LNG Research Study

Ultra Low NO_X Steam Boiler

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Disclaimer

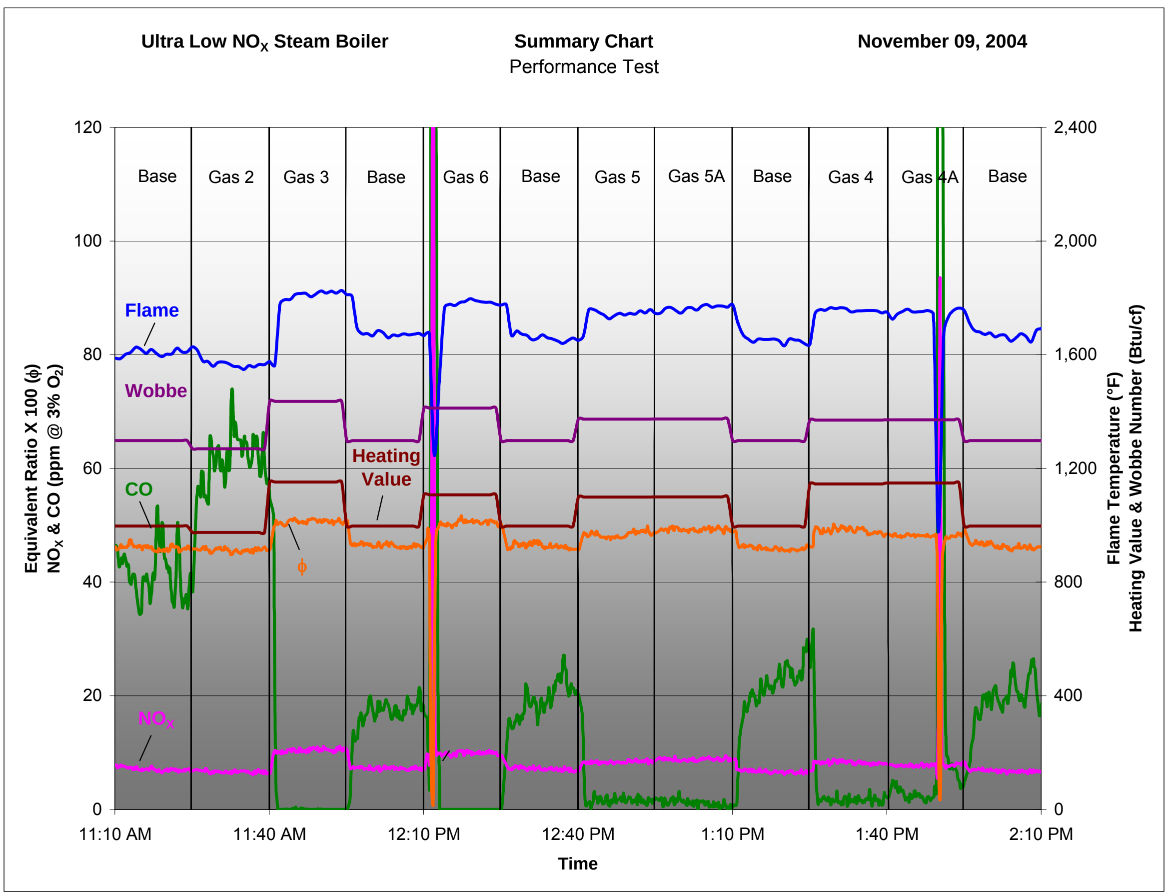
Table of Contents

Results Summary

Results obtained for all tests conducted with different gases reveal (a) there were no operational, ignition, flame stability, or safety problems during testing of each gas or during transitions between gases; (b) NO_X emissions did not exceed 13 ppm (corrected to 3% O_2) and (c) CO emissions did not exceed 100 ppm (corrected to 3% O_2) for all tests conducted.

Performance Test

NO_X values for all gases were below 12 ppm. CO values ranged from 0 ppm (Gas 6) to 61.6 ppm (Gas 2). Over fire percentages for all high-heat content gases (medium to high Wobbe Number) ranged between 4.7 - 9.5% while under fire percentages ranging between 1.2 – 3.9% were observed for all low Wobbe/low heat-content gases (all percentages are with respect to the units input rate). During the beginning of the Gas 6 run and towards the end of the Gas 4A run, the boiler shut off due to insufficient gas supply.

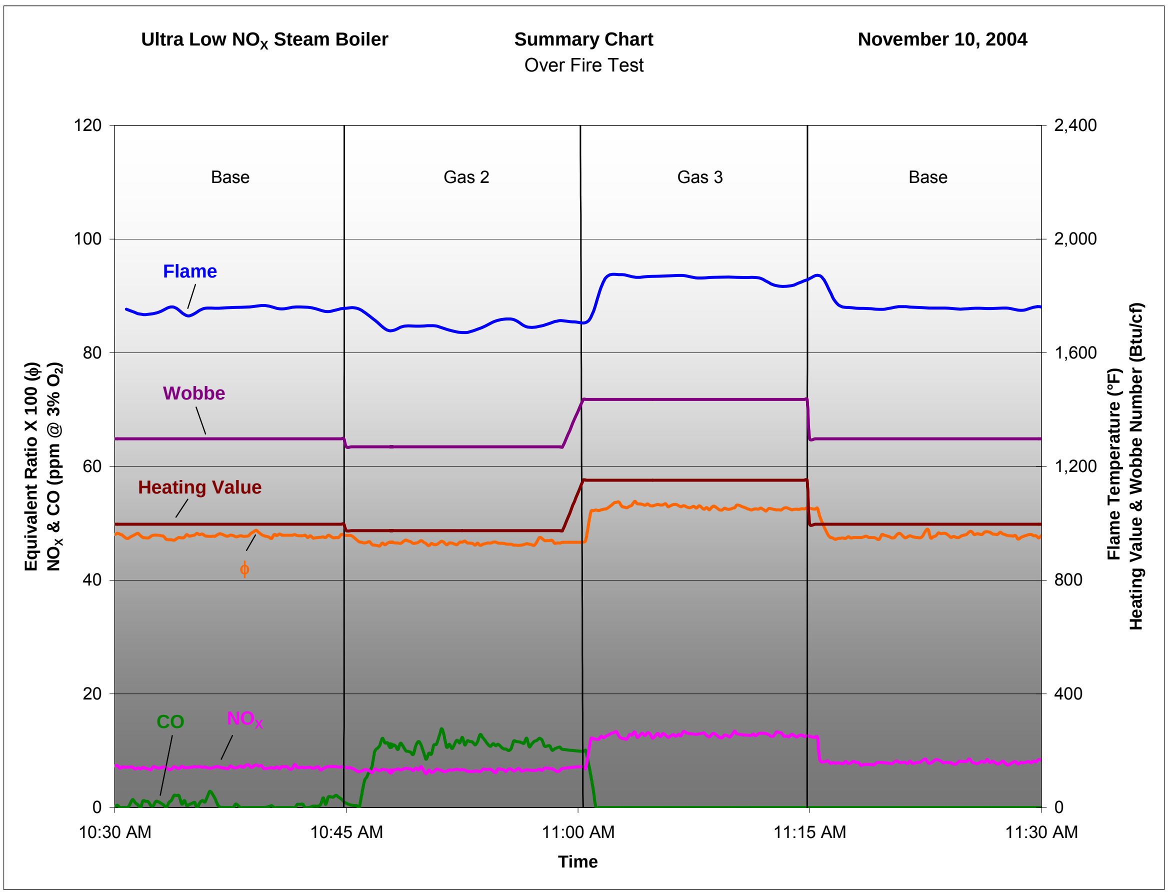


NOTE: Emission test results are for information purposes, they were not the result of certified tests.

Over Fire Test

NO_X values for all gases were below 13 ppm. CO values were highest with Gas 2 (11.1 ppm) while values for Gas 3 and both Baseline Gas runs were negligible (below 0.7 ppm). The highest input rate was observed for Gas 3 (731,684 Btu/hr – 13.4% over fired) while the lowest was observed with Gas 2 (644,437 Btu/hr – 0.08% under fired).

The manufacturer adjusted the boiler to operate at normal operating conditions while maintaining NO_X emissions below 12 ppm and CO emissions below 100 ppm (both corrected to 3% O_2). When the Performance Test was performed, the gas delivery system supply pressure was adjusted to 3.0 ± 0.3 psig because the manifold pressure did not remain stable at lower pressure settings. When the Over Fire Test was performed, the gas delivery system supply pressure was raised to 8.0 ± 0.3 psig to over fire the boiler 6% with Baseline Gas.



NOTE: Emission test results are for information purposes, they were not the result of certified tests.

Equipment Selection Criteria

The Ultra Low NO_X Steam Boiler was selected because some customers within the Southern California Gas Company service territory have opted to purchase equipment capable of meeting more stringent emissions standards than what is required by the regulatory agencies. In order for manufacturers to meet these more stringent requirements, the burners and controls that they utilize are more sophisticated/complex and could be more sensitive to natural gases with different calorific values.

Equipment Specifications

- **Description:** 15 HP Ultra Low NO_X Steam Boiler
- **Burner:** Surface premix power burner (operating on blue flame mode)
- **Maximum Input Rating:** 645,000 Btu/hr
- **Type of Fuel:** Natural Gas
- **Supply Pressure:** 7 – 14" w.c.

Standards

A detailed description of the test protocol and some of the rationale used to develop testing procedures are included in the appendix. The test protocol was developed based on the following test standards.

