# LNG Research Study

## Commercial Water Boiler

September 2004

Prepared By:

The Southern California Gas Company
Engineering Analysis Center – Applied Technologies
Jorge Gutierrez
Firas Hamze
Juan R. Mora
Andre Saldivar

**Acknowledgements**

The authors express appreciation to the following associates whose efforts contributed much to the success of this project.

Monica Clemens

Alfonso Duarte

David Kalohi

Johnny Lozano

William F. Raleigh

Larry Sasadeusz

Rod Schwedler

Kevin Shea

Dale Tomlinson

**Disclaimer**

LEGAL NOTICE

- The Southern California Gas Company, its officers, employees, and contractors, make no warranty, expressed or implied, and assume no legal liability for accuracy of the information contained in this report; neither do they individually or collectively assume any liability with respect to the use of such information or report or for any damages which may result from the use of or reliance on any information, apparatus, methods, or process disclosed or described in or by this report.
- No information contained in this report can be copied, reported, quoted, or cited in any way in publications, papers, brochures, advertising, or other publicly available documents without the prior written permission of the Southern California Gas Company.

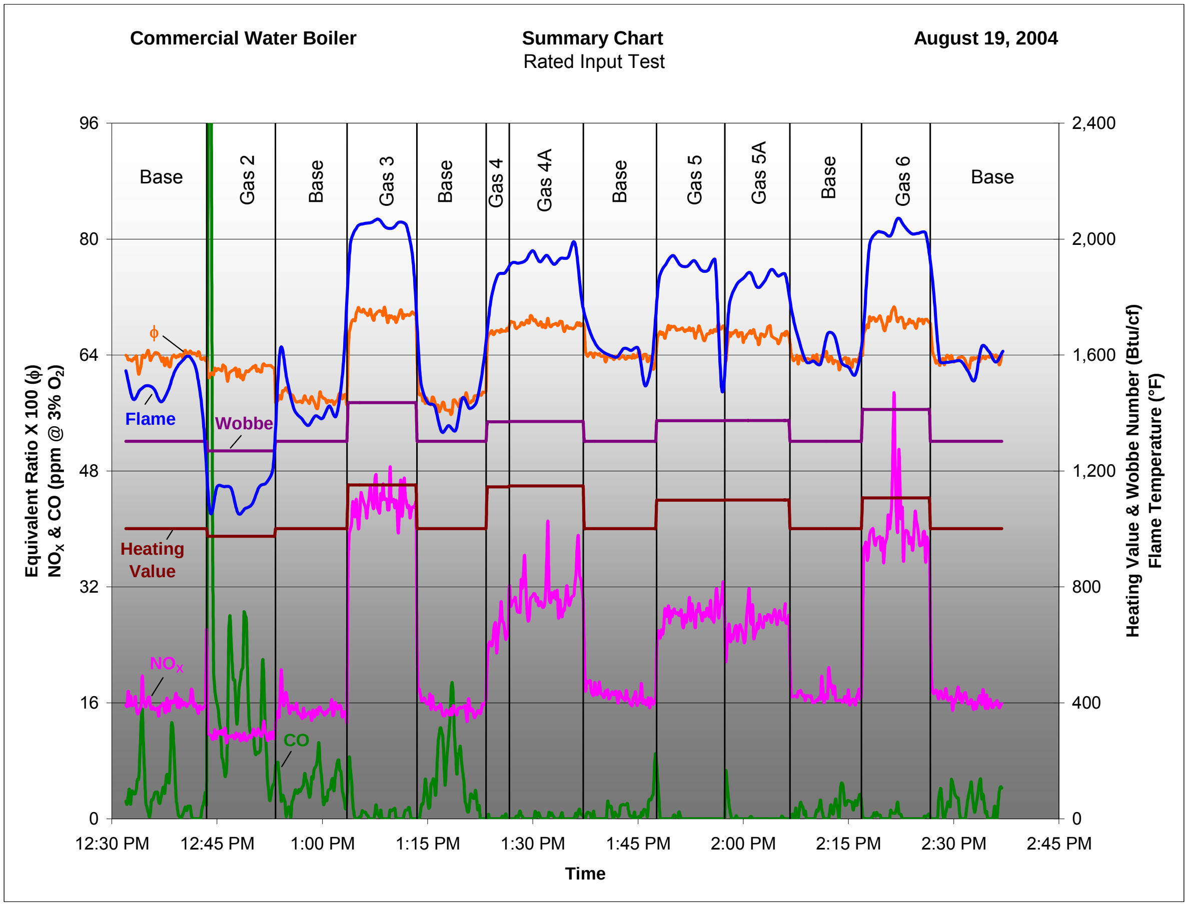
## Table of Contents

## Results Summary

Results obtained from all tests reveal (a) there were no operational, ignition, flame stability, or safety problems; (b) CO emissions were below 14 ppm; (c) Flame temperature, flame length, 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 manufacturer reviewed the data they expresed concerns with the higher emissions, higher temperatures, and longer flames observed with richer gases.

