LNG Research Study

Low NO_X Steam Boiler

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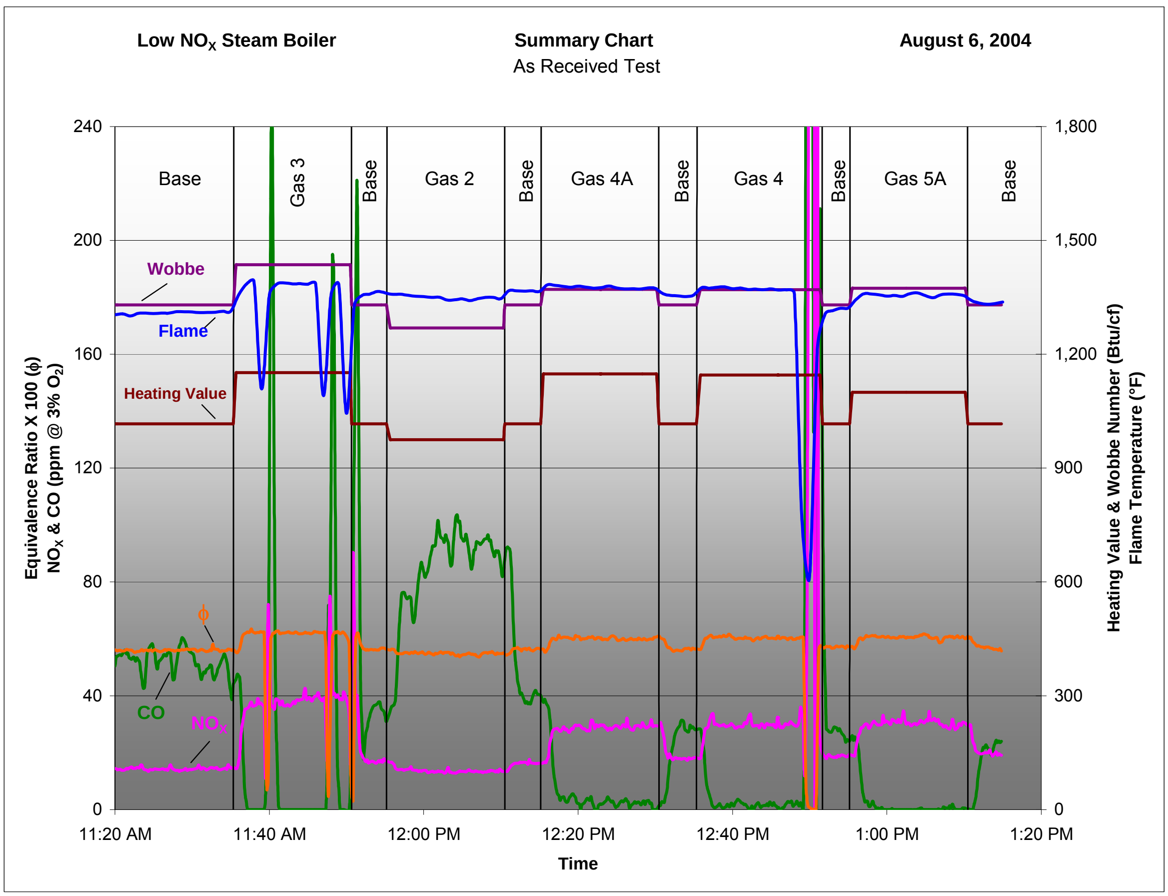
Results Summary

Results obtained from all tests conducted with the different gases reveal that (a) there were no operational, ignition, flame stability, or safety problems during testing of each gas or during transitions between gases; (b) CO emissions were below 90 ppm, corrected to 3% O_2; (c) Flame temperature, partial orange tinting of the flame, NO_X, and equivalence ratio followed the same pattern as the Wobbe Number; (d) CO and HC followed the opposite pattern as the Wobbe Number. After the manufacturer reviewed the data, they expresed concerns with higher NO_X emissions observed with richer gases.

As Received Test

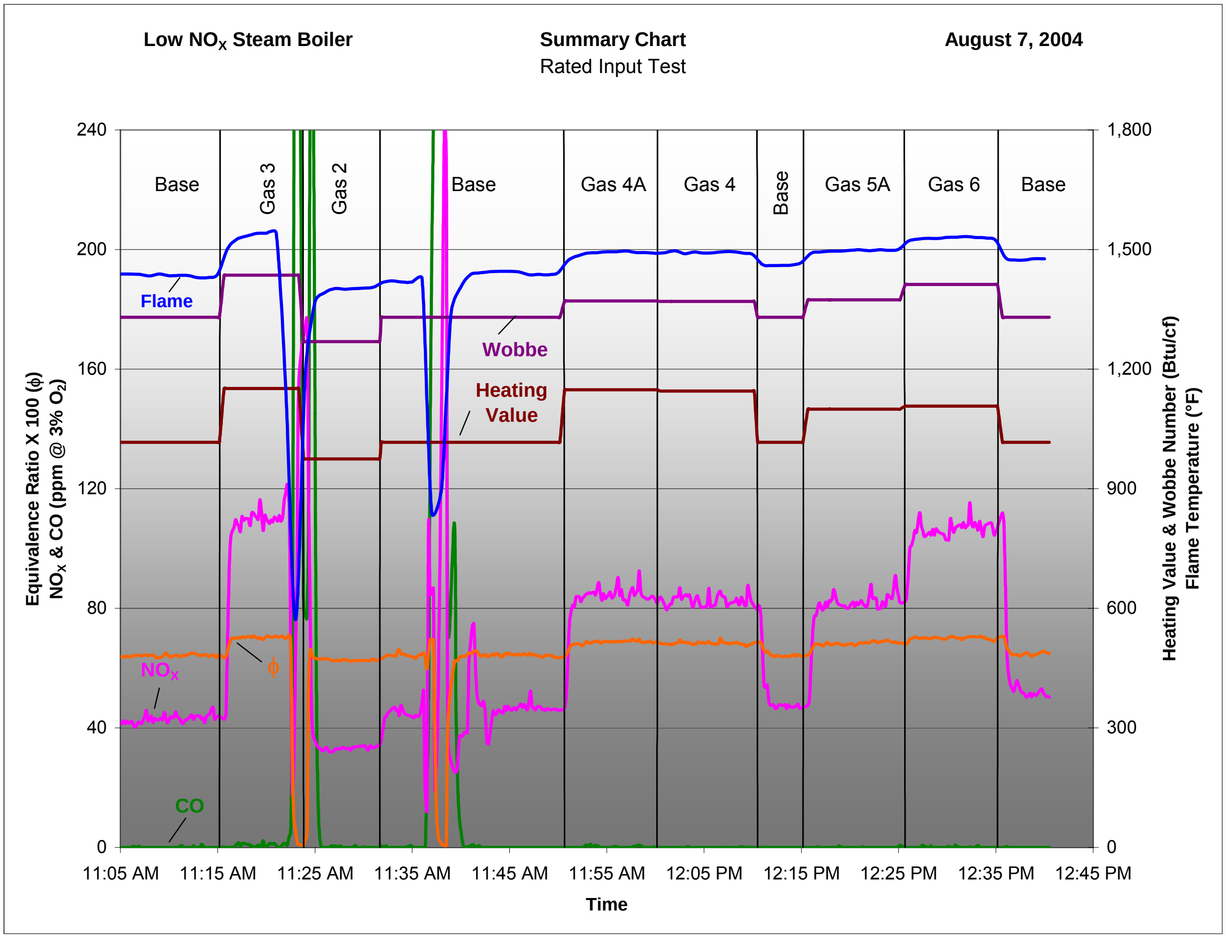
Average NO_X emissions values were below 40 ppm for all gases tested. Average CO emissions values were below 52 ppm for all test gases with the exception of Gas 2 — during that run, the average CO emissions value increased to 89 ppm.



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

Rated Input Test

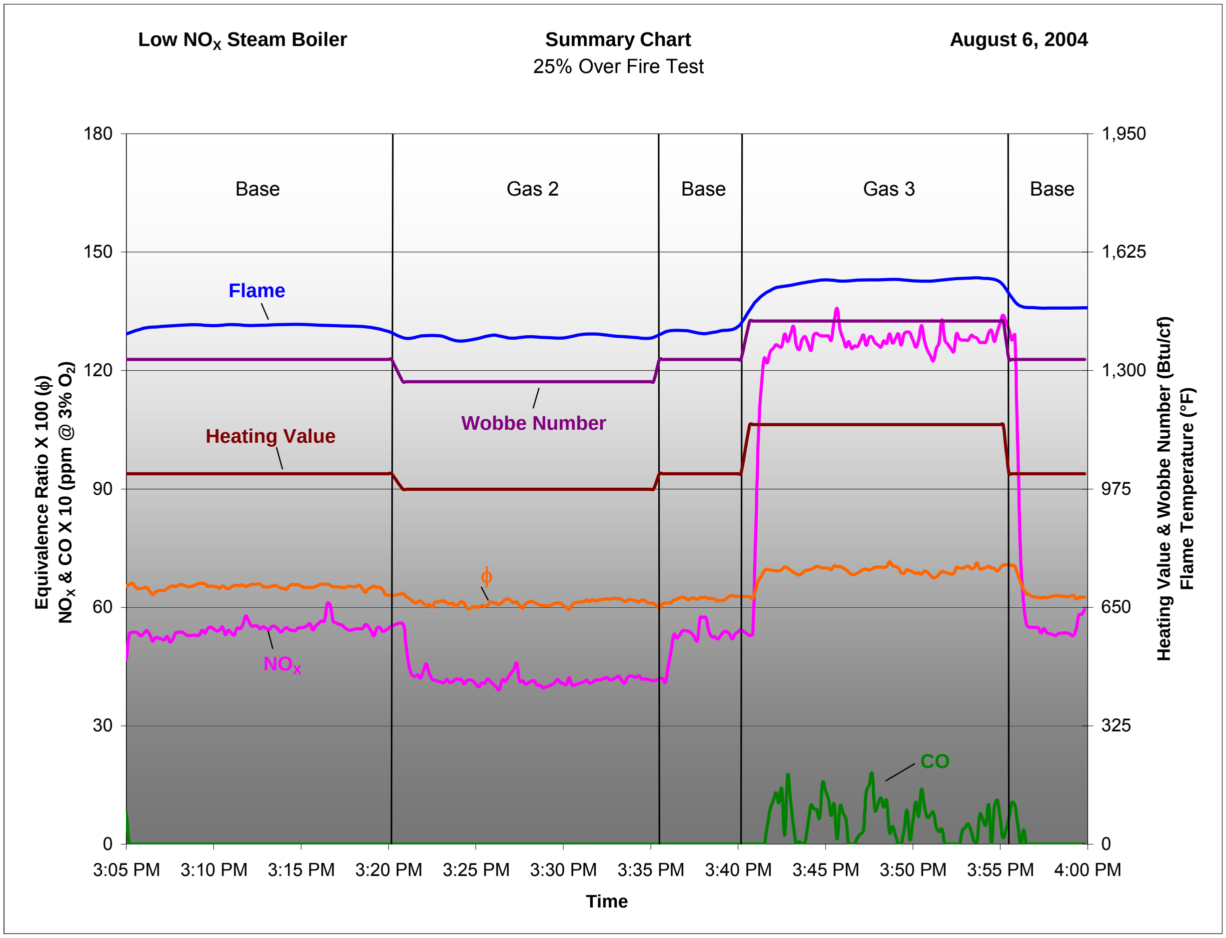
Average NO_X emissions from Gases 3 and 6 were the highest (110 and 107 ppm). Average NO_X for gases 4, 4A and 5A were above 82 ppm. Average CO emissions values were neglegible with all the test gases. There were a few short CO spikes when the boiler cycled "Off" and "On"



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

25% Over Fire Test

NO_X emissions were 54 ppm with Baseline Gas and 42 ppm with Gas 2. When Gas 3 was introduced, they increased to 128 ppm. Average CO emissions values were negligible for the gases tested. This test is performed by the manufacturer to meet standards for international customers and for quality control purposes.