- UL795
- ANSI Z21.13-2000, Standard for Gas-Fired Low-Pressure Steam and Hot Water Boilers.
- South Coast Air Quality Management District Rule 1146.2, Emission of NO_X from Large Water Heaters and Small Boilers, adopted January 9, 1998.
- South Coast Air Quality Management District Protocol, NO_X Compliance Testing for Natural Gas-fired Water Heaters and Small Boilers, last amended January 1998.
- South Coast Air Quality Management District – Instrumental analyzer procedure for continuous gaseous emissions - District Method 100.1.

Installation

The manufacturer installed the boiler according to their specifications for outdoor installation. Instrumentation was installed following input from manufacturers, consultants and the above test standards. Thermocouples were installed to measure flame, stack, interior steam, inlet water, ambient and gas temperatures. Pressure transducers were installed to measure manifold and supply pressures. A dry gas meter was used to measure gas flow.

A straight vertical vent pipe, five feet in length and of the diameter of the boiler vent collar, was provided. An integrated sampling probe, constructed per the AQMD protocol, ten inches from the bottom of the vent pipe was installed and a thermocouple was placed six inches from the bottom of the vent pipe.

Once all testing instruments were installed, the boiler was run on the facilities pipeline gas to verify that the boiler and all instrumentation operated properly. Manifold and supply pressures were not adjusted during set-up.

Test Gases

The following gases have been specifically formulated to cover the range of gas compostions and calorific values of natural gases that could be delivered in the Southern California Gas Company territory by current natural gas suppliers and future LNG suppliers. Composition details are specified in Appendix C.

- **Baseline Gas** (Gas 1) - Low Wobbe (1,298 Btu/cf), low heat content gas (997 Btu/cf)
- **Gas 2** – Lowest Wobbe (1,269 Btu/cf), lowest-heat content gas (974 Btu/cf)
- **Gas 3** – Highest Wobbe (1,436 Btu/cf), highest-heat content gas (1,152 Btu/cf)
- **Gas 4** – Medium Wobbe (1,370 Btu/cf), highest-heat content gas (1,145 Btu/cf)
- **Gas 4A** (4 component mix) – Medium Wobbe (1,371 Btu/cf), highest-heat content gas (1,148 Btu/cf)
- **Gas 5** – Medium Wobbe (1,373 Btu/cf), high-heat content gas (1,099 Btu/cf)
- **Gas 5A** (4 component mix) – Medium Wobbe (1,374 Btu/cf), high-heat content gas (1,100 Btu/cf)
- **Gas 6** - High Wobbe (1,412 Btu/cf), high-heat content gas (1,107 Btu/cf)

Test Procedure

Test procedures were developed based on the above test standards. However, due to time limitations and variations between the different test standards, test procedures were simplified with input from consultants and information obtained from previous studies.

Before every test the following steps were performed:

- All emissions analyzers were calibrated and linearity was checked.
- Data loggers were checked and temperatures, pressures, and gas flow readings were verified.

During every test, the following steps were performed:

- Baseline and Substitute Gases were run continuously with switching between gases taking less than 14 seconds.
- Emissions, pressure and temperature data was observed and recorded before, during and after changeover.

After every test, the following steps were performed:

- Data was transferred from data logger to laptop.
- Linearity and drift inspections were performed on all emissions analyzers.

Performance Test

Starting with Baseline Gas, the boiler was adjusted by the manufacturer to normal operating conditions and the firing rate was verified after 15 minutes. Once steady-state conditions were achieved, testing and collection of temperature, pressure and emissions data began. During this test, the gases were run in the following order:

- Baseline Gas for 15 minutes
- Gas 2 for 15 minutes
- Gas 3 for 15 minutes
- Reestablish Baseline Gas for 15 minutes
- Gas 6 for 15 minutes
- Reestablish Baseline Gas for 15 minutes
- Gas 5 for 15 minutes
- Gas 5A for 15 minutes
- Reestablish Baseline Gas for 15 minutes
- Gas 4 for 15 minutes
- Gas 4A for 15 minutes
- Conclude testing with Baseline Gas for 15 minutes

Over Fire Test

Starting with Baseline Gas, the manifold and supply pressures were adjusted to over fire the boiler by 6%. After 15 minutes, the firing rate was verified. Once steady-state conditions were achieved, testing and collection of temperature, pressure and emissions data began. During this test, the gases were run in the following order:

- Baseline Gas for 15 minutes
- Gas 2 for 15 minutes
- Gas 3 for 15 minutes
- Conclude testing with Baseline Gas for 15 minutes

Hot Ignition Test

Using Baseline Gas, the manifold pressure was adjusted to allow for a rated input of 645,000 Btu/hr ± 2%. The gas delivery system was purged of Baseline Gas with Gas 3. Using Gas 3, the steam boiler was ignited and operated for one minute. During this time, visual observations of the flame, ignition delays and other phenomena observed were documented. This test was repeated 2 more times with no more than one minute elapsing between tests.

The gas delivery system was purged of Gas 3 with Gas 2. Using Gas 2, the steam boiler was ignited and operated for one minute. During this time, visual observations of the flame, ignition delays and other phenomena observed were documented. This test was repeated 2 more times with no more than one minute elapsing between tests.

Results [1, 2]

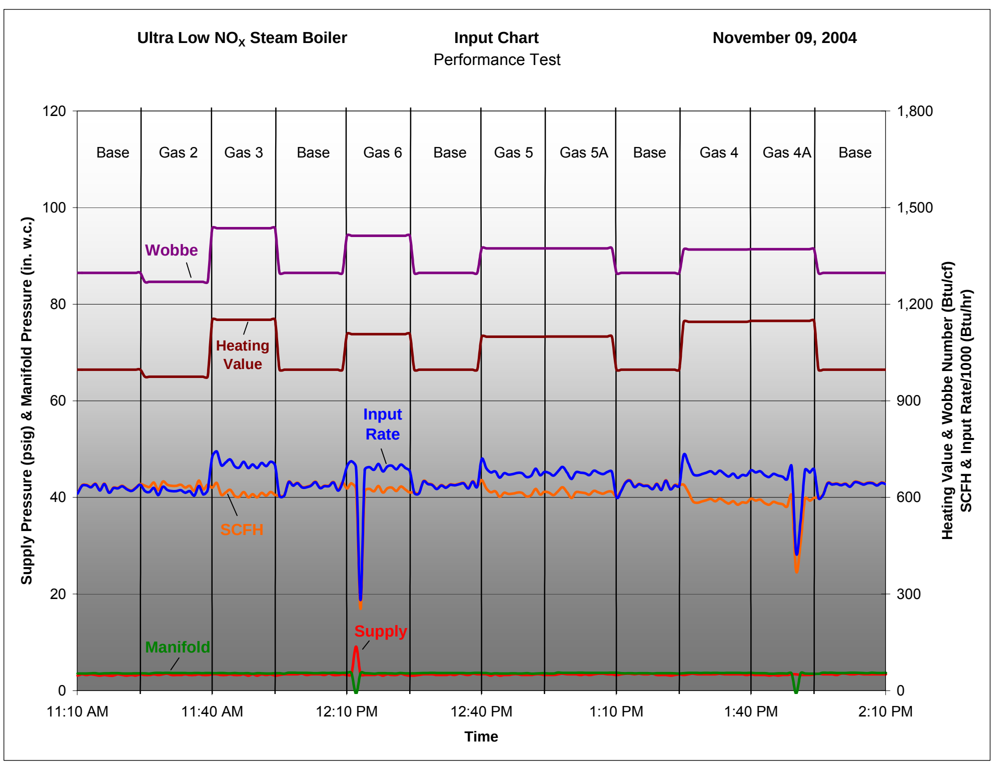
Performance Test

Input

The Ultra Low NO_X Steam Boiler was under fired by approximately 2.41% during the 1st Baseline Gas run. The highest input rate was observed for Gas 3 (706,227 Btu/hr) followed by Gas 6 (693,247 Btu/hr), Gas 4 (678,418 Btu/hr) and Gas 5 (677,770 Btu/hr). Baseline Gas input rates ranged from 629,472 Btu/hr (1st run) to 636,670 Btu/hr (5th run) and the lowest input rate was observed with Gas 2 (619,932 Btu/hr). Also, the highest gas flow rate was observed during the 5th Baseline Gas run (638.6 scfh).

Manifold and supply pressure remained stable throughout most of the test although the boiler shut off at the beginning of the Gas 6 run and again towards the end of the Gas 4 run. In both instances, the cylinders that were connected to the Gas Delivery System (GDS) ran out of gas.

The fluctuation in gas flow (and input rate) originates from the number of pulses counted by the data logger during each minute. The number of pulses counted is dependant on the position of the dial relative to the location of the sensor.



