace #12. The burners were tested at various heat release rates ranging from absolute minimum to design and CO breakthrough, as well as other fuel blends. Emissions data was recorded, including NO_x (ppm), CO (ppm), and O₂ (vol. dry). The burners successfully met the required performance conditions.

Heat Release (MMBtu/hr)	Furnace 1	Furnace 2		
Number of Burners	12	8		
Maximum Heat Release	9.75	8.38		
Normal Heat Release	7.82	6.7		
Historical Heat Release	6.2	4.73		
Minimum Heat Release	3.25	2.79		

• Heat releases are in lower heating value (LHV)

The burners were demonstrated and met the following guarantees.

- NOx less than 5 ppm, corrected to 3%O₂ (volume, dry)
- CO less than 50 ppm (volume, dry)
- Noise level less than 85 dBA @ 3 feet from a single burner

1. Test Objective

This burner test was conducted to prove the performance of the ClearSign Core-8 burner operating under simulated field conditions. The test objective was to demonstrate stable operation throughout the firing range while meeting the emissions levels of NOx less than 5 ppm when corrected to 3% O₂. Raw and tabulated data that was collected during this demonstration appears in Section *3. Test Description and Tabulated Data*.

2. Installation

The demonstration was conducted using two ClearSign Core-8 burners installed and fired vertically up in Zeeco's Test Furnace #12. The furnace is a single-pass, with a tube circle diameter (TCD) 16 feet – 4 inches in diameter and has a radiant section measuring 35 feet in height. The furnace has 46 single pass water-cooling tubes from the bottom to the top of the heater. The tubes were partially covered with insulation to obtain representative floor and firebox temperatures. A photograph of the furnace is shown in Figures 1 below.

The two burners were installed on an arc representing a 45-inch burner circle, simulating the burner spacing of 31.8 inches (burner centerline to burner centerline).



Figure 1 - Zeeco Test Furnace #12

Emissions samples were measured at the base of the furnace stack, below the stack damper. The sampling equipment used is shown below. Oxygen (recorded as a volume, dry value) was measured with a *Servomex 1440* analyzer which utilizes a paramagnetic detector. The CO was measured with a *Thermo Environmental 48C* utilizing an infrared



detector and NO_x was measured with a *Thermo Environmental Instruments 42C* analyzer utilizing a chemiluminescence detector. The analyzers are calibrated daily.



Figure 2 - Emissions Analyzer Bench

The floor and firebox temperatures were measured with velocity thermocouples (suction pyrometer) located approximately 1 foot, 16 feet and 25 feet above the furnace floor, respectively. Furnace draft was measured at the floor of the furnace next to the burner. Combustion air flow to the burner was controlled via an air damper controlled with a 4-20 mA signal connected to an air actuator on each burner.

3. Test Fuels & Tabulated Data

Test Fuels

The test fuels included Fuel A which approximated the typical refinery fuel gas blend, Fuel B as the High Hydrogen blend, and Fuel C as Natural Gas. The compositions are listed in Table 1 below. The Natural Gas composition utilized at Zeeco's test facility is listed in Appendix B.

FUEL (LHV)									
GAS	А	В	С	(VOL %)					
Natural Gas	69	60	100	%					
Hydrogen	12	24	0	%					
Propane	19	12	0	%					
Butane	0	0	0	%					
LHV	1110	990	923	BTU/SCF					
Btu/lb	20,777	21,265	20,851	Btu/lb					
S.G.	0.70	0.61	0.58						

Table 1 – Test Fuel Compositions

Tabulated Data

Furnace 1:

# Burners	Firing Rate per Burner	Firing Rate Descrip	Fuel	Fuel P	Fuel T	Floor Draft	A.D. Setting	NOx	02	cNOx (corr. to 3% O2)	Floor Temp	16 ft Temp	Bridgewall Temp
	(MMBtu/hr)		(A, B)	(PSIG)	(°F)	(in. w.c.)	(mA)	(ppm)	(%, dry)	(ppm)	(°F)	(°F)	(°F)
2	8.775	90%	В	26	86	-0.59	20	3.14	6.6	3.9	956	1147	1223
2	8.775	90%	В	26	86	-0.59	18.1	3.6	6	4.3	NR	NR	NR
2	3.25	Minimum	В	5	79	-0.58	11.7	3.53	6.2	4.3	720	880	NR
2	8.775	90%	А	24.5	81	-0.58	18.1	3.68	6	4.4	NR	NR	NR
2	9.75	100%	А	27	68	-0.59	20	3.4	5.7	4.0	965	NR	1247

Furnace 2:

# Burners	Firing Rate per Burner	Firing Rate Descrip	Fuel	Fuel P	Fuel T	Floor Draft	A.D. Setting	NOx	02	cNOx (corr. to 3% O2)	Floor Temp	16 ft. Temp	Bridgewall Temp
	(MMBtu/hr)			(PSIG)	(°F)	(in. w.c.)	(mA)	(ppm)	(%, dry)	(ppm)	(°F)	(°F)	(°F)
2	8.38	Max	А	32.5	85	-0.55	17.5	3.6	5	4.05	908	1144	1226
2	8.38	Max	А	32.5	85	-0.54	20	2.57	6.3	3.15	930	1157	1237
2	6.7	Normal	А	24	86	-0.56	15.5	3.37	5.1	3.82	920	1095	1175
2	6.7	Normal	А	24	86	-0.52	17.4	1.9	7.1	2.46	884	1065	
2	2.79	Min	А	5.5	82	-0.53	11.6	2.54	6.1	3.07	678	850	900
2	2.79	Min	А	5.5	81	-0.5	10.9	3.32	4.5	3.62	660	848	905
2	6.7	Normal	В	24	80	-0.53	16.9	2.3	6.8	2.92	857	1055	1145

NR = Not Recorded



Summary

The burner test yielded results that demonstrate the ClearSign Core technology works as intended and is capable of meeting the 5 ppm NOx guarantee as required for the project.

Key findings from the test demonstrated:

- Sub 5 ppm NOx emissions throughout turndown range
- Sub 5 ppm NOx emissions over a range of fuels
- Further NOx reduction possible by increasing excess air rates
- Stable operation over operating range
- Stable at stoichiometric conditions



Appendices



Appendix A – Test Photos

Furnace 1



Picture: Furnace 1, 110% Fuel B



Picture: Furnace 1, Maximum Fuel A



Picture: Furnace 1, Maximum Fuel B



Picture: Furnace 1, Normal Fuel B





Picture: Furnace 1, Maximum Fuel B

Furnace 2



Picture: Furnace 2, 115% Fuel A



Picture: Furnace 2, Maximum Fuel A



Picture: Furnace 2, Minimum CO Break Fuel A



Picture: Furnace 2, Minimum Fuel A



Picture: Furnace 2, Normal Fuel A



Picture: Furnace 2, Normal Fuel A, 5% O₂



Picture: Furnace 2, Minimum CO Break Fuel B



Picture: Furnace 2, Normal High O₂ Fuel B



Picture: Furnace 2, Normal Fuel B



Picture: Furnace 1, Maximum Fuel A, 5% O₂



Picture: Furnace 1, Maximum Fuel A, 5.7% O₂

Appendix B – Zeeco Test Facility Natural Gas Fuel Composition

ZEEGU	2022 TEST FACILITY NATURAL GAS
	COMPOSITION

Component	VOL%
Methane	93.8594%
Ethane	4.1673%
Propane	0.2062%
Butane	0.0195%
lso-Butane	0.0103%
Pentane	0.0042%
Iso-Pentane	0.0047%
Hexanes+	0.0117%
Nitrogen	1.2320%
Carbon Dioxide	0.4848%
Total:	100%

Lower Heating Value							
927.0 BTU/SCF							
Molecula	Molecular Weight						
16.99	lb/lb-mol						
Specific Gravity							
opeenie	Gravity						



3/7/2023

Cirrus Research plc

Measurement Summary Report

	Name Timo	36	·14·44 AM	Person		Diaco	Project
	Duration	00.00.33		Person		Flace	Fioject
	Instrument	G301112 CI	R-161C				
	Instrument	0501112, 0					
	Calibration						
	Before		Offset		After		Offset
	Basic V	alues	Projected E	xposure			
	LAeq	76.1 dB	30 Minutes	64.1 dB			
	LCPeak	99.1 dB	1 Hour	67.1 dB			
	C-A	9.9 dB	2 Hours	70.1 dB			
	LEX8	46.7 dB	4 Hours	73.1 dB			
	LAFMax	77.7 dB	6 Hours	74.9 dB			
			8 Hours	76.1 dB			
			10 Hours	77.1 dB			
			12 Hours	77.9 dB			
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1	10						
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	2/28/2023 1:	14:44 AM	lime	2/28/	2023 1:15:17 A	IVI	Frequency (Hz)
							requercy (riz)

Noise data: Fuel B, Maximum Heat Release



3/7/2023

Cirrus Research plc

Measurement Summary Report

Name Time	39 3/1/2023 12:06:24 AM Person Pla					Project
Duration	00:00:33					
Instrume	ent G301112, C	R:161C				
Calibrati	on					
Before		Offset		After		Offset
Bas	sic Values	Projected I	xposure			
LAeq	73.8 dB	30 Minutes	61.8 dB			
LCPeak	97.5 dB	1 Hour	64.8 dB			
C-A	9.1 dB	2 Hours	67.8 dB			
LEX8	44.4 dB	4 Hours	70.8 dB			
LAFMax	79.9 dB	6 Hours	72.6 dB			
		8 Hours	73.8 dB			
		10 Hours	74.8 dB			
		12 Hours	75.6 dB			
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3/1/202	3 12:06:24 AM	Time	3/1/2	023 12:06:57	AM	υ υοο ×
						Frequency (Hz)

Noise data: Fuel B, Normal Heat Release