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

Equipment Selection Criteria

This Low NO_X Steam Boiler was selected because it has been difficult for boiler and burner manufacturers to meet SCAQMD Rule 1146.2 while adhering to the Gas-Fired Low Pressure Steam and Hot Water Boilers Standard (ANSI Z21.13) and UL–795 from the Underwriters Laboratory. Rule 1146.2 limits the NO_X and CO emissions for Type 1 boilers (from 75,000 Btu/hr up to and including 400,000 Btu/hr). The ANSI Z21.13 and UL standards cover safety, construction and performance, with each having combustion tests that limit CO emissions. In addition, this unit was selected because both the boiler manufacturer and the burner system are widely used in our service territory.

Equipment Specifications

- **Description:** 7 HP Low NO_X Steam Boiler
- **Burner:** Surface premix power burner operating on blue flame mode
- **Maximum input rating:** ~301,000 Btu/hr
- **Minimum input rating:** ~150,000 Btu/hr
- **Type of fuel:** Natural Gas
- **Required 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 Appendix A 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. The outlet steam valve was adjusted to maintain approximately 50 psig inside the boiler, allowing the boiler to run without opening the pressure relief valve.

Instrumentation was installed following the above test standards and input from the manufacturer and a consultant. Thermocouples were installed to measure flame, make-up water, steam, flue gas, ambient and gas temperatures. Pressure transducers were installed to measure manifold, skid, supply and steam pressures inside the boiler. A gas meter was installed to measure the gas flow and an emissions probe was installed in the flue vent of the boiler.

Once all test instruments were installed, the boiler was run on the facility's 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 compositions 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 (1,302 Btu/cf), low heat content gas (1,001 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 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 differences between the test standards, the time limitations, and restrictions of the facilities, the test procedures were simplified with input from the manufacturers and consultants directed to develop a sound test procedure.

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 30 seconds.
- Emissions, pressure and temperature data was observed before, during and after changeover.

After every test, the following steps were performed:

- Test data was downloaded.
- Linearity and drift inspections were performed on all emissions analyzers.

As Received Test

The low NO_X boiler was operated with Baseline Gas to verify that it ran properly and the manifold pressure remained unchanged throughout the test. Once steady state operation was established, testing and data collection was started and the gases were run in the following order:

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

Rated Input Test

Using Baseline Gas, the manifold pressure was adjusted to allow for a rated input of 301,000 BTU/hr ± 2%. Once readings were stable, data collection was started and the gases were run in the following order:

- Baseline Gas for 10 minutes.
- Gas 3 for 10 minutes.
- Gas 2 for 10 minutes.
- Reestablish Baseline Gas for 5 minutes.
- Gas 4A for 10 minutes.
- Gas 4 for 10 minutes.
- Reestablish Baseline Gas for 5 minutes.
- Gas 5A for 10 minutes.
- Gas 6 for 10 minutes.
- Conclude testing with Baseline Gas for 5 minutes.

25% Over Fire Test

Using Baseline Gas, the manifold pressure was adjusted to over fire the steam boiler by 25% above its rated input of 301,000 BTU/hr. When this condition was met, the gases were run in the following order:

- Baseline Gas was tested for 10 minutes.
- Gas 2 for 15 minutes.
- Reestablish Baseline Gas for 5 minutes.
- Gas 3 for 15 minutes.
- Conclude testing with Baseline Gas for 5 minutes.

Cold Ignition Test

Using Baseline Gas, manifold pressure was adjusted to allow for a rated input of 301,000 Btu/hr ± 2%. The following steps were followed:

- The gas delivery system was purged with Gas 3.
- The steam boiler was ignited (using Gas 3) from a cold start and operated for one minute. For each time the boiler was ignited, visual observations of the flame, ignition delays and other phenomena observed was documented. This test was repeated 2 more times, allowing the water heater to reestablish cold start conditions in between each ignition.
- The gas delivery system was purged with Gas 2.
- The steam boiler was ignited (using Gas 2) from a cold start and operated for one minute. For each time the boiler was ignited, visual observations of the flame, ignition delays and other phenomena observed was documented. This test was repeated 2 more times, allowing the water heater to reestablish cold start conditions in between each ignition.

Hot Ignition Test

Using Baseline Gas, manifold pressure was adjusted to allow for a rated input of 301,000 Btu/hr ± 2%. The following steps were followed:

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

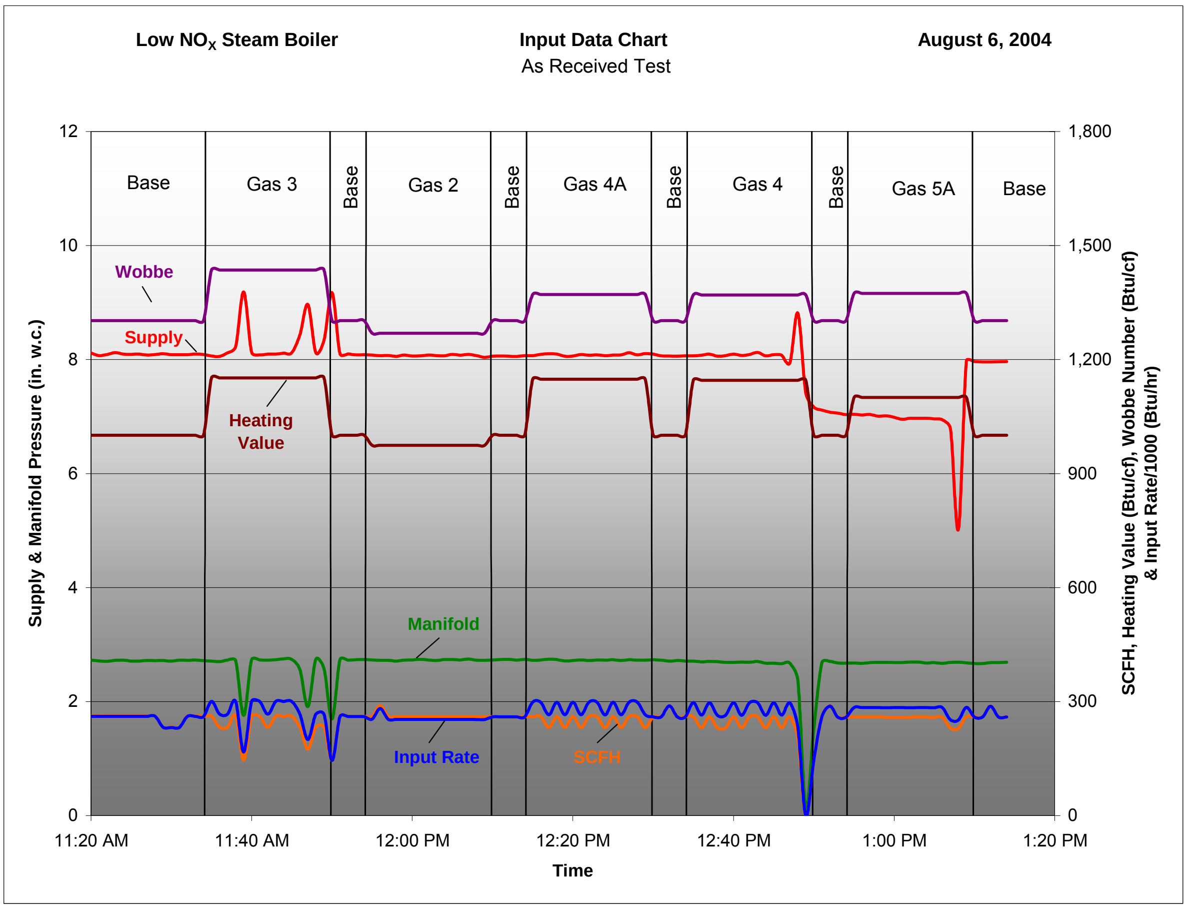
Results[1, 2]

As Received Test

Input

The steam boiler was recieved at approximately 12% below the rated input. The input rate for all of the gases tested increased as the heating value increased with the highest input rate occurring during Gas 3 (301,129 Btu/hr). The highest gas flow value measured was during the 5th run of Baseline Gas with a value of 267 scfh.

For all runs, with the exception of the 5th Baseline Gas run and the Gas 5A run, the supply pressure was well within the limits set by the test protocol (8.0 ± 0.3" w.c.) despite the steam boiler shutting off twice during the Gas 3 run and once during the Gas 4 run. The manifold pressure remained within the limits set by the protocol (2.7 ± 0.27" w.c.) for all gases despite supply pressure drops during the 5th Baseline Gas run and the Gas 5A run.