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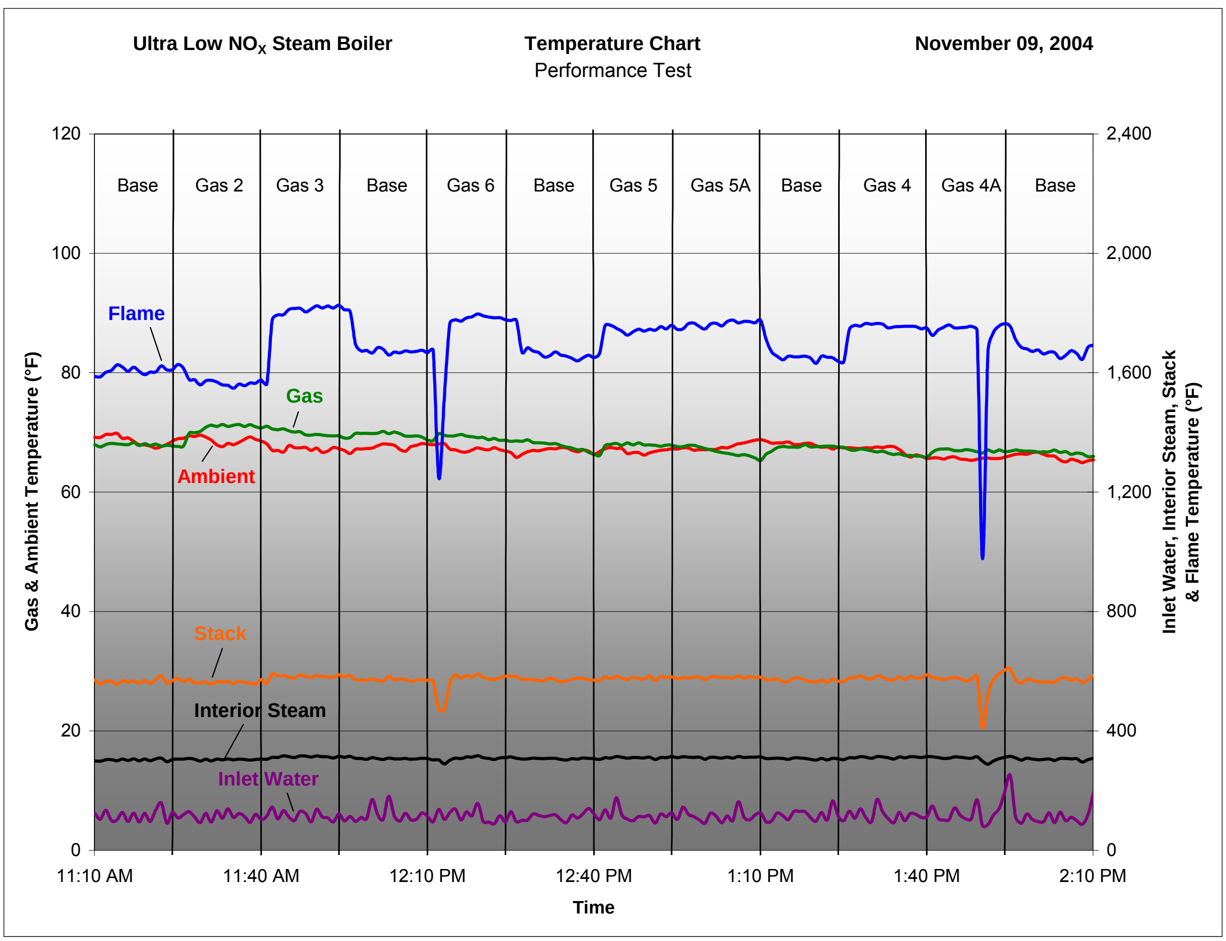
[1] All emissions, temperature and input values mentioned throughout the results section are average values.
[2] CO, HC & NO_X emissions values are corrected to 3% O_2.

Temperature

The highest flame temperature was observed with Gas 3 (1,778°F) followed by Gas 6 (1,765°F) and Gas 5A (1,762°F). Baseline Gas flame temperatures ranged from 1,606°F (1st run) to 1,691°F (2nd run) and the lowest flame temperature was observed with Gas 2 (1,572°F). Although most temperatures observed reacted to changes with the gases tested, the flame temperature depended on the location of the fixed thermocouple tip in the flame region.

Stack Temperature was highest with Gas 3 (581.1°F) and lowest with Gas 2 (563.9°F). Baseline Gas stack temperatures ranged from 566.1°F (1st run) to 573.2°F (2nd run). Interior steam temperatures ranged between 302 - 313°F and inlet water temperatures ranged between 110 – 129°F for the gases tested.

The boiler turned off during the beginning of the Gas 6 run and towards the end of the Gas 4 run. In both instances, the cylinders that were connected to the Gas Delivery System (GDS) ran out of gas.



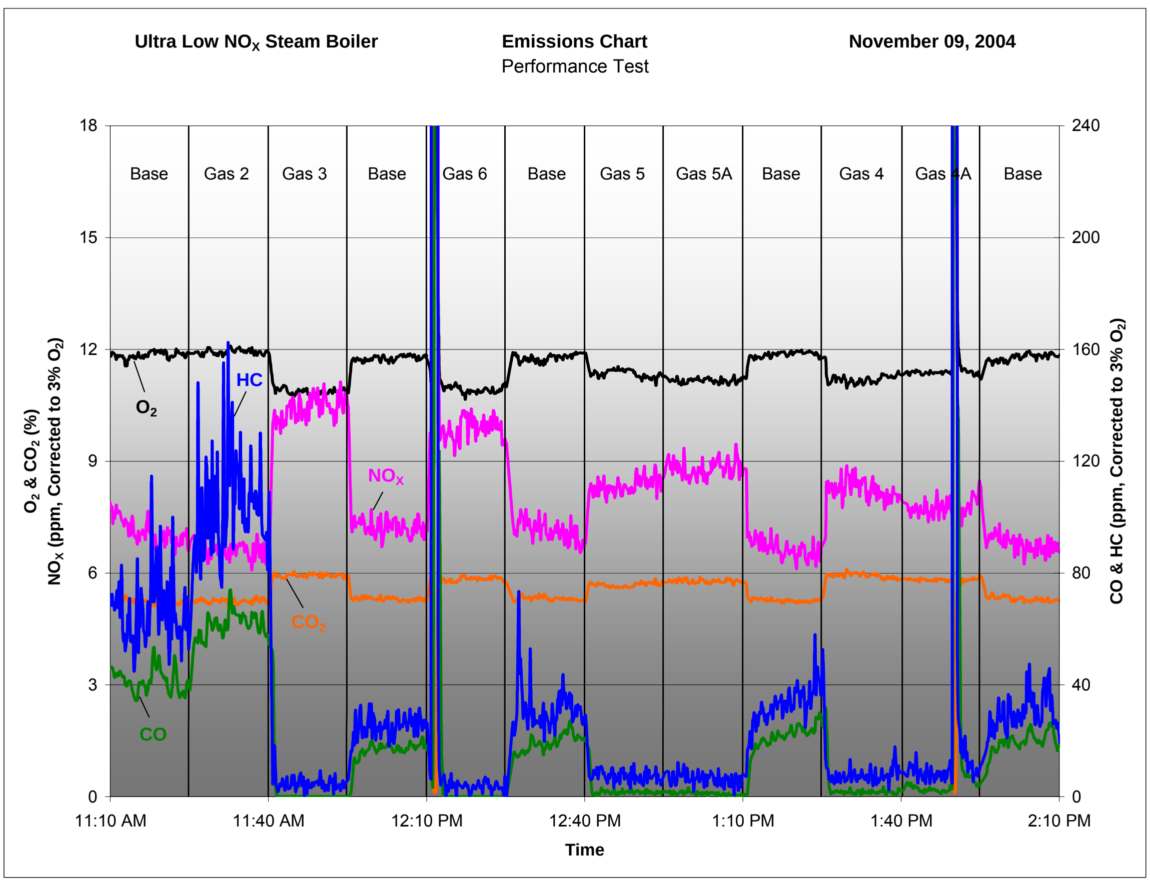
Emissions

CO values were highest for all low Wobbe/low heat content gases. Gas 2 (61.6 ppm) had the highest CO value followed by all Baseline Gas runs with values ranging between 17 – 42 ppm. CO values for all high Wobbe/high-heat content gases ranged between 0 – 3 ppm.

HC values were highest for all low Wobbe/low heat content gases. Gas 2 (104.5 ppm) had the highest HC value followed by all Baseline Gas runs with values ranging between 25 – 67 ppm. HC values for all high Wobbe/high-heat content gases ranged between 3 – 9 ppm.

NO_X values for all gases were below 12 ppm. The highest NO_X value was observed with Gas 3 (10.4 ppm) followed by Gas 6 (9.9 ppm), Gas 5A (8.8 ppm) and Gas 5 (8.3 ppm). All Baseline Gas and Gas 2 runs had NO_X values ranging between 6 – 8 ppm.

The boiler turned off during the beginning of the Gas 6 run and towards the end of the Gas 4 run. In both instances, the cylinders that were connected to the Gas Delivery System (GDS) ran out of gas.