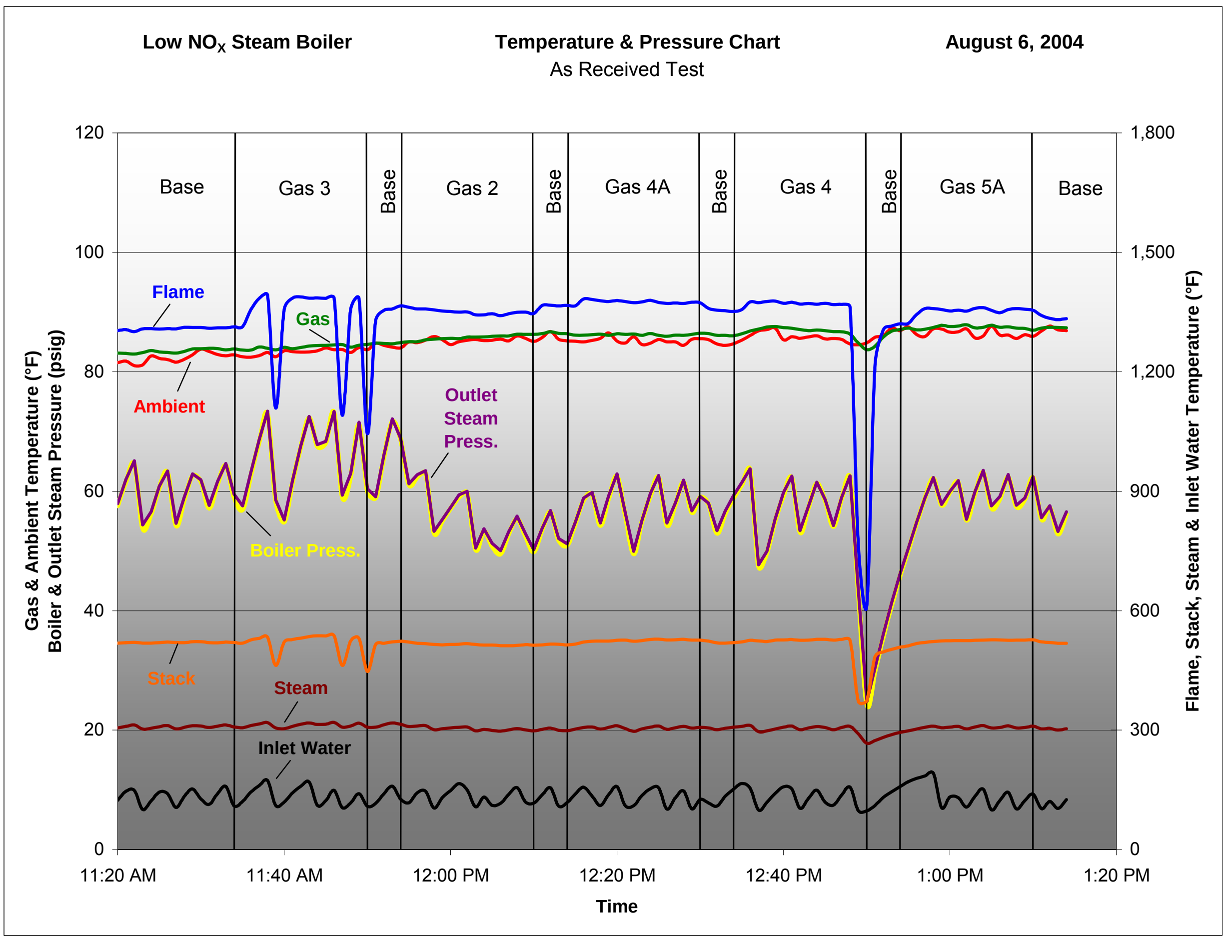
[1] All emissions, temperature and input values mentioned throughout the results section are average values.
[2] CO, HC & NO_X emissions values are corrected to 3% O_2.

Temperature

The highest flame temperature was achieved with Gas 3 at 1,386°F, followed by Gas 4A (1,375°F) and Gas 4 (1,372°F) – the three highest heating value and Wobbe number valued gases tested on this day. The flame temperature averages for Baseline Gas varied from 1,367°F (3rd run) to 1,309°F (1st run) throughout the test period. Although the flame temperature, as measured with a fixed thermocouple tip, fluctuated when different test gases were introduced. Some of the temperature fluctuations were due to the changes of flame height and shape with respect to the thermocouple tip, which was not moved during the series of tests. The thermocouple tip was installed, during the instrumentation set up, in the secondary cone of the flame when the equipment was operating with Baseline Gas.

Stack temperature was highest with Gas 3 (534°F), followed by Gas 4 (526°F) and Gas 4A (525°F). Baseline Gas stack temperatures ranged from 508°F (5th run) to 520°F (1st run) and Gas 2 had a stack temperature of 515°F.

The ambient temperature rose gradually throughout the test day ranging between 83°F (Baseline Gas: 1st run) and 87°F (Baseline Gas: 6th run). However, combustion air temperatures may have been higher due to radiation and convective heat transfer to the air manifold duct from the steam boiler itself and exposure to the sun.

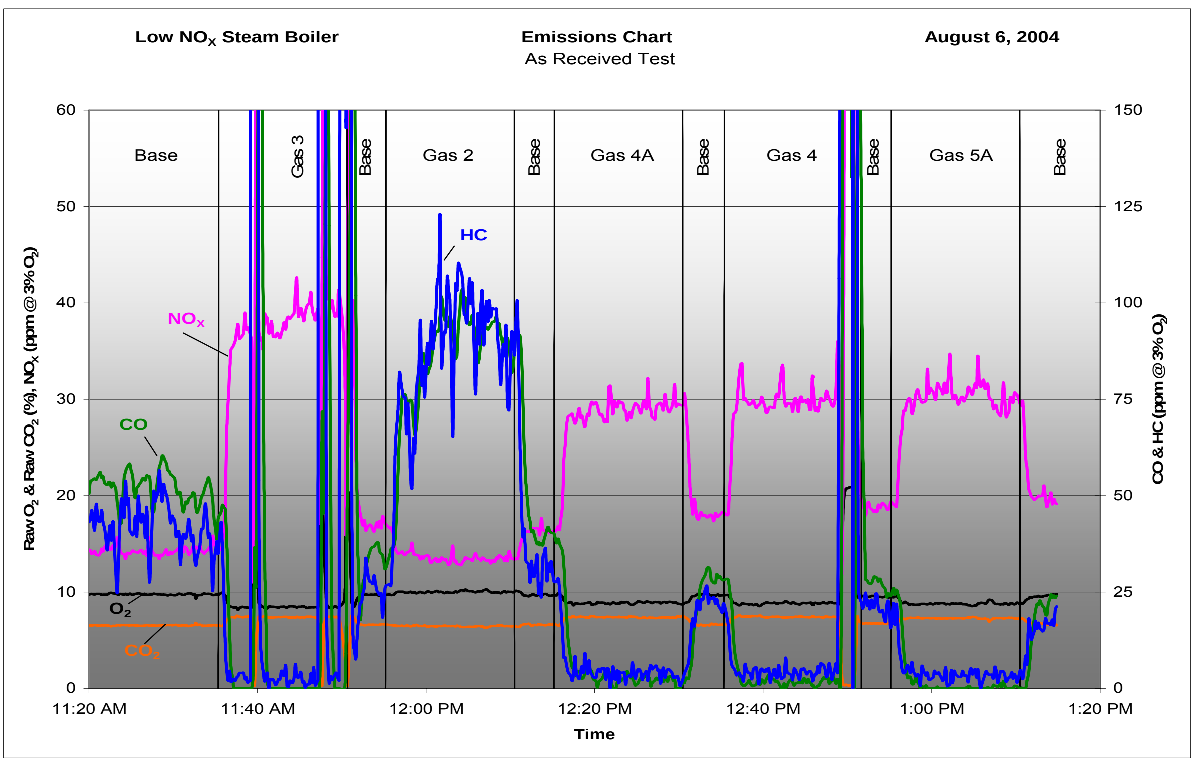


Emissions

NO_X emissions values did not exceed 38 ppm and CO emissions values did not exceed 89 ppm for all gases tested. The highest NO_X emissions value was observed with Gas 3 (38 ppm) while NO_X emissions values for Gas 4, 4A and 5A were between 29 and 30 ppm. Baseline Gas and Gas 2 achieved the lowest NO_X emissions values with all runs achieving lower than 20 ppm.

Conversely, the highest CO emissions values were observed with Baseline Gas and Gas 2. Baseline Gas averaged values between 22 ppm (6th run) amd 52 ppm (1st run). Gas 2 had the highest CO value of 89 ppm. For Gas 3, 4, 4A and 5A, the CO values did not exceed 3 ppm. Also, HC emissions followed the same patterns as CO emissions. The differences from the results with Gas 4 and 4A (4 component mix) were insignificant and inconsistent to draw any conclusions.

In the case of Gas 3, the steam boiler shut off twice (once in the middle of the run and again at the end of the run) when the interior steam pressure reached 70 psig or above. Due to this circumstance, the average emissions results for Gas 3 were not stable, but did return to the same range of values after shut off. Boiler shut off also occurred during the Gas 4 run due to insufficient gas supply, however, steady state conditions for all emissions values were still achieved.



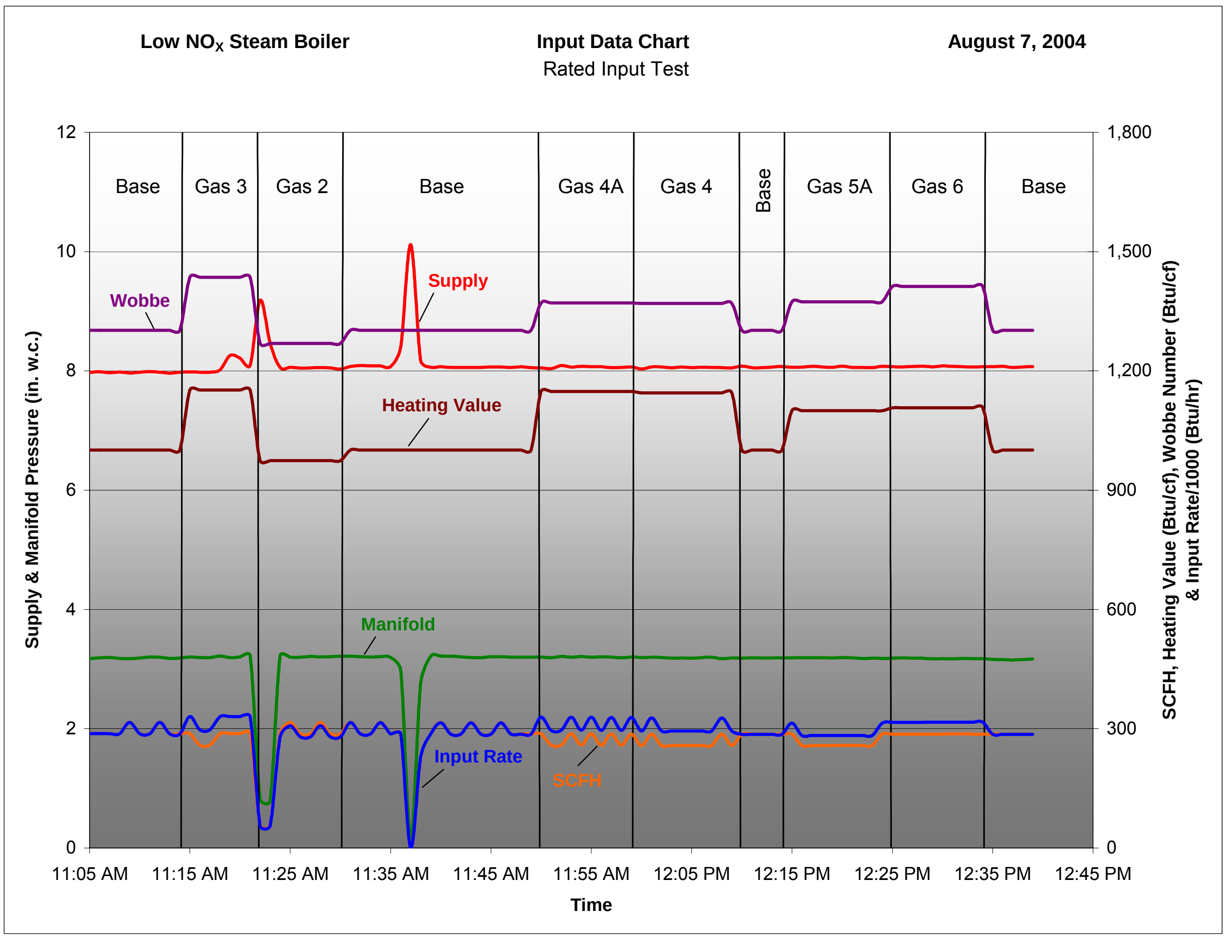
NOTE: Emission test results are for information purposes. They were not the result of certified tests.

Rated Input Test

Input

The 1st Baseline Gas run (293,743 Btu/hr) operated at 2.4% below the rated input. During runs with high-heat content gases, the boiler was over fired with Gas 4A (3.98%), Gas 6 (5.33%) and Gas 3 (6.89%) but under fired while operating on Gas 5A (3.72%). Although the ± 2% range requirment only applied to runs with Baseline Gas, Gas 4 was the only high-heat content gas to remain within this range with an input rate of 301,662 Btu/hr. For Baseline Gas, the 2nd run (295,709 Btu/hr) stayed within the ± 2% range, but the 3rd and 4th runs fell below the 2% limit.

Aside from the changes in manifold pressure due to boiler shut off during the end of the Gas 3 run and the middle of the 2nd Baseline Gas run, both the manifold and supply pressures were stable and within the parameters set in the test protocol.

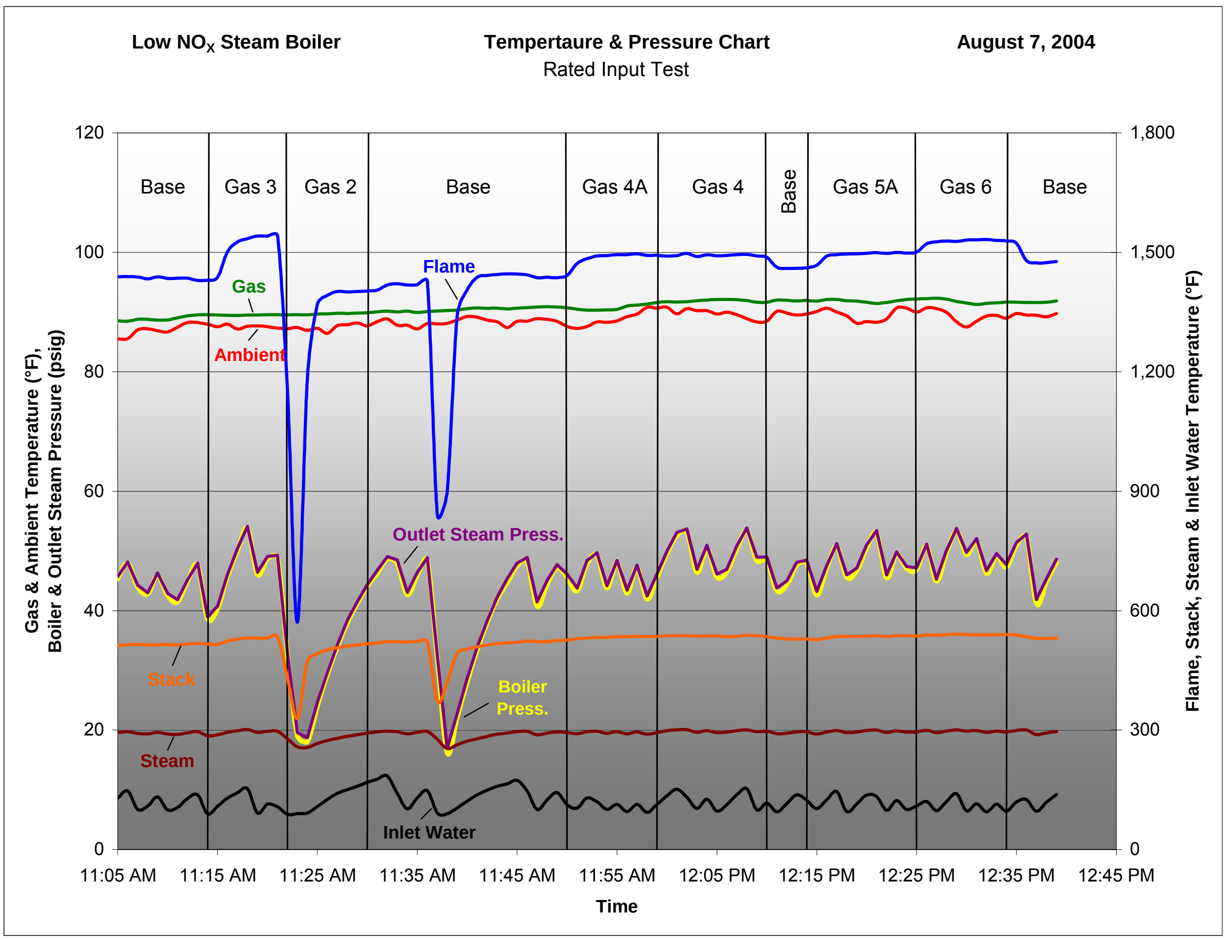


Temperature

For all gases tested, Gas 3 had the highest flame temperature average at 1,537°F, followed by Gas 6 (1,530°F) and Gas 5A (1,497°F). Baseline Gas flame temperatures ranged from 1,434°F (2nd run) to 1,476°F (4th run) and the lowest flame temperature occurred with Gas 2 (1,400°F). Although the flame temperature, as measured with a fixed thermocouple tip, fluctuated when different test gases were introduced. Some of the temperature fluctuations were due to the changes of flame height and shape with respect to the thermocouple tip, which was not moved during the series of tests. The thermocouple tip was installed, during the instrumentation set up, in the secondary cone of the flame when the equipment was operating with Baseline Gas.

Stack temperature was highest with Gas 6 (540°F), followed by Gas 4 (537°F) and Gas 5A (536°F). Baseline Gas stack temperatures ranged from 515°F (1st run) to 532°F (4th run) while Gas 2 had the lowest stack temperature at 510°F.

The ambient temperature rose gradually throughout the test day ranging between 87°F (Baseline Gas: 1st run) and 90°F (Gas 4). However, combustion air temperatures may have been higher due to radiation and convective heat transfer to the air manifold duct from the steam boiler itself and exposure to the sun.

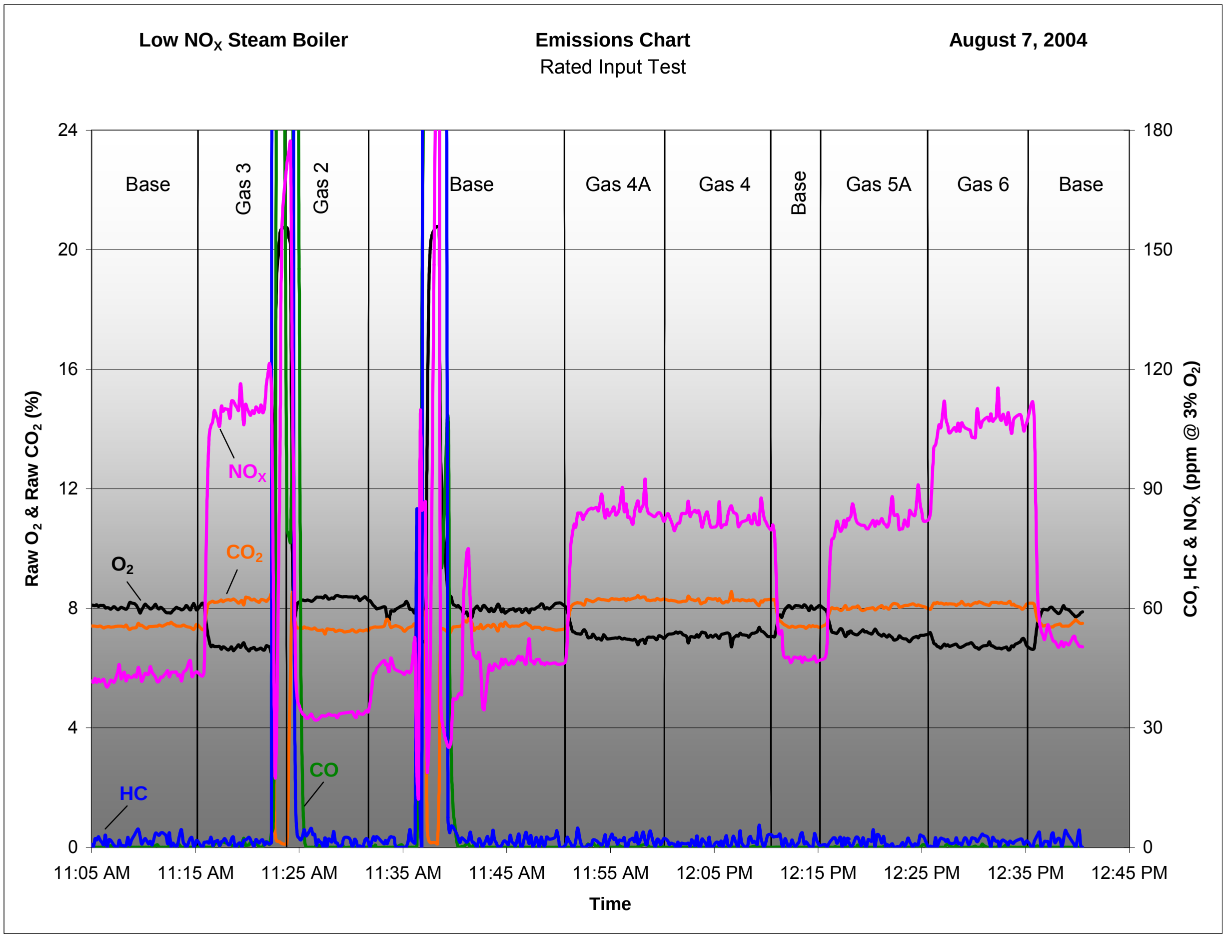


Emissions

The highest NO_X value was observed with Gas 3 (110 ppm) followed by Gas 6 (107 ppm), Gas 4A (84 ppm), Gas 4 (83 ppm) and Gas 5A (82 ppm). Baseline Gas NO_X values ranged between 43 ppm (1st run) and 52 ppm (4th run) while the lowest value for all runs occurred during Gas 2 (33 ppm).