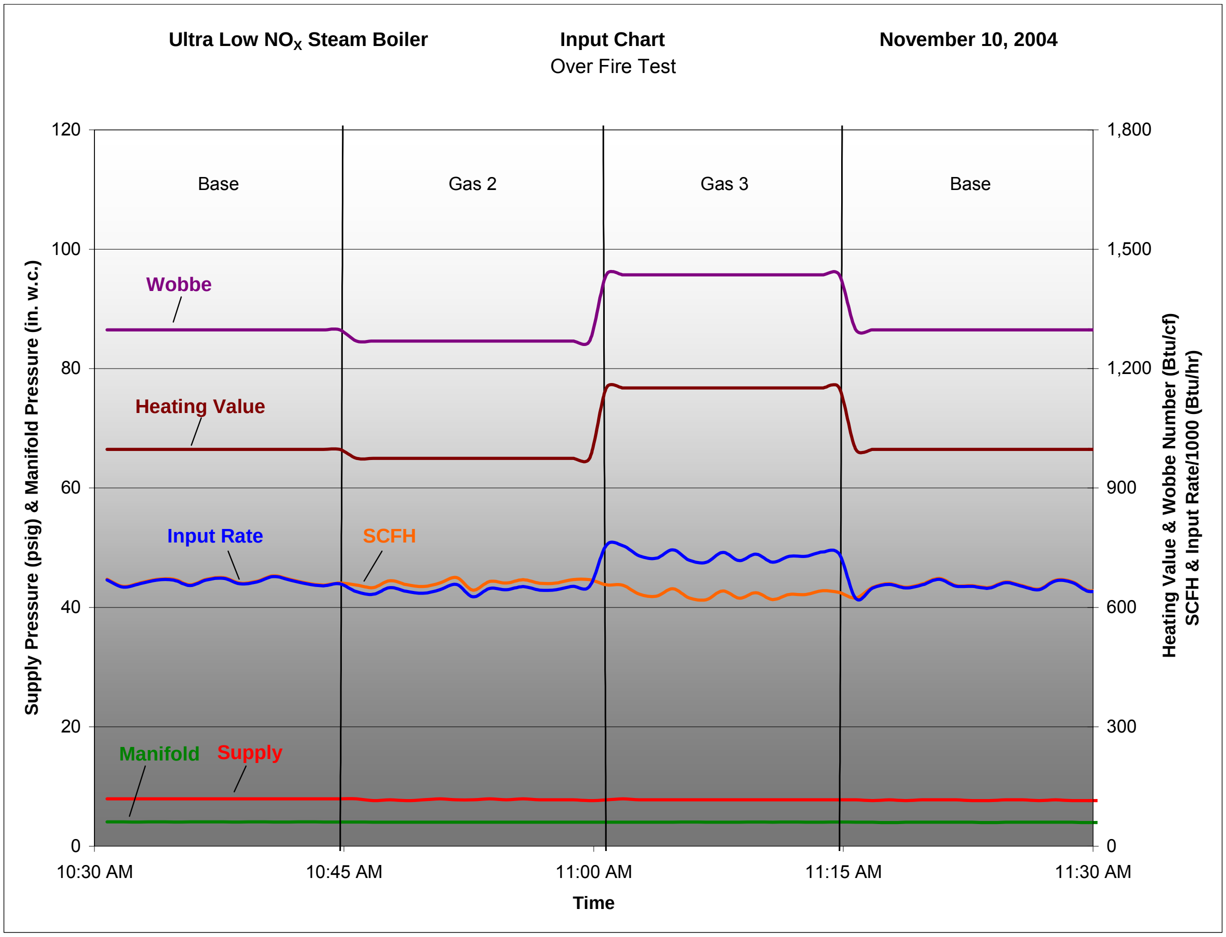
NOTE: Emission test results are for information purposes, they were not the result of certified tests.

Over Fire Test

Input

The Ultra Low NO_X Steam Boiler was over fired by approximately 2.91% during the 1st Baseline Gas run. The highest input rate was observed for Gas 3 (731,684 Btu/hr – 13.4% over fired) while the lowest input rate was observed with Gas 2 (644,437 Btu/hr – 0.08% under fired). Also, the highest gas flow rate was observed for the 1st Baseline Gas run (665.8 scfh) and both manifold and supply pressures remained stable throughout most of the test.

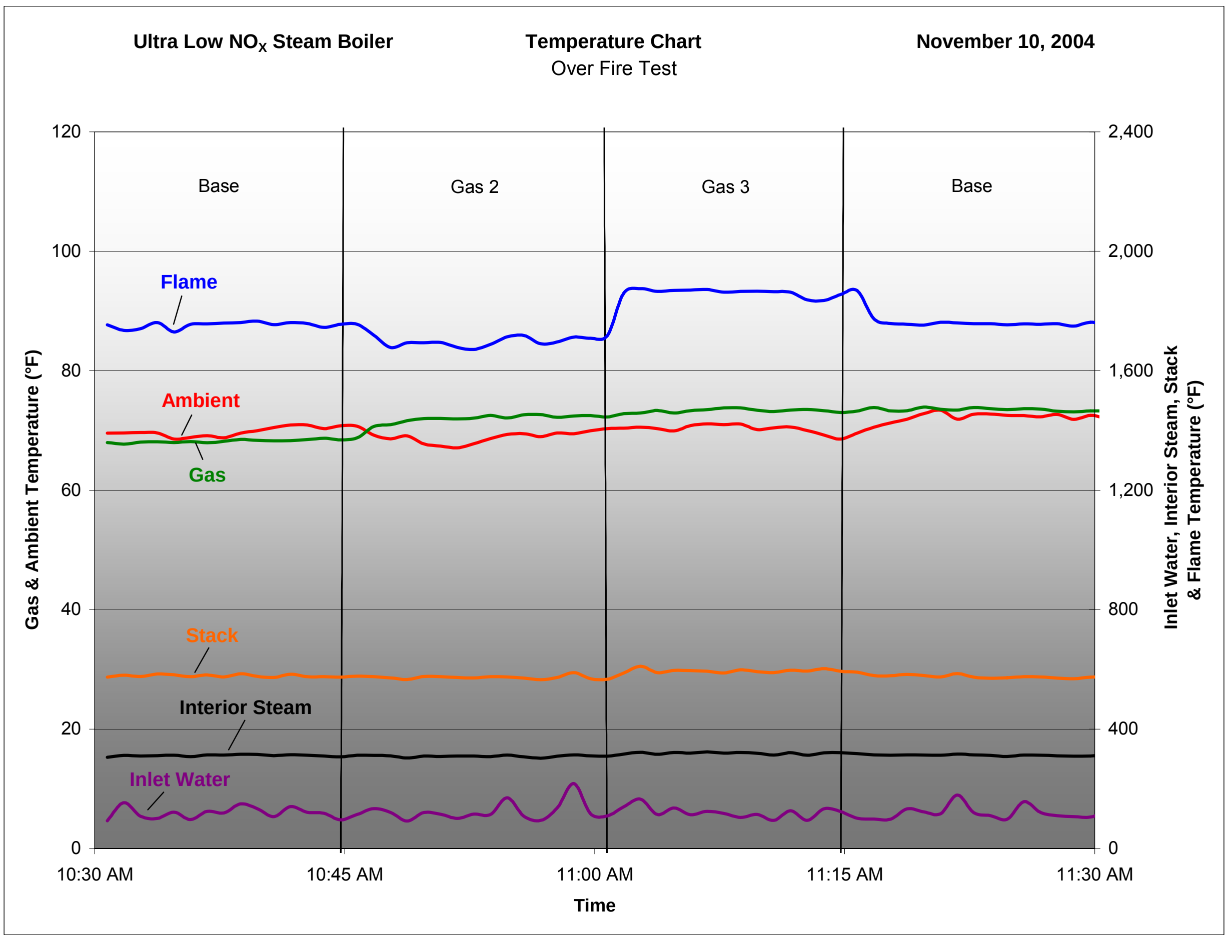
The fluctuation in gas flow (and input rate) originates from the number of pulses counted by the data logger during each minute. The number of pulses counted is dependant on the position of the dial relative to the location of the sensor.



Temperature

The highest flame temperature was observed with Gas 3 (1,852°F) and the lowest flame temperature was observed for Gas 2 (1,701°F). Baseline Gas flame temperatures were 1,765°F (2nd run) and 1,753°F (1st run). Although most temperatures observed reacted to changes with the gases tested, the flame temperature depended on the location of the fixed thermocouple tip in the flame region.