CO emissions values did not exceed 1 ppm for all gases tested and HC emissions followed the same patterns as CO emissions.

During the test, the steam boiler shut off during the end of the Gas 3 run and in the middle of the 2nd Baseline Gas run. Emissions values for both gases were not compromised and the boiler was able to achieve steady state conditions during both runs.



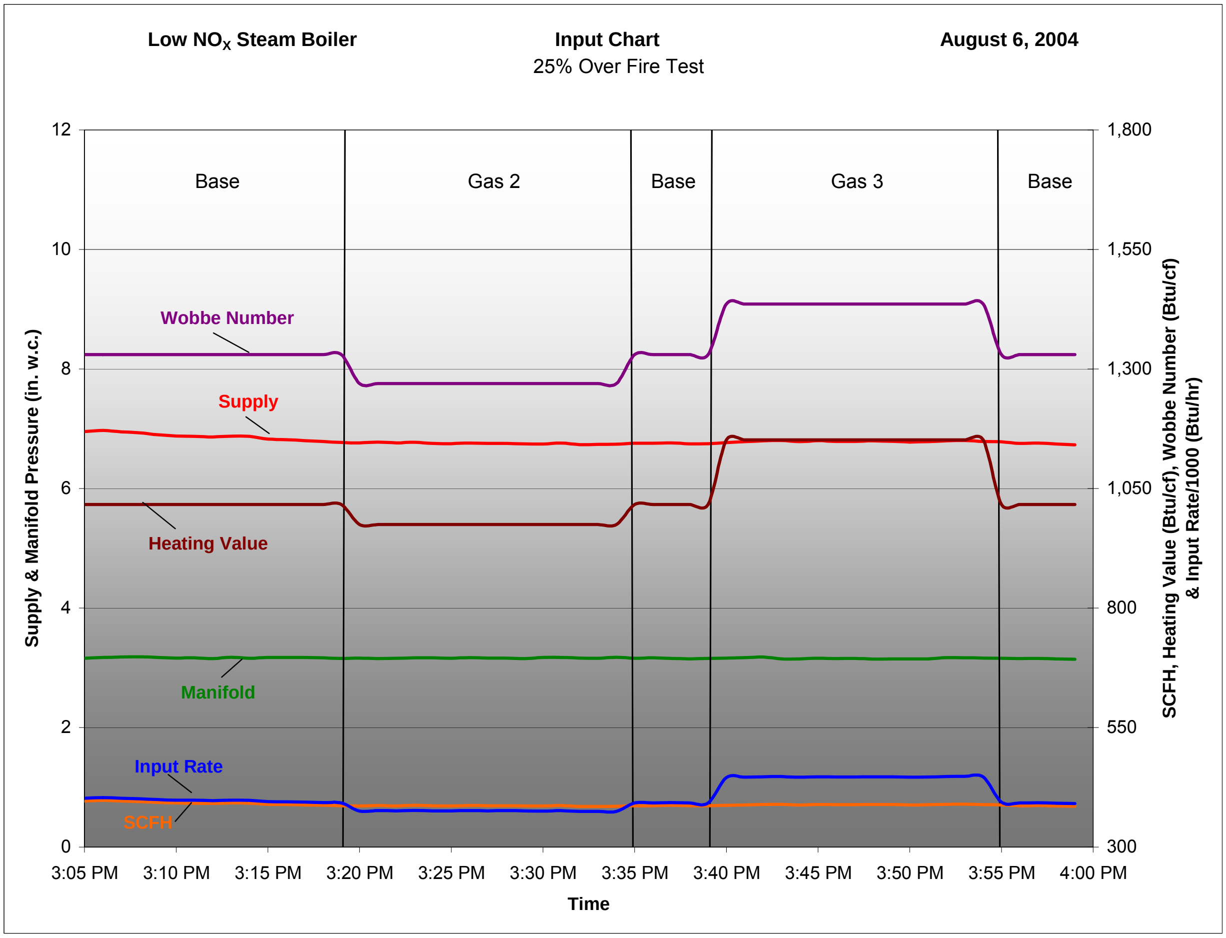
NOTE: Emission test results are for information purposes. They were not the result of certified tests.

25% Over Fire Test

Input

During the 1st Baseline Gas run, the steam boiler was over fired by approximately 32.4%. Gas 3 (447,607 Btu/hr) was over-fired at 48.7% while the 2nd and 3rd Baseline Gas runs were over fired by approximately 30.6%. Although the ± 2% range requirment only applied to runs with Baseline Gas, Gas 2 was the only gas to remain within this range with an input rate of 376,325 Btu/hr (25.02% over fired).

Both the manifold and supply pressures were stable throughout the test and the gas flow was highest for the 1st Baseline Gas run (392 scfh).

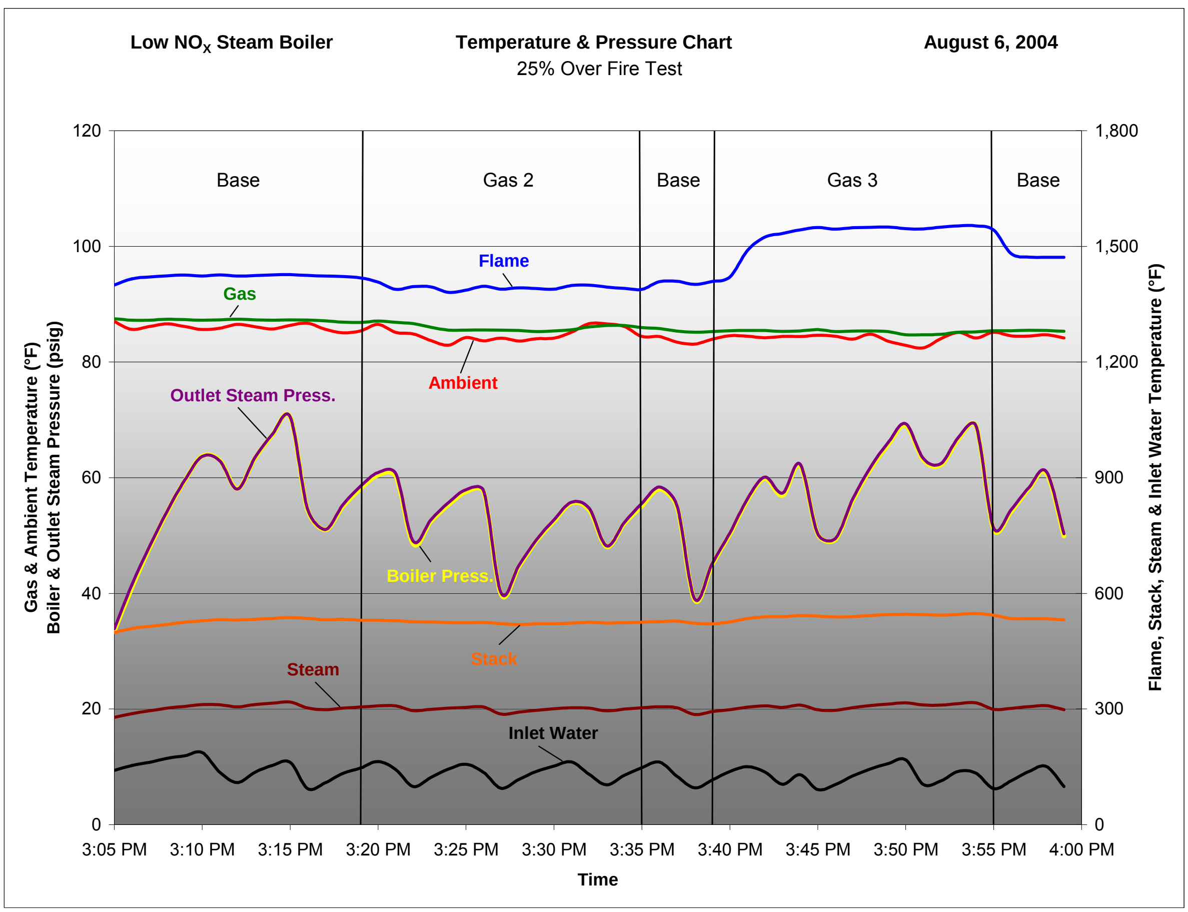


Temperature

For all gases tested, flame and stack temperatures increased with increasing heating value. Gas 3 had the highest flame temperature average at 1,548°F. Baseline Gas flame temperatures ranged from 1,407°F (2nd run) to 1,472°F (3rd run) and the lowest flame temperature occurred with Gas 2 (1,392°F). Although the flame temperature, as measured with a fixed thermocouple tip, fluctuated when different test gases were introduced. Some of the temperature fluctuations were due to the changes of flame height and shape with respect to the thermocouple tip, which was not moved during the series of tests. The thermocouple tip was installed, during the instrumentation set up, in the secondary cone of the flame when the equipment was operating with Baseline Gas.

Stack temperature was highest with Gas 3 (541°F), followed by the 3rd Baseline Gas run (535°F) and the 1st Baseline Gas run (526°F). Gas 2 had the lowest stack temperature at 524°F.