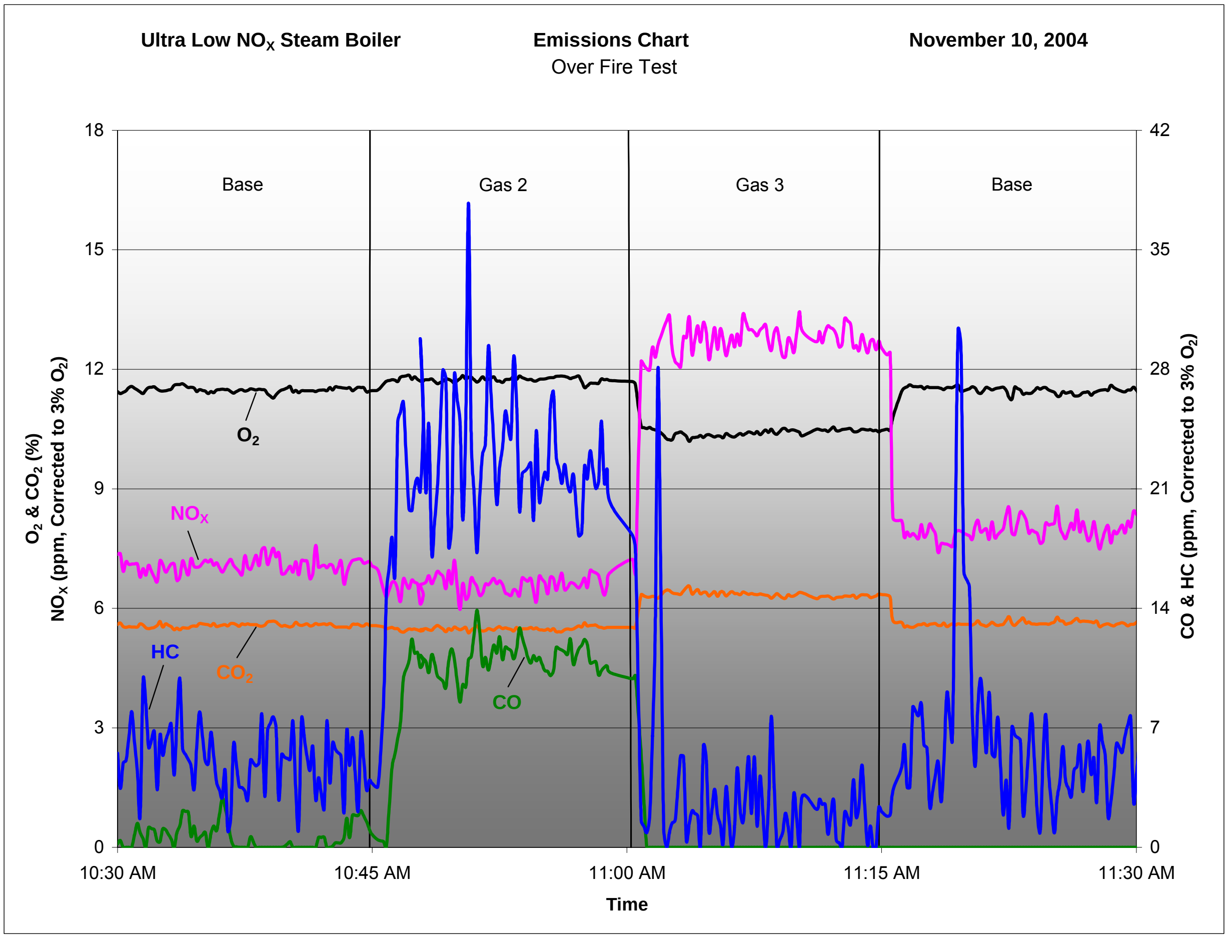
Stack Temperature was highest with Gas 3 (593.0°F) and lowest with Gas 2 (573.4°F). Baseline Gas stack temperatures were 578.1°F (1st run) to 576.6°F (2nd run). Interior steam temperatures ranged between 309 - 319°F and inlet water temperatures ranged between 118 – 125°F for the gases tested.



Emissions

CO values were highest with Gas 2 (11.1 ppm) while CO values for both Baseline Gas runs and Gas 3 were negligible. HC values were highest with Gas 2 (22.9 ppm) and lowest with Gas 3 (2.1 ppm) while both Baseline Gas runs had values of 5.2 ppm.

NO_X values for all gases were below 13 ppm. The highest NO_X value was observed with Gas 3 (12.7 ppm) followed by both Baseline Gas runs with values of 8.0 ppm (2nd run) and 7.1 (1st run). The lowest NO_X value was observed with Gas 2 (6.6 ppm).



NOTE: Emission test results are for information purposes, they were not the result of certified tests.

Hot Ignition Test

Orange tipping is normally luminance associated to high temperatures and not related with incomplete combustion.

Hot Ignition Test			
Gas	**Ignition**	**Start-Up #**	**Comments & Observations**
2	Normal and without delays	1	Long and even blue flame with no orange tipping
		2	Long and even blue flame with no orange tipping
		3	Long and even blue flame with no orange tipping
3	Normal and without delays	1	Short, sharp and uneven blue flame with continuous orange tipping
		2	Short, sharp and uneven blue flame with continuous orange tipping
		3	Short, sharp and uneven blue flame with continuous orange tipping

Appendix A: Test Protocol

1. Standards

- UL795 for Commercial- Industrial Equipment.
- ANSI Z21.13-2000, Standard for Gas-Fired Low-Pressure Steam and Hot Water Boilers.
- South Coast Air Quality Management District Rule 1146.2, Emission of NO_X from Large Water Heaters and Small Boilers, adopted January 9, 1998.
- South Coast Air Quality Management District Protocol, NO_X Compliance Testing for Natural Gas-fired Water Heaters and Small Boilers, last amended January 1998.
- South Coast Air Quality Management District – Instrumental analyzer procedure for continuous gaseous emissions - District Method 100.1.

2. Equipment Specifications

- **Description:** 15 HP Ultra Low NO_X Steam Boiler
- **Maximum Input Rating:** ~645,000 Btu/hr
- **Type of Fuel:** Natural Gas
- **Required Supply Pressure:** 7 – 14" w.c.

3. Test Arrangement

3.1. **Basic Set-up** – The boiler will be tested outdoors on a paved surface. Fuel gas, electrical power and water will be provided at conditions in accordance with the manufacturers specifications. A sample probe will be constructed to measure the combustion products in the vent pipe.

3.2. **Water Flow & Piping** – Water will be supplied as closely as possible to the temperature, pressure and flow rate specified in the manufacturer specifications to ensure proper boiler operation. If necessary, a supply water pump and valves may be used to adjust water temperature and flow rate.

3.3. **Vent Pipe** - For all testing, a straight vertical sheet metal vent pipe (at least three feet in length and of the diameter of the boiler vent collar) is to be provided along with an integrated sampling probe constructed per the AQMD protocol (placed six inches from the top of the vent pipe). Also, a thermocouple was used to measure stack temperature.

3.4. **Fuel Gas** - Fuel gases are to be provided at the pressures required by test methods specified later in this protocol and is to be measured at the manifold of the boiler.

3.5. **Electrical Power** - Electrical power is to be provided at the voltage specified by the manufacturer's boiler rating plate.

3.6. **Instrumentation** - Instrumentation is to be as close as possible to the SCAQMD Protocol for Rule 1146.2.

3.7. **Temperatures -** Thermocouples for interior steam and outlet steam piping are to be installed as close to the boiler as possible. A thermocouple for measurement of the ambient temperature will be located about 6 feet away from the boiler and elevated to approximately the mid-height of the boiler and shielded from abnormal radiation and convective effects. If necessary, provide thermocouples in other locations to record possible effects of gas blend changes. Seek assistance from the manufacturer in selecting thermocouple locations whenever possible.

4. Basic Operating Conditions

Unless required otherwise by specific test requirements, the following are to apply:

4.1. **Ambient Temperature** – Hold between 65 and 75°F and measured as specified in Sections 7.4.1.6 & 7.1.6 of the AQMD Protocol.

4.2. **Gas Delivery System Supply Pressure** – 3.0 ± 0.3 psig during Performance Test and 8.0 ± 0.3 psig during the Over Fire Test (pressure taken immediately after the gas meter).

4.3. **Basic Firing Set-Up** – The basic firing setup is a combination of gas valve and manifold pressure required for delivering rated input with Baseline Gas. Manifold pressure is to be within ± 10% of that specified on the rating plate. With gases other than Baseline Gas, the firing rate generally will *not* be at rated input.

5. Test Gases

The following gases will be utilized during testing and their composition details are specified in the appendix.

- **Baseline Gas** (Gas 1) - Low Wobbe (1,298 Btu/cf), low heat content gas (997 Btu/cf)
- **Gas 2** – Lowest Wobbe (1,269 Btu/cf), lowest-heat content gas (974 Btu/cf)
- **Gas 3** – Highest Wobbe (1,436 Btu/cf), highest-heat content gas (1,152 Btu/cf)
- **Gas 4** – Medium Wobbe (1,370 Btu/cf), highest-heat content gas (1,145 Btu/cf)
- **Gas 4A** (4 component mix) – Medium Wobbe (1,371 Btu/cf), highest-heat content gas (1,148 Btu/cf)
- **Gas 5** – Medium Wobbe (1,374 Btu/cf), high-heat content gas (1,100 Btu/cf)
- **Gas 5A** (4 component mix) – Medium Wobbe (1,374 Btu/cf), high-heat content gas (1,100 Btu/cf)
- **Gas 6** - High Wobbe (1,412 Btu/cf), high-heat content gas (1,107 Btu/cf)

6. Testing

6.1. Start-up Run

Operate boiler on Baseline Gas as received (**i.e.** gas orifices in the boiler and manifold pressure as set by manufacturer). The purpose of this run is to burn off manufacturing process oils (ensuring proper boiler operation) and to verify that testing instrumentation (thermocouples, pressure transducers, data logger, etc.)

is working properly. If it is evident that manufacturing oils are not totally driven off within 15 minutes, continue until oils are completely burned off. After break-in, allow the boiler to reach steady state conditions and determine the approximate as received firing rate. During this time, record temperature, pressure, gas flow and emissions[3] data.

6.2. Performance Test

Starting with Baseline Gas, operate the boiler at rated input by adjusting the manifold pressure and other parameters to manufacturer specifications. After 15 minutes, verify the firing rate is within ± 2% of the rated input. Once steady-state conditions are achieved, begin testing and collection of temperature, pressure and emissions data. Ensure that both manifold and supply pressures and the water temperature remain within acceptable limits set by this protocol throughout the entire test. Unless otherwise specified, each run for Baseline and Substitute Gases will be 15 minutes. Also, manual switching between gases should take approximately 14 seconds.

Continue steady-state boiler operation with Baseline Gas and then conduct a high-speed switch to Gas 2. Continue data acquisition (per above) while operating with Gas 2, observing changes in data before, during and after changeover.

Continue steady-state boiler operation with Gas 2 and then conduct a high-speed switch to Gas 3. Continue data acquisition (per above) while operating with Gas 3, observing changes in data before, during and after changeover.