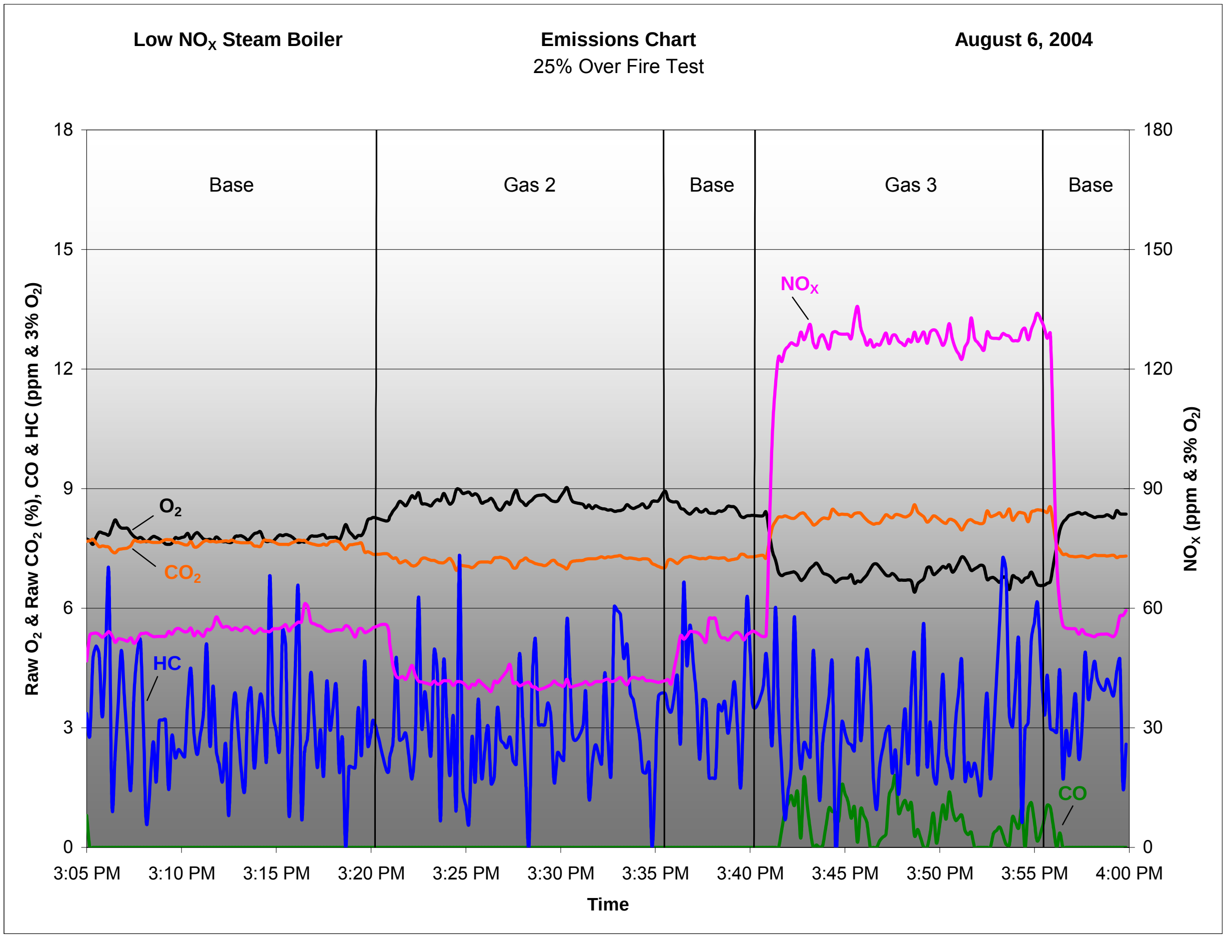
The ambient temperature decreased gradually throughout the test day ranging from 84°F (Baseline Gas: 2nd run) to 86°F (Baseline Gas: 1st run). However, combustion air temperatures may have been higher due to radiation and convective heat transfer to the air manifold duct from the steam boiler.



Emissions

The NO_X emissions value for Gas 3 was highest with a value of 128 ppm. NO_X emissions values for all Baseline Gas runs fell within the 54 ± 1 ppm range while the lowest NO_X emissions value for all runs occurred during Gas 2 (42 ppm).

CO emissions values did not exceed 1 ppm for all gases tested and HC emissions varied for all runs, but never rose above 4 ppm.



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

Cold Ignition Test

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

Cold Ignition Test			
Gas	**Ignition**	**Start-Up #**	**Comments & Observations**
3	Normal and without delays	1	Crossover tube smoothly carried flame to second burner
		2	Crossover tube smoothly carried flame to second burner
		3	Crossover tube smoothly carried flame to second burner
2	Normal and without delays	1	Crossover tube smoothly carried flame to second burner
		2	Crossover tube smoothly carried flame to second burner
		3	Crossover tube smoothly carried flame to second burner

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**
3	Normal and without delays	1	Crossover tube smoothly carried flame to second burner
		2	Crossover tube smoothly carried flame to second burner
		3	Crossover tube smoothly carried flame to second burner
2	Normal and without delays	1	Crossover tube smoothly carried flame to second burner
		2	Crossover tube smoothly carried flame to second burner
		3	Crossover tube smoothly carried flame to second burner

Appendix A: Test Protocol

1. 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.

2. Boiler Data

- **Description:** 7 HP Low NO_X Steam Boiler
- **Burner:** Surface premix power burner operating on blue flame mode
- **Maximum input rating:** ~301,000 BTU/hr
- **Minimum input rating:** ~150,000 BTU/hr
- **Type of fuel:** natural gas
- **Required gas supply pressure:** 7” w.c. – 14” w.c.

3. Test Arrangement

3.1. **Basic setup**

The boiler is to be tested outdoors on a paved parking lot. Fuel gas, electrical power, and water are to be provided at rates and conditions according to manufacturer specifications. Combustion products are to be sampled in a vent stack constructed permission measurement standards.

3.2. **Water flow and piping**

Provide water at the flow rate and temperature as close as possible to those required by the test standards and manufacturer specifications. If necessary, provide a supply water pump and valves necessary to adjust water flow rate and temperatures. Maintain water pressure at a level sufficient to assure proper boiler operation.

3.3. **Vent pipe**
The existing vent pipe was used because it meets AQMD requirements for outdoor testing requirements. For all testing, a straight vertical vent pipe, at least three feet in length and of the diameter of the boiler vent collar, is to be provided. Provide an integrated sampling probe, constructed per the AQMD protocol, six inches from the top of the vent pipe. Provide a three-point thermocouple grid, wired as a thermopile. The following is a description of the vent pipe and instruments:

Diameter of vent pipe: 8 inch

Length of vent pipe: 3 ft – 6 in

Material of vent pipe: Sheet metal

Three thermocouples location: 1 ft – 6 in below top

Emission probe location: 6 in from the top

3.4. **Fuel gas**
Fuel gases are to be provided at the pressures required by test methods specified later in this protocol. Pressure is to be measured at the inlet pressure tap of the boiler gas control.

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**
In addition to data required for firing rate calculation, provide thermocouples in inlet and outlet steam piping as prescribed in Figure #8 of the SCAQMD protocol, as close to the boiler as possible. Also provide a thermocouple for measurement of the ambient temperature. This instrument 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. Provide thermocouples in other locations as appropriate to record possible effects of gas blend changes. If possible, seek assistance from the manufacturer selecting locations.

3.8. **Special measures** – Windows & camera access
Windows or openings for viewing the flame are to be provided to the extent that they will provide useful information and not affect boiler operation.

4. **Test Gases**
The following gases have been specifically formulated to cover the range of gas compositions 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.
   - **Baseline Gas** (Gas 1) – Low Wobbe (1,302 Btu/cf), low heat content gas (1,001 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 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)

5. **Basic Operating Condition**
Unless required otherwise by specific test requirements, the following are to apply:

5.1. **Ambient temperature -** Hold between 75°F and 85°F and measured as specified in Sections 7.4.1.6 & 7.1.6 of the AQMD Protocol.

5.2. **Gas supply pressure -** 8.0 ± 0.3" w.c. (Measured during steady operation).

5.3. **Basic firing setup**
The basic firing setup is to be that the combination of gas valve and manifold pressure required delivering rated input with the baseline gas. Manifold pressure is to be within ± 10% of that specified on the rating plate. With gases other than the baseline gas the firing rate generally will *not* be at rated input.

5.4. **Steam flow, temperature and pressure**
Set steam pressure as high as possible while maintaining steady state conditions. This results in a steam pressure set to approximately 50 psig.

6. **Testing – Startup Run (As Found)**

Operate boiler on Baseline Gas as found – i.e. with gas orifices in the boiler and manifold pressure as set by manufacturer. After starting, record firing rate data, O_2, NO_X, CO, CO_2 and HC. Also record room ambient temperature, water temperatures and stack temperature. (Note: If it is evident that manufacturing oils, insulation binder, etc. are not totally driven off at 15 minutes, delay data acquisition until "break-in" is complete. After break-in allow unit to cool one-half hour with water flowing through the heat exchanger, and re-start to obtain the as found data.)
At the end of the break-in, experiment with the boiler gas and water temperature controls to determine what procedures should be used to start and operate the boiler at maximum firing rates.

6.1. **Gas changeover and steady operation with substitute gases**
Verify proper operation of all equipment and instrumentation. Continue steady boiler operation with baseline gas and conduct a high-speed switch to the substitute gas. Record data before, during and after changeover and observe transient phenomena. Possible phenomena include flame color change, flame lifting, flashback or rollout, pilot burner instability or outage, etc. (Note that the firing rate is not to be adjusted and that boiler controls must not be allowed to adjust firing rate in response to a water temperature change).

When steady state is achieved record all operating data including firing rate, stack temperature, and other temperatures per section 7.2.1.1. Continue operation and determine NO_X emission per the AQMD protocol. During the testing, observe flames and note yellow tipping and flame lifting or flashback phenomena or lack of the same.

With the boiler continuing to operate at steady state on the substitute gas, conduct a high-speed switch to the baseline gas and record observations and data per above. Continue testing by reestablishing steady state conditions with Baseline gas and repeat the test sequence for each of the remaining substitute gas blends.

When testing has been conducted with all gases, shut down boiler and examine flue collector and vent connection area for presence of soot by means of the swab technique specified in section 7.0. If soot is found, clean surfaces and repeat testing with suspect gas blend(s), selected on the basis of earlier yellow tipping observations. Establish which gas(es) tends to burn with soot deposition.

7. **Steady operation testing at 25% over rated input**

Adjust boiler to operate at 25% over rated input by adjusting manifold pressure. From a cold start, record input and combustion data (O_2, NO_X, CO, CO_2 and HC) and verify that the firing rate is over 25% of rated input after 15 minutes.

During the testing, observe flames and note yellow tipping and flame lifting or flashback phenomena or lack of the same. Record these observations. If significant yellow tipping was observed, inspect flue collector and vent connection area and swab with a white cloth to determine if soot has been deposited. If soot is present, remove it prior to continuation of testing.

7.1. **Gas changeover and steady operation with substitute gases**
Continue steady boiler operation with Baseline Gas and conduct a high-speed switch to Gas 2. Record data before, during and after changeover and observe transient phenomena. Possible phenomena include flame color change, flame lifting, flashback or rollout, pilot burner instability or outage, etc. (Note that the firing rate is not to be adjusted and that boiler controls must not be allowed to adjust firing rate in response to a water temperature change.)

When steady state is achieved, record all operating data including firing rate, stack temperature, and other temperatures per section 7.2.1.1. Continue operation and determine NO_X emission per the AQMD protocol.

During the testing, observe flames and note yellow tipping and flame lifting or flashback phenomena or lack of the same.

With the boiler continuing to operate at steady state on the substitute gas, conduct a high-speed switch to Baseline gas and record observations and data per above.

Continue testing by reestablishing steady state conditions with the baseline gas and repeat the test sequence for Gas 3 and all the other gases.

When testing has been conducted with all gases, shut down boiler and examine flue collector and vent connection area for presence of soot by means of the swab technique specified in section 7.1. If soot is found, clean surfaces and repeat testing with suspect gas blend(s), selected on the basis of earlier yellow tipping observations. Establish which gas(es) tends to burn with soot deposition.

7.2 **Steady operation tests – baseline and substitute gases**

7.2.1 Rated input

7.2.1.1 Steady operation with baseline gas

Starting with Baseline Gas, operate boiler at the basic operating condition. Verify that firing rate is at ± 2% of rated input at 15 minutes and record combustion data.

Continue operation to establish stack temperature changes by no more than ± 5°F in 15 minutes and that inlet and outlet water temperatures remain within acceptable limits. Record stack temperature and that of other components identified in Section 3.7 proceeding.

Continue operation and record NO_X emission data as required by the AQMD Protocol.

During the testing, observe flames and note yellow tipping and flame lifting or flashback phenomena or lack of the same.

7.2.1.2 Gas changeover and steady operation with substitute gases

Continue steady boiler operation with Baseline Gas and conduct a high-speed switch to Gas 2, 3, 4, 4A and 5A. Record data before, during and after changeover and observe transient phenomena. Possible phenomena include flame color change, flame lifting, flashback or rollout, pilot burner instability or outage, etc. (Note that the firing rate is not to be adjusted and that boiler controls must not be allowed to adjust firing rate in response to a water temperature change.)

When steady state is achieved, record all operating data including firing rate, stack temperature, and other temperatures per section 8.2.1.1. Continue operation and determine NO_X emission per the AQMD protocol.

During the testing, observe flames and note yellow tipping and flame lifting or flashback phenomena or lack of the same.

With the boiler continuing to operate at steady state on the substitute gases, conduct a high-speed switch to the Baseline Gas and record observations and data per above.

Continue testing by reestablishing steady state conditions with the baseline gas and repeat the test sequence for each of the remaining substitute gas blends.

When testing has been conducted with all gases, shut down boiler and examine flue collector and vent connection area for presence of soot by means of the swab technique specified in section 7.1. If soot is found, clean surfaces and repeat testing with suspect gas blend(s), selected on the basis of earlier yellow tipping observations. Establish which gas(es) tends to burn with soot deposition.

8. Ignition Tests

8.1 Cold Ignition

Using Baseline Gas, the manifold pressure was adjusted for a rated input of 301,000 Btu/hr ± 2%. Purge the gas delivery system of Baseline Gas with Gas 3. Using Gas 3, ignite the water heater from a cold start for one minute. Document visual observations of the flame, ignition delays and any other phenomena observed. Repeat this process 2 more times, allowing the boiler to reestablish cold start conditions in between each ignition.

Purge the gas delivery system of Gas 3 with Gas 2. Using Gas 2, ignite the water heater from a cold start for one minute. Document visual observations of the flame, ignition delays and any other phenomena observed. Repeat this process 2 more times, allowing the boiler to reestablish cold start conditions in between each ignition.

8.2 Hot Ignition

Using Baseline Gas, the manifold pressure was adjusted for a rated input of 301,000 Btu/hr ± 2%. Purge the gas delivery system of Baseline Gas with Gas 3. Using Gas 3, ignite the water heater for one minute. Document visual observations of the flame, ignition delays and any other phenomena observed. Repeat this process 2 more times.

Purge the gas delivery system of Gas 3 with Gas 2. Using Gas 2, ignite the water heater for one minute. Document visual observations of the flame, ignition delays and any other phenomena observed. Repeat this process 2 more times.

9. 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.

10. 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.

11. Calculations

CO, HC & NO_X emissions (ppm, Corrected to 3% O_2) are to be calculated per the AQMD protocol for Rule 1146.2.

12. Measurements

The following test measurements will be taken:

- Ambient temperature
- Flame temperature
- Exhaust temperature
- Steam temperature
- Inlet water temperature
- Gas flow rate
- Boiler interior steam pressure
- Boiler steam supply pressure
- Boiler manifold pressure
- Natural gas temperature before cooling coil
- Natural gas pressure before cooling coil
- Natural gas temperature after cooling coil
- Natural gas temperature at gas meter

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.

Appendix B: Table of Averages

As Found

Table of Averages Low NO_X Steam Boiler As Received Test August 6, 2004											
Gases	**Base**	**3**	**Base**	**2**	**Base**	**4A**	**Base**	**4**	**Base**	**5A**	**Base**
HHV (Btu/cf)	1,001	1,152	1,001	974	1,001	1,148	1,001	1,145	1,001	1,100	1,001
Wobbe (Btu/cf)	1,302	1,436	1,302	1,269	1,302	1,371	1,302	1,370	1,302	1,374	1,302
Input Rate (Btu/hr)	261,987	301,129	261,310	253,985	260,502	285,831	260,592	282,562	267,300	280,775	265,788
Corrected SCFH	261.8	261.5	261.1	260.7	260.3	248.9	260.4	246.8	267.1	255.3	265.6
Emissions (not from certified tests)											
Raw O_2 (%)	9.8	8.5	9.5	10.0	9.7	8.9	9.7	8.8	9.5	8.8	9.6
Raw CO_2 (%)	6.5	7.4	6.7	6.5	6.6	7.4	6.6	7.4	6.7	7.3	6.7
CO (ppm @ 3% O_2)	51.9	0.0	32.5	88.5	40.0	2.6	28.8	1.5	27.0	0.4	21.8
HC (ppm @ 3% O_2)	41.9	2.6	26.0	88.7	30.7	4.0	22.5	4.1	21.3	3.4	16.5
NO_X (ppm @ 3% O_2)	14.4	38.0	17.3	13.6	16.4	29.0	18.0	30.2	18.8	30.4	19.8
Ultimate CO_2 (%)	12.3	12.4	12.3	12.4	12.3	12.8	12.3	12.8	12.4	12.6	12.3
Equivalence Ratio (Φ)	0.56	0.62	0.57	0.55	0.56	0.60	0.56	0.60	0.57	0.61	0.57
Temperatures (°F)											
Ambient	82.3	83.3	84.2	85.3	85.6	85.2	84.9	85.8	86.2	86.5	86.9
Gas	83.5	84.1	84.7	85.7	86.4	86.2	86.2	86.8	85.5	87.5	87.3
Inlet Water	131.2	136.6	130.2	132.4	127.5	132.3	127.7	135.4	128.5	138.7	118.6
Stack	520.1	533.9	519.6	514.9	515.3	525.4	519.3	525.8	507.7	525.4	519.5
Steam	308.3	316.9	313.6	304.0	301.3	305.6	305.2	305.5	293.6	307.6	303.0
Flame	1,309	1,386	1,352	1,350	1,367	1,375	1,355	1,372	1,319	1,356	1,333
Pressures											
Supply (in. w.c.)	8.1	8.2	8.1	8.1	8.1	8.1	8.1	8.1	**7.1**	**6.9**	8.0
Manifold (in. w.c.)	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Interior Boiler (psig)	59.7	66.1	66.2	55.7	52.5	57.3	57.0	57.4	38.0	58.4	56.8
Outlet Steam (psig)	60.1	66.5	66.5	56.0	52.8	57.7	57.3	57.7	38.5	58.7	57.1

At Rated Input

Table of Averages Low NO_X Steam Boiler Rated Input Test August 7, 2004										
Gases	**Base**	**3**	**2**	**Base**	**4A**	**4**	**Base**	**5A**	**6**	**Base**
HHV (Btu/cf)	1,001	1,152	974	1,001	1,148	1,145	1,001	1,100	1,107	1,001
Wobbe (Btu/cf)	1,302	1,436	1,269	1,302	1,371	1,370	1,302	1,374	1,413	1,302
Input Rate (Btu/hr)	293,743	321,740	288,064	295,709	313,004	301,662	286,526	289,786	317,046	286,633
Corrected SCFH	293.5	279.4	295.6	295.5	272.6	263.5	286.3	263.5	286.4	286.4
Emissions (not from certified tests)										
Raw O_2 (%)	8.0	6.7	8.3	8.0	7.0	7.1	8.0	7.1	6.7	7.9
Raw CO_2 (%)	7.4	8.3	7.3	7.4	8.3	8.3	7.4	8.0	8.1	7.5
CO (ppm @ 3% O_2)	0.1	0.8	0.1	0.1	0.2	0.0	0.0	0.0	0.1	0.0
HC (ppm @ 3% O_2)	1.7	1.3	1.8	1.7	1.6	1.2	1.2	1.4	1.6	1.8
NO_X (ppm @ 3% O_2)	43.0	109.7	33.3	45.7	84.4	82.6	47.2	82.1	106.7	51.9
Ultimate CO_2 (%)	12.0	12.1	12.1	12.0	12.5	12.5	12.0	12.2	12.0	12.0
Equivalence Ratio (Φ)	0.64	0.70	0.63	0.64	0.69	0.68	0.64	0.68	0.70	0.65
Temperatures (°F)										
Ambient	87.1	87.6	87.4	88.4	88.8	89.8	89.5	89.5	89.3	89.5
Gas	88.9	89.5	89.7	90.4	90.8	91.9	91.9	91.9	91.8	91.7
Inlet Water	118.0	121.1	125.0	136.5	109.8	124.7	117.8	117.8	110.8	120.0
Stack	515.0	530.0	510.0	521.1	532.9	536.6	530.6	536.1	539.7	531.5
Steam	292.2	297.3	284.0	293.4	293.7	297.9	294.5	296.9	297.4	294.8
Flame	1,435	1,537	1,400	1,434	1,493	1,493	1,461	1,497	1,530	1,476
Pressures										
Supply (in. w.c.)	8.0	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1
Manifold (in. w.c.)	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Interior Boiler (psig)	44.1	47.7	35.1	40.2	45.5	49.6	46.3	47.8	48.9	47.5
Outlet Steam (psig)	44.4	48.0	35.5	40.8	46.0	50.1	46.9	48.3	49.3	48.0

25% Over-Fired

Table of Averages Low NO_X Steam Boiler 25% Over Fire Test August 6, 2004					
Gases	**Base**	**2**	**Base**	**3**	**Base**
HHV (Btu/cf)	1,017	974	1,017	1,152	1,017
Wobbe (Btu/cf)	1,330	1,269	1,330	1,436	1,330
Input Rate (Btu/hr)	398,455	376,325	393,047	447,607	392,972
Corrected SCFH	391.9	386.2	386.6	388.7	386.5
Emissions (not from certified tests)					
Raw O_2 (%)	7.8	8.7	8.4	6.8	8.3
Raw CO_2 (%)	7.6	7.2	7.3	8.3	7.3
CO (ppm @ 3% O_2)	0.0	0.0	0.0	0.6	0.0
HC (ppm @ 3% O_2)	3.1	3.0	3.7	3.0	3.6
NO_X (ppm @ 3% O_2)	54.3	41.5	53.7	127.8	54.6
Ultimate CO_2 (%)	12.2	12.3	12.2	12.3	12.2
Equivalence Ratio (Φ)	0.65	0.61	0.62	0.69	0.64
Temperatures (°F)					
Ambient	86.0	84.8	83.9	84.1	84.6
Gas	87.2	85.9	85.5	85.2	85.4
Inlet Water	144.8	132.7	129.2	129.4	119.0
Stack	526.1	524.0	524.5	541.0	535.4
Steam	303.4	299.9	298.2	307.4	302.7
Flame	1,422	1,392	1,407	1,548	1,472
Pressures					
Supply (in. w.c.)	6.9	6.8	6.8	6.8	6.8
Manifold (in. w.c.)	3.2	3.2	3.2	3.2	3.2
Interior Boiler (psig)	56.0	52.5	50.4	59.9	54.8
Outlet Steam (psig)	56.2	52.8	50.7	60.1	55.1