Continue steady-state boiler operation with Gas 3 and then conduct a high-speed switch to reestablish Baseline Gas. Continue data acquisition (per above) while operating with Baseline Gas, observing changes in data before, during and after changeover.

The remaining Substitute Gases will be tested in the following order:

- Gas 6 (High Wobbe: 1,412 Btu/cf),
- Reestablish Baseline Gas (Low Wobbe: 1,302 Btu/cf)
- Gas 5 (Medium Wobbe: 1,374 Btu/cf)
- Gas 5A (Medium Wobbe: 1,374 Btu/cf)
- Reestablish Baseline Gas (Low Wobbe: 1,302 Btu/cf)
- Gas 4 (Medium Wobbe: 1,370 Btu/cf)
- Gas 4A (Medium Wobbe: 1,371 Btu/cf)
- Conclude with Baseline Gas (Low Wobbe: 1,302 Btu/cf)

When testing has been conducted with all gases, shut down the boiler, remove the burner assembly and examine the combustion chamber for the presence of soot by means of the white cloth technique. If soot is found, clean the chamber

[3] The term "*Emissions Data*" refers to O_2, CO_2, CO, HC and NO_X emissions values.

and repeat testing with suspect gas blend(s); selected on the basis of yellow tipping observations during testing. Establish which gas(es) tends to burn with soot deposition.

6.3. Over Fired Test

Starting with Baseline Gas, adjust the manifold pressure to over fire the boiler by 6% and verify the firing rate after 15 minutes. Once steady-state conditions are achieved, begin testing and collection of temperature, pressure and emissions data. Unless otherwise specified, each run for Baseline and Substitute Gases will be 15 minutes. Also, manual switching between gases should take approximately 14 seconds.

Continue steady-state boiler operation with Baseline Gas and then conduct a high-speed switch to Gas 2. Continue data acquisition (per above) while operating with Gas 2, observing changes in data before, during and after changeover.

Continue steady-state boiler operation with Gas 2 and then conduct a high-speed switch to Gas 3. Continue data acquisition (per above) while operating with Gas 3, observing changes in data before, during and after changeover.

Continue steady-state boiler operation with Gas 3 and then conduct a high-speed switch to reestablish Baseline Gas. Continue data acquisition (per above) while operating with Baseline Gas, observing changes in data before, during and after changeover.

When testing has been conducted with all gases, shut down the boiler, remove the burner assembly and examine the combustion chamber for the presence of soot by means of the white cloth technique. If soot is found, clean the chamber and repeat testing with suspect gas blend(s); selected on the basis of yellow tipping observations during testing. Establish which gas(es) tends to burn with soot deposition.

6.4. Ignition Test

6.4.1. Hot Ignition

Using Baseline Gas, adjusted the manifold pressure to allow for a rated input of 645,000 Btu/hr ± 2%. Purge the gas delivery system of Baseline Gas with Gas 3. Using Gas 3, ignite the steam boiler. Collect emissions temperature and pressure data for one minute and document visual observations of the flame and ignition delays. Repeat this process 2 more times.

Purge the gas delivery system of Gas 3 with Gas 2. Using Gas 2, ignite the steam boiler. Collect emissions temperature and pressure data for one minute and document visual observations of the flame and ignition delays. Repeat this process 2 more times.

7. Special Tests

Special tests may be conducted to investigate phenomena of concern to the boiler manufacturer. The decision of whether or not to test, and the design of appropriate tests are to be discussed with the manufacturer.

8. Additional Testing

Conduct additional testing and/or testing with other gas blends, per the Phase II protocol, when test results or observations indicate it is necessary. If indicated additional testing is outside of the project scope, include appropriate comment in the test report.

9. Calculations

CO, HC & NO_X emissions values are to be corrected to 3% Oxygen per the AQMD protocol for Rule 1146.

10. Measurements

The following test measurements will be taken:

- Gas Delivery System Parameters (Temperatures & Pressures)
- Supply & Manifold Pressure
- Fuel Gas Temperature
- Ambient Temperature
- Flame Temperature
- Stack Temperature
- Steam Temperature
- Gas Flow Rate
- Boiler Interior Steam Pressure
- Steam Supply Pressure

Rationale - Test Setup and Procedure

Firing rate:

A degree of de-rating by manufacturers is not uncommon because they must accommodate things beyond their control such as component and process tolerances and fuel gas property variation. Such de-rating is to be evaluated in a "startup run" during which the boiler will be operated "as shipped" on Baseline Gas. After the startup, "base case" data is to be obtained with the boiler adjusted to its rated input. The gas orifice size and manifold pressure required to achieve that condition with baseline gas are to be maintained during operation with the various gas blends being evaluated.

Allowing boiler operation to "float" with gas blend makes it possible to associate performance change with only the gas change. Existence of "as shipped" startup data allows inference as to how a factory de-rate practice might affect conclusions.

Burner and ignition operating characteristics:

Substitute gas compositions do not indicate likely problems and full-blown testing of burner and ignition systems per the safety standards would be more extensive than the program allows for. The testing specified in this protocol provides for observation of deviant phenomena, but does not include investigation of pilot and valve turndown characteristics, ignition system timing, etc.

Vent pipe choice:

For Performance Testing, the ANSI Standard Z21.13 specifies that the vent pipe consist of an elbow at the vent collar, a 2 ft horizontal section, a second elbow and a sufficient length of vertical vent pipe; providing a total height of five feet measured form the highest point on the draft hood relief opening to the top of the vertical vent pipe. The AQMD protocol requires a five-foot vertical vent pipe.

To minimize test time, the vent pipe height is specified at five feet for all testing and is allowed to be as short as four feet if necessary for compatibility with laboratory ceiling height. The height compromise departs from standards, but is not considered to materially affect results, especially with respect to performance comparison when gas fuel blend is changed. With respect to Standard Z21.13, a shortened vertical stack is considered to have an effect on the order of, and probably less than, a stack with two elbows and a horizontal section.

Water temperature:

ANSI Standard Z21.13 specifies an inlet temperature of 80 ± 10°F and an outlet temperature of 180 ± 2°F, unless the manufacturer states a maximum permissible water temperature rise.

The AQMD protocol specifies an inlet temperature of 70 ± 2°F and an outlet temperature of 180 ± 2°F, unless the manufacturer states a maximum permissible water temperature rise. In the latter case, inlet water is tempered to meet the manufacturer's requirement.

Interior Steam Pressure:

In order to prevent the boiler from cycling "off" and "on" the internal steam pressure was adjusted to remain just below the setting of the high-pressure limit switch. In addition, when a continuous steam load was not available a by pass valve was opened and steam was blown off in the atmosphere.

Appendix B: Table of Averages

Performance Test

Table of Averages Ultra Low NO_X Steam Boiler Performance Test November 9, 2004												
Gases	**Base**	**2**	**3**	**Base**	**6**	**Base**	**5**	**5A**	**Base**	**4**	**4A**	**Base**
HHV (Btu/cf)	997	974	1,152	997	1,107	997	1,099	1,100	997	1,145	1,148	997
Wobbe (Btu/cf)	1,298	1,269	1,436	1,298	1,412	1,298	1,373	1,374	1,298	1,370	1,371	1,298
Input Rate (Btu/hr)	629,472	619,932	706,227	633,081	693,247	634,615	677,770	676,168	633,494	678,418	675,472	636,670
Corrected SCFH	631.4	636.2	613.2	635.0	626.2	636.6	616.5	614.8	635.4	592.4	588.2	638.6
Emissions (not from certified tests)												
Raw O_2 (%)	11.8	11.9	10.9	11.8	10.9	11.8	11.3	11.2	11.9	11.2	11.4	11.8
Raw CO_2 (%)	5.2	5.2	5.9	5.3	5.8	5.3	5.7	5.8	5.3	5.9	5.8	5.3
CO (ppm @ 3% O_2)	41.6	61.6	0.0	17.2	0.0	19.2	1.6	1.1	22.5	1.6	2.6	20.1
HC (ppm @ 3% O_2)	66.4	104.5	4.8	25.6	3.8	31.5	7.3	6.4	33.7	7.6	8.5	30.1
NO_X (ppm @ 3% O_2)	7.1	6.6	10.4	7.2	9.9	7.1	8.3	8.8	6.6	8.2	7.7	6.8
Ultimate CO_2 (%)	12.1	12.2	12.4	12.1	12.2	12.2	12.4	12.4	12.2	12.8	12.8	12.2
Equivalence Ratio (Φ)	0.46	0.46	0.51	0.46	0.50	0.46	0.48	0.49	0.46	0.49	0.48	0.46
Temperatures (°F)												
Ambient	68.6	68.7	67.3	67.5	67.2	66.9	66.9	67.6	68.0	67.1	65.6	65.8
Gas	67.9	70.4	70.0	69.6	69.1	67.9	67.7	66.9	67.3	66.7	66.9	66.7
Stack	566.1	563.9	581.1	573.2	577.3	573.1	576.7	578.8	570.5	577.1	579.8	572.5
Interior Steam	302.9	304.3	312.4	307.9	308.7	307.4	309.9	311.3	307.5	310.7	310.0	306.1
Inlet Water	116.0	114.8	115.8	118.0	110.9	113.4	117.5	114.2	117.9	117.6	128.4	120.3
Flame	1,606	1,572	1,778	1,691	1,765	1,676	1,734	1,762	1,663	1,748	1,749	1,678
Pressures												
Supply (psig)	3.2	3.3	3.3	3.3	3.3	3.3	3.3	3.4	3.3	3.4	3.2	3.4
Manifold (in. w.c.)	3.6	3.6	3.6	3.7	3.6	3.7	3.6	3.7	3.6	3.7	3.6	3.7