Appendix C: Test Gases

Gas Sample Date	Baseline 8/4/04	2 8/5/04	3 7/27/04	4 8/5/04	4A 7/27/04	5A 7/19/04	6 8/7/04
COMPONENTS	**MolPct**	**MolPct**	**MolPct**	**MolPct**	**MolPct**	**MolPct**	**MolPct**
C6 + 57/28/14	0.0200	0.0307	0.0297	0.1858	0.0406	0.0435	0.0000
NITROGEN	1.9100	1.0866	0.0609	1.0608	1.0782	0.7777	0.0000
METHANE	94.3900	95.8713	86.7978	84.9713	84.3951	90.8094	91.6800
CARBON DIOXIDE	1.2400	2.9973	0.0000	3.0005	3.0516	1.4130	0.0000
ETHANE	1.6600	0.0000	9.3416	4.7846	0.0220	0.0230	5.5300
PROPANE	0.3100	0.0141	2.7663	2.4015	11.3998	6.9175	1.7500
i-BUTANE	0.0600	0.0000	1.0037	1.1936	0.0094	0.0113	0.5200
n-BUTANE	0.0500	0.0000	0.0000	1.2074	0.0033	0.0046	0.5200
NEOPENTANE	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
i-PENTANE	0.0200	0.0000	0.0000	0.5944	0.0000	0.0000	0.0000
n-PENTANE	0.0100	0.0000	0.0000	0.6001	0.0000	0.0000	0.0000
OXYGEN	0.3300	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOTAL	**100.0000**	**100.0000**	**100.0000**	**100.0000**	**100.0000**	**100.0000**	**100.0000**
Compressibility Factor	0.9980	0.9980	0.9972	0.9969	0.9969	0.9974	0.9975
HHV (Btu/real cubic foot)	**1000.66**	**974.40**	**1151.62**	**1145.13**	**1148.33**	**1099.82**	**1107.06**
LHV (Btu/real cubic foot)	901.62	877.27	1041.31	1035.92	1039.51	993.61	999.82
Specific Gravity	0.5906	0.5895	0.6434	0.6989	0.7018	0.6410	0.6143
Wobbe Number	**1302.13**	**1269.12**	**1435.73**	**1369.72**	**1370.73**	**1373.72**	**1412.47**

Appendix D: Zero, Span and Linearity Tables

August 6, 2004 (As Received & 25% Over Fire Tests)

	Zero, Span & Linearity Data Low NO_X Steam Boiler August 6, 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 - 10:39:56 AM	0.22	0.15	-0.03	0.38	0.00
Zero	Zero Drift Check - 1:32:54 PM	0.21	0.25	-1.27	0.84	2.31
Zero	**Total Drift Over Test Period**	**0.01**	**0.10**	**1.24**	**0.46**	**2.31**
Zero	**Was the Zero Drift Within Allowable Deviation?**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Span	**Span Calibration Gas (High-Range Values)**	**20.90**	**12.20**	**182.40**	**434.00**	**42.86**
Span	**Allowable Span Drift (Less Than ± 3% of Range)**	**0.75**	**0.60**	**6.00**	**30.00**	**3.00**
Span	Span Calibration - 10:50:40 AM	20.94	12.19	181.51	432.24	43.01
Span	Span Drift Check - 1:25:05 PM (**CO:** 1:55:01 PM)	21.43	12.27	182.59	425.32	43.84
Span	**Total Drift Over Test Period**	**0.49**	**0.08**	**1.08**	**6.92**	**0.83**
Span	**Was the Span Drift Within Allowable Deviation?**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Linearity	**Linearity Calibration Gas (Mid-Range Values)**	**9.03**	**8.00**	**79.50**	**217.00**	**17.80**
Linearity	**Allowable Linearity Drift (Less Than ±1% of Range)**	**0.25**	**0.20**	**2.00**	**10.00**	**1.00**
Linearity	Linearity Check - 9:18:24 AM	n/a	n/a	77.91	n/a	17.53
Linearity	**Difference From Mid-Range Values**	n/a	n/a	**1.59**	**n/a**	**0.27**
Linearity	**Was the Linearity Within Allowable Deviation?**	n/a	n/a	**Yes**	**n/a**	**Yes**
Linearity	Linearity Check - 4:28:27 PM	9.22	8.01	74.42	n/a	19.07
Linearity	**Difference From Mid-Range Values**	**0.19**	**0.01**	**5.08**	**n/a**	**1.27**
Linearity	**Was the Linearity Within Allowable Deviation?**	**Yes**	**Yes**	**No**	**n/a**	**No**

August 7, 2004 (Rated Input Test)

Zero, Span & Linearity Data
Low NO_X Steam Boiler
August 7, 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 - 10:04:02 AM	0.22	0.02	-0.44	0.85	0.03
Zero	Zero Drift Check - 12:55:10 PM	0.20	0.10	-0.99	0.64	1.00
Zero	**Total Drift Over Test Period**	**0.02**	**0.08**	**0.55**	**0.21**	**0.97**
Zero	**Was the Zero Drift Within Allowable Deviation?**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Span	**Span Calibration Gas (High-Range Values)**	**20.90**	**12.20**	**182.40**	**434.00**	**42.86**
Span	**Allowable Span Drift (Less Than ± 3% of Range)**	**0.75**	**0.60**	**6.00**	**30.00**	**3.00**
Span	Span Calibration - 10:18:15 AM	20.90	12.20	181.97	437.79	42.93
Span	Span Drift Check - 12:45:00 PM	21.00	12.14	182.63	441.71	45.06
Span	**Total Drift Over Test Period**	**0.10**	**0.06**	**0.66**	**3.92**	**2.13**
Span	**Was the Span Drift Within Allowable Deviation?**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Linearity	**Linearity Calibration Gas (Mid-Range Values)**	**9.03**	**8.00**	**79.50**	**217.00**	**17.80**
Linearity	**Allowable Linearity Drift (Less Than ±1% of Range)**	**0.25**	**0.20**	**2.00**	**10.00**	**1.00**
Linearity	Linearity Check - 10:33:53 AM	9.24	7.97	74.09	n/a	18.03
Linearity	**Difference From Mid-Range Values**	**0.21**	**0.03**	**5.41**	**n/a**	**0.23**
Linearity	**Was the Linearity Within Allowable Deviation?**	**Yes**	**Yes**	**No**	**n/a**	**Yes**
Linearity	Linearity Check - 12:48:58 PM	9.22	7.88	75.30	n/a	19.07
Linearity	**Difference From Mid-Range Values**	**0.19**	**0.12**	**4.20**	**n/a**	**1.27**
Linearity	**Was the Linearity Within Allowable Deviation?**	**Yes**	**Yes**	**No**	**n/a**	**No**

Appendix E: Calculations

Emission Concentrations

Corrected to O_2 Standard (3% O_2)

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

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)	$CH_4 + 2O_2 + 2(3.78)N_2 \Longrightarrow 1CO_2 + 2H_2O + 2(3.78)N_2$	9.56	8.56
Ethane (C_2H_6)	$C_2H_6 + 3.5O_2 + 3.5(3.78)N_2 \Longrightarrow 2CO_2 + 3H_2O + 3.5(3.78)N_2$	16.73	15.23
Propane (C_3H_8)	$C_3H_8 + 5O_2 + 5(3.78)N_2 \Longrightarrow 3CO_2 + 4H_2O + 5(3.78)N_2$	23.90	21.90
i-Butane (C_4H_{10})	$C_4H_{10} + 6.5O_2 + 6.5(3.78)N_2 \Longrightarrow 4CO_2 + 5H_2O + 6.5(3.78)N_2$	31.07	28.57
n-Butane (C_4H_{10})	$C_4H_{10} + 6.5O_2 + 6.5(3.78)N_2 \Longrightarrow 4CO_2 + 5H_2O + 6.5(3.78)N_2$	31.07	28.57
i-Pentane (C_5H_{12})	$C_5H_{12} + 8O_2 + 8(3.78)N_2 \Longrightarrow 5CO_2 + 6H_2O + 8(3.78)N_2$	38.24	35.24
n-Pentane (C_5H_{12})	$C_5H_{12} + 8O_2 + 8(3.78)N_2 \Longrightarrow 5CO_2 + 6H_2O + 8(3.78)N_2$	38.24	35.24
Hexanes (C_6H_{14})	$C_6H_{14} + 9.5O_2 + 9.5(3.78)N_2 \Longrightarrow 6CO_2 + 7H_2O + 9.5(3.78)N_2$	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 DTM-325 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: DTM-325
Date: August 1, 2004
Meter Number: U655220
Prepared By: David Ceballos
5 CU. FT. BELL NO. 1922
CPUC CERTIFICATE OF BELL PROVER ACCURACY # 1008

REPEATABILITY						
CFH	**% CORR.**	**% CORR.**	**% CORR.**	**% CORR.**	**% CORR.**	**Average**
50	-0.04	-0.08	-0.10	0.05	0.05	**-0.02**
150	0.42	0.38	0.36	0.44	0.45	**0.41**
250	0.69	0.75	0.63	0.72	0.54	**0.67**
325	0.72	0.71	0.72	0.58	0.66	**0.68**

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 Analyzers				
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	ARH	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 Gases			
Gas	**Manufacturer**	**Type**	**Accuracy**
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 %
Zero	Scott Specialty Gases	Certified Master Class – 0 %	± 2 %

Test Equipment			
Type	**Manufacturer**	**Model**	**Accuracy**
Gas Chromatograph	Agilent	6890	± 0.5 BTU/scf
Type J Thermocouple	Omega Engineering Co.	JMQSS	2.2°C or 0.75%
Type K Thermocouple	Omega Engineering Co.	KMQSS	2.2°C or 0.75%
Type R Thermocouple	Omega Engineering Co.	RMQSS	2.2°C or 0.75%
Type T Thermocouple	Omega Engineering Co.	TMQSS	2.2°C or 0.75%
Dry Test Gas Meter 325 cf/h max	American Meter Company	DTM-325	N/A
Gas Meter Pulser 2 pulses per 1/10 cf	Rio Tronics	4008468	N/A
Gas Pressure Regulator	Fisher	299H	± 1.0 %
Data Logger	Logic Beach	Hyper Logger	N/A

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.