Over Fire Test

Table of Averages Ultra Low NO_X Steam Boiler Over Fire Test November 10, 2004				
Gases	**Base**	**2**	**3**	**Base**
HHV (Btu/cf)	997	974	1,152	997
Wobbe (Btu/cf)	1,298	1,269	1,436	1,298
Input Rate (Btu/hr)	663,773	644,437	731,684	652,376
Corrected SCFH	665.8	661.4	635.4	654.4
Emissions (not from certified tests)				
Raw O_2 (%)	11.5	11.7	10.4	11.5
Raw CO_2 (%)	5.6	5.5	6.3	5.6
CO (ppm @ 3% O_2)	0.6	11.1	0.0	0.0
HC (ppm @ 3% O_2)	5.2	22.9	2.1	5.2
NO_X (ppm @ 3% O_2)	7.1	6.6	12.7	8.0
Ultimate CO_2 (%)	12.4	12.5	12.6	12.5
Equivalence Ratio (Φ)	0.48	0.47	0.53	0.48
Temperatures (°F)				
Ambient	69.8	68.9	70.3	72.1
Gas	68.2	71.8	73.2	73.5
Stack	578.1	573.4	593.0	576.6
Interior Steam	311.4	309.3	318.4	312.6
Inlet Water	118.9	124.6	120.7	119.0
Flame	1,753	1,701	1,852	1,765
Pressures				
Supply (psig)	7.9	7.8	7.8	7.7
Manifold (in. w.c.)	4.1	4.0	4.0	4.0

Appendix C: Test Gases

Gas Analysis Sample Date	**Baseline** 10/22/04	**2** 8/5/04	**3** 7/27/04	**4** 8/5/04	**4A** 7/27/04	**5** 8/18/04	**5A** 7/19/04	**6** 8/7/04
COMPONENTS	**MolPct**	**MolPct**	**MolPct**	**MolPct**	**MolPct**	**MolPct**	**MolPct**	**MolPct**
C6 + 57/28/14	0.0193	0.0307	0.0297	0.1858	0.0406	0.0737	0.0435	0.0000
NITROGEN	1.8773	1.0866	0.0609	1.0608	1.0782	0.8003	0.7777	0.0000
METHANE	94.5236	95.8713	86.7978	84.9713	84.3951	88.8139	90.8094	91.6800
CARBON DIOXIDE	1.3922	2.9973	0.0000	3.0005	3.0516	1.4074	1.4130	0.0000
ETHANE	1.4587	0.0000	9.3416	4.7846	0.0220	5.2987	0.0230	5.5300
PROPANE	0.2748	0.0141	2.7663	2.4015	11.3998	2.6048	6.9175	1.7500
i-BUTANE	0.0503	0.0000	1.0037	1.1936	0.0094	0.0022	0.0113	0.5200
n-BUTANE	0.0478	0.0000	0.0000	1.2074	0.0033	0.8424	0.0046	0.5200
NEOPENTANE	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
i-PENTANE	0.0152	0.0000	0.0000	0.5944	0.0000	0.1567	0.0000	0.0000
n-PENTANE	0.0102	0.0000	0.0000	0.6001	0.0000	0.0000	0.0000	0.0000
OXYGEN	0.3305	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOTAL	**100.0001**	**100.0000**	**100.0000**	**100.0000**	**100.0000**	**100.000**	**100.0000**	**100.0000**
Compressibility Factor	0.998	0.998	0.997	0.997	0.997	0.997	0.997	0.998
HHV (Btu/real cubic foot)	**996.93**	**974.40**	**1151.62**	**1145.13**	**1148.33**	**1099.38**	**1099.82**	**1107.06**
LHV (Btu/real cubic foot)	898.18	877.27	1041.31	1035.92	1039.51	993.10	993.61	999.82
Specific Gravity	0.5903	0.5895	0.6434	0.6989	0.7018	0.6407	0.6410	0.6143
WOBBE Index	**1297.57**	**1269.12**	**1435.73**	**1369.72**	**1370.73**	**1373.49**	**1373.72**	**1412.47**

Appendix D: Zero, Span and Linearity Tables

November 9, 2004 (Performance Test)

	Zero, Span & Linearity Data Performance Test November 9, 2004	O_2 (%)	CO_2 (%)	CO (ppm)	HC (ppm)	NO_x (ppm)
	Analyzer Emission Ranges	**0 - 25**	**0 - 20**	**0 - 200**	**0 - 1000**	**0 - 100**
Zero	**Zero Calibration Gas (Low-Range Values)**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Zero	**Allowable Zero Drift (Less Than ± 3% of Range)**	**0.75**	**0.60**	**6.00**	**30.00**	**3.00**
Zero	Zero Calibration - 8:02 AM	0.18	0.03	-0.16	0.51	-0.26
Zero	Zero Drift Check - 2:29 PM	0.19	0.01	-0.46	0.31	0.84
Zero	**Total Drift Over Test Period**	**0.01**	**0.02**	**0.30**	**0.20**	**1.10**
Zero	**Was the Zero Drift Within Allowable Deviation?**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Span	**Span Calibration Gas (High-Range Values)**	**20.90**	**12.00**	**182.40**	**443.00**	**84.37**
Span	**Allowable Span Drift (Less Than ± 3% of Range)**	**0.75**	**0.60**	**6.00**	**30.00**	**3.00**
Span	Span Calibration - 8:24 AM	20.87	12.05	182.29	443.56	84.38
Span	Span Drift Check - 2:22 PM	21.03	12.01	182.57	444.09	82.75
Span	**Total Drift Over Test Period**	**0.16**	**0.04**	**0.28**	**0.53**	**1.63**
Span	**Was the Span Drift Within Allowable Deviation?**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Linearity	**Linearity Calibration Gas (Mid-Range Values)**	**9.03**	**8.00**	**81.60**	**443.00**	**17.80**
Linearity	**Allowable Linearity Drift (Less Than ±1% of Range)**	**0.25**	**0.20**	**2.00**	**10.00**	**1.00**
Linearity	Linearity Check - 8:28 AM	9.17	7.94	77.76	444.37	17.82
Linearity	**Difference From Mid-Range Values**	**0.14**	**0.06**	**3.84**	**1.37**	**0.02**
Linearity	**Was the Linearity Within Allowable Deviation?**	**Yes**	**Yes**	**No**	**Yes**	**Yes**
Linearity	Linearity Check - 2:25 PM	9.20	7.94	77.84	451.88	17.94
Linearity	**Difference From Mid-Range Values**	**0.17**	**0.06**	**3.76**	**8.88**	**0.14**
Linearity	**Was the Linearity Within Allowable Deviation?**	**Yes**	**Yes**	**No**	**Yes**	**Yes**

November 10, 2004 (Over Fire Test)

Zero, Span & Linearity Data
6% Over Fired Test
November 10, 2004

		O_2 (%)	CO_2 (%)	CO (ppm)	HC (ppm)	NO_x (ppm)
	Analyzer Emission Ranges	**0 - 25**	**0 - 20**	**0 - 200**	**0 - 1000**	**0 - 100**
Zero	**Zero Calibration Gas (Low-Range Values)**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	Allowable Zero Drift (Less Than ± 3% of Range)	**0.75**	**0.60**	**6.00**	**30.00**	**3.00**
	Zero Calibration - 8:30 AM	0.21	0.04	0.56	-0.08	-0.42
	Zero Drift Check - 11:35 AM	0.19	0.15	-0.60	-0.27	1.58
	Total Drift Over Test Period	**0.02**	**0.11**	**1.16**	**0.19**	**2.00**
	Was the Zero Drift Within Allowable Deviation?	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Span	**Span Calibration Gas (High-Range Values)**	**20.90**	**12.00**	**182.40**	**443.00**	**84.37**
	Allowable Span Drift (Less Than ± 3% of Range)	**0.75**	**0.60**	**6.00**	**30.00**	**3.00**
	Span Calibration - 8:35 AM	20.88	12.05	182.53	444.79	84.88
	Span Drift Check - 11:37 AM	20.85	12.22	181.33	430.77	82.95
	Total Drift Over Test Period	**0.03**	**0.17**	**1.20**	**14.02**	**1.93**
	Was the Span Drift Within Allowable Deviation?	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Linearity	**Linearity Calibration Gas (Mid-Range Values)**	**9.03**	**8.00**	**81.60**	**443.00**	**17.80**
	Allowable Linearity Drift (Less Than ±1% of Range)	**0.25**	**0.20**	**2.00**	**10.00**	**1.00**
	Linearity Check - 8:40 AM	9.23	8.06	77.95	443.01	18.01
	Difference From Mid-Range Values	**0.20**	**0.06**	**3.65**	**0.01**	**0.21**
	Was the Linearity Within Allowable Deviation?	**Yes**	**Yes**	**No**	**Yes**	**Yes**
	Linearity Check - 11:42 AM	9.18	8.16	77.34	430.23	19.05
	Difference From Mid-Range Values	**0.15**	**0.16**	**4.26**	**12.77**	**1.25**
	Was the Linearity Within Allowable Deviation?	**Yes**	**Yes**	**No**	**No**	**No**

Appendix E: Calculations

Emission Concentrations

Corrected to O_2 Standard (3% O_2)

$$\text{CO, HC \& NO}_x\text{ Concentrations (corrected to 3\% O}_2\text{)} = \text{Raw Concentrations (ppm)} \times \left[\frac{20.9 - 3}{20.9 - \%O_2}\right]$$

Where

Raw Concentration = Measured CO, HC & NO_x concentrations, by volume (ppm)

% O_2 = Measured O_2 Concentration

Ultimate CO_2

$$\text{Ult. CO}_2 = \text{Raw CO}_2 \times \left[\frac{20.9}{20.9 - \text{Raw O}_2}\right]$$

Where

Ult. CO_2 = Ultimate CO_2 (%)

Raw CO_2 = Measured CO_2 Concentration (%)

Raw O_2 = Measured O_2 Concentration (%)

% Excess Air

Constituent	Balanced Chemical Composition	Theo. Air	Theo. Flue Gas
Methane (CH_4)	$CH_4 + 2O_2 + 2(3.78)N_2 \Rightarrow 1CO_2 + 2H_2O + 2(3.78)N_2$	9.56	8.56
Ethane (C_2H_6)	$C_2H_6 + 3.5O_2 + 3.5(3.78)N_2 \Rightarrow 2CO_2 + 3H_2O + 3.5(3.78)N_2$	16.73	15.23
Propane (C_3H_8)	$C_3H_8 + 5O_2 + 5(3.78)N_2 \Rightarrow 3CO_2 + 4H_2O + 5(3.78)N_2$	23.90	21.90
i-Butane (C_4H_{10})	$C_4H_{10} + 6.5O_2 + 6.5(3.78)N_2 \Rightarrow 4CO_2 + 5H_2O + 6.5(3.78)N_2$	31.07	28.57
n-Butane (C_4H_{10})	$C_4H_{10} + 6.5O_2 + 6.5(3.78)N_2 \Rightarrow 4CO_2 + 5H_2O + 6.5(3.78)N_2$	31.07	28.57
i-Pentane (C_5H_{12})	$C_5H_{12} + 8O_2 + 8(3.78)N_2 \Rightarrow 5CO_2 + 6H_2O + 8(3.78)N_2$	38.24	35.24
n-Pentane (C_5H_{12})	$C_5H_{12} + 8O_2 + 8(3.78)N_2 \Rightarrow 5CO_2 + 6H_2O + 8(3.78)N_2$	38.24	35.24
Hexanes (C_6H_{14})	$C_6H_{14} + 9.5O_2 + 9.5(3.78)N_2 \Rightarrow 6CO_2 + 7H_2O + 9.5(3.78)N_2$	45.41	41.91

To determine the % Excess Air, the theoretical air and theoretical flue gas values for each gas tested must be calculated. The table above lists the constituents found in natural gas, the balanced chemical equations for each constituent and their respective theoretical air and theoretical flue gas values (expressed in moles).

The theoretical air value for each constituent is the sum of moles for both O_2 and N_2 on the reactants side of the balanced chemical equation (ex: For Methane, 2 moles of O_2 plus 7.56 moles of N_2 = 9.56 moles of Theoretical Air). The theoretical flue value for each constituent is the sum of moles for both CO_2 and N_2 on the product side of the balanced chemical equation (ex: For Methane, 1 mole of CO_2 plus 7.56 moles of N_2 = 8.56 moles of Theoretical Flue Gas).

Once the test gases have been analyzed (via gas chromatography), the % composition of each gas is used to determine the theoretical air and theoretical flue gas values for each gas tested. Thus,

$$\text{Theoretical Air} = \sum C_1P + C_2P + \ldots + C_nP$$

$$\text{Theoretical Flue} = \sum D_1P + D_2P + \ldots + D_nP$$

Where *C* is the theoretical air value for each constituent, *D* is the theoretical flue gas value for each constituent and *P* is the percent composition for each constituent (expressed as a decimal, not a percentage). Therefore, the % Excess Air is calculated as follows:

$$\%\,\text{Excess Air} = \left[\text{Theo. Flue Value} \times \frac{\text{Ult.}CO_2 - \text{Raw } CO_2}{\text{Theo. Air Value} \times \text{Raw } CO_2}\right] \times 100$$

Air/Fuel Ratio

$$\text{Air/Fuel Ratio} = \text{Theo. Air Value} + \frac{\text{Theo. Air Value} \times \%\,\text{Excess Air}}{100}$$

Equivalence Ratio (ϕ)

$$\text{Equivalence Ratio}\,(\phi) = \frac{100}{100 + \%\,\text{Excess Air}}$$

Gas Meter Correction

To determine the corrected SCFH for each appliance tested, the accuracy of the 8C gas meter was checked to determine the correction factor for each meter (Table shown below).

Given the range of the input rate, the slope (m) of the line was determined setting y = average correction percentage and x = cubic feet per hour (cfh). Next, the y-intercept/correction factor (b) was determined using the y-intercept equation (y = mx + b). Once the correction factor (b) is known, the y-intercept equation was used again to calculate the corrected SCFH; this time x = uncorrected SCFH value.

Model Number: 8C **Date:** September 22, 2004 **Meter Number:** 11335393 TESTS WERE CONDUCTED USING 20 CU. FT. BELL PROVER #3226		
CFH	**OK Counts**	**Proofs (%)**
800	961	+ 0.10
700	961	+ 0.20
600	960	+ 0.10
500	958	- 0.30
400	958	- 0.30
200	955	- 0.10
100	955	- 0.10

SCFH (Uncorrected)

$$SCFH = ACFH \times \left[\frac{P_{Fuel}\,(psig) + P_1\,(psia)}{P_{standard}} \right] \times \left[\frac{T_{standard}}{T_{Fuel}\,(^{\circ}F) + 459.67} \right]$$

Where

SCFH = Standard Cubic Feet per Hour

ACFH = Actual Cubic Feet per Hour

P_{Fuel} = Gas Supply Pressure (psig)

P_1 = Average Pressure in Los Angeles @ average elevation of 257 ft (psia)

$P_{standard}$ = Standard. Atmospheric Pressure (14.696 psia)

$T_{standard}$ = Standard. Atmospheric Temperature (519.67 R @ 1 atm)

T_{Fuel} = Fuel Temperature (°F)

SCFH (Corrected)

$$\text{Corrected SCFH} = \text{SCFH} + \text{Meter Correction Factor}$$

Input Rate (Btu/cf)

$$\text{Input Rate} = \text{Corrected SCFH} \times \text{HHV}$$

Where

HHV = Higher Heating Value (Btu/cf)

Wobbe Number (Btu/cf)

$$W_0 = \frac{HHV}{\sqrt{G}}$$

Where

W_0 = Wobbe Number (Btu/cf)

HHV = Higher Heating Value (Btu/cf)

G = Specific gravity of gas sample

Appendix F: Test Equipment

Emissions Analyzer				
Analyzer	**Manufacturer**	**Model**	**Type**	**Accuracy**
NO/NO_X	Thermo Environmental Instruments Inc.	10AR	Chemiluminescent	± 1% of full scale
CO	Thermo Environmental Instruments Inc.	48	Nondispersive infrared (NDIR) gas analyzer	± 1% of full scale
CO_2	Fuji	ZRH	Nondispersive infrared (NDIR) gas analyzer	± 1% of full scale
HC	California Analytical Instruments, Inc.	300 HFID	Flame ionization detector (FID)	± 1% of full scale
O_2	Teledyne	326RA	Electrochemical cell	± 1% of full scale

Calibration & Span Gases			
Gas	**Manufacturer**	**Type**	**Accuracy**
Calibration	Scott Specialty Gases	Certified Master Class - 0 %	± 2%
NO/NO_X	Scott Specialty Gases	Certified Master Class - 18.95 ppm	± 2%
CO	Scott Specialty Gases	Certified Master Class - 79.3 ppm	± 2%
CO_2	Scott Specialty Gases	Certified Master Class -12.1 %	± 2%
HC	Scott Specialty Gases	Certified Master Class - 0.5 ppm	± 2%
O_2	Scott Specialty Gases	Certified Master Class - 9.1 %	± 2%

Test Equipment			
Equipment	**Manufacturer**	**Model**	**Accuracy**
Datalogger	Delphin	D51515	n/a
Gas Chromatigraph	Agilent	6890	± 0.5 BTU/scf
K	Omega Engineering Co.	KMQSS	2.2^{o}C or 0.75%
J	Omega Engineering Co.	JMQSS	2.2^{o}C or 0.75%
R	Omega Engineering Co.	RMQSS	2.2^{o}C or 0.75%
T	Omega Engineering Co.	TMQSS	2.2^{o}C or 0.75%
Drytest Gas Meter 800 cf/h max	Roots Meter	8C175	n/a
Gas Meter Pulser 2 pulses per 1/10 cf	Rio Tronics	4008468	n/a
Gas Pressure Regulator	Fisher	299H	± 1.0 %
Differential Pressure Transmitter	Dwyer	607-4	±0.25 -0.50%
Pressure Transducer	Omega	PX205-100GI	±0.25% of full scale

Appendix G: Test Set-Up/Schematic

Equipment utilized for testing adheres to industry standards for testing laboratories that certify such equipment. The test rig is transportable and includes a data logger, emissions cart, gas meter, thermocouples and pressure transducers; plus, a gas regulation system that can take natural gas from 3,000 psig and deliver up to 2,000 cfh at low pressure (~8" w.c.). The test rig is illustrated below.