### Rated Input Test

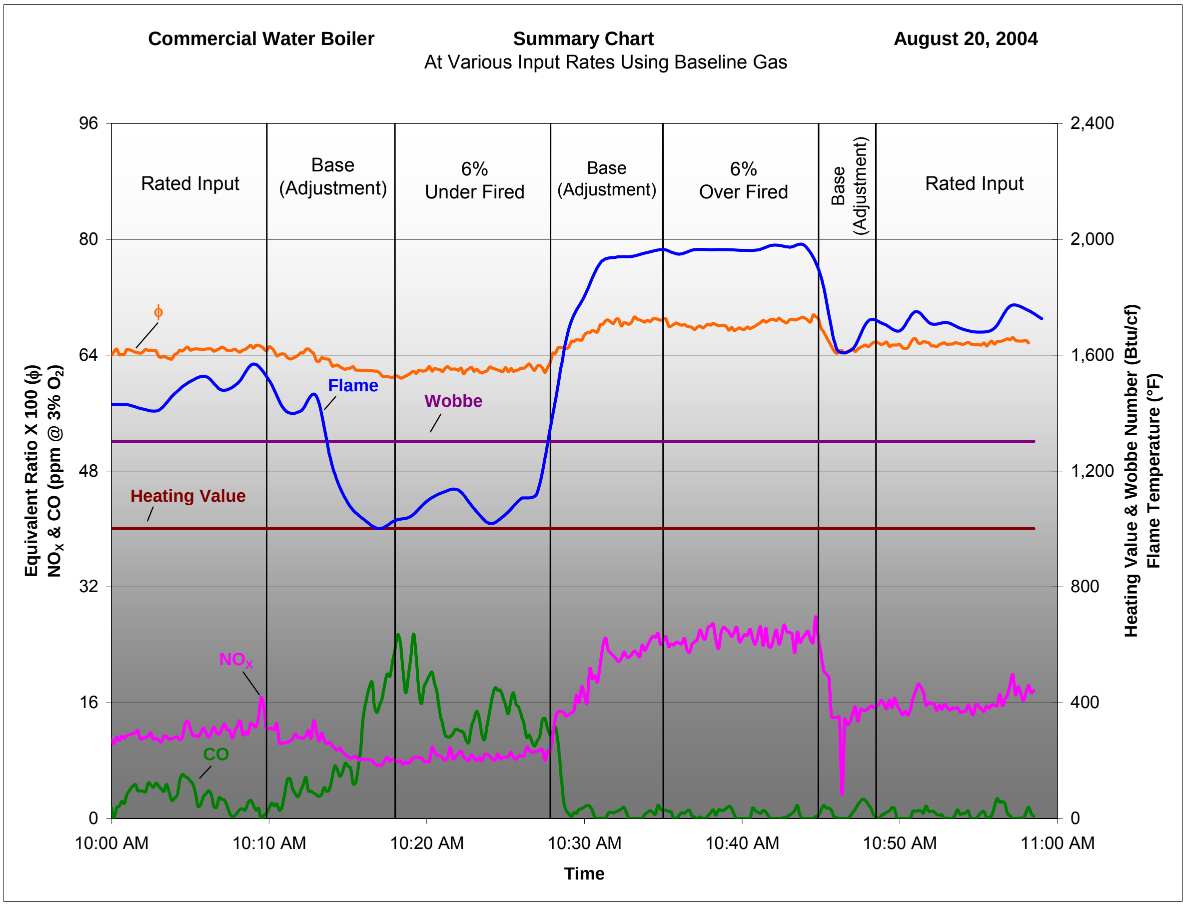
Average $NO_X$ emissions values were below 44 ppm (corrected to 3% $O_2$), average CO emissions values were below 15 ppm (corrected to 3% $O_2$) and average flame temperatures ranged between 1,100°F and 2,000°F for all gases tested.




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

## At Various Input Rates Using Baseline Gas Test

Results show there were no problems with the boiler set to rated input, 6% under fired or 6% over fired conditions while utilizing Baseline Gas.




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

## Equipment Selection Criteria

This unit was selected because it is used extensively in our service territory and it uses a ceramic power burner adjusted to operate at a very high firing intensity rate for a surface burner (6,369 Btu/hr-in$^2$). This could create the following issues when high-energy content gases are utilized: 1) This type of burner generates a long flame that, if it becomes too long, could be quenched by the heat exchanger and generate high CO or damage the heat exchanger and 2) CO, HC and $NO_X$ emissions can easily increase since air for combustion is fixed.

In addition, this unit was selected because it has to meet very stringent regulations. Rule 1146.2 from the SCAQMD limits $NO_X$ to 30 ppm (corrected to 3% $O_2$) and CO to 400 ppm (corrected to 3% $O_2$). The ANSI Z21.10.3 and UL standards cover safety, construction, performance and limit CO emissions to 400 ppm (corrected to 0% $O_2$).

## Equipment Specifications

- **Description:** Space heating commercial water boiler with tube type heat exchanger
- **Burner:** Gas fired premix surface burner operating on a blue flame mode
- **Maximum input rating:** ~500,000 Btu/hr
- **Minimum input rating:** ~250,000 Btu/hr
- **Type of fuel:** Natural Gas
- **Required gas supply pressure:** 5” w.c. - 14” w.c.

## Standards

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

- 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 boiler inlet water temperature and pressure were set and maintained at 125 ± 5°F and 25 ± 1 psig to ensure steady state boiler operation and prevent it from cycling while performing the test sequence.

Instrumentation was installed following the above test standards and input from manufacturers and consultants. Thermocouples were installed to measure flame, make-up water, inlet & outlet hot water, flue gas, ambient and gas temperatures. Also, pressure transducers were installed to measure manifold, skid, and inlet water supply pressures. A gas meter was set to measure the 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 three-point thermocouple grid (wired as a thermopile) 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 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 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

Tests procedures were developed following the above test standards. When the test standards were difficult to meet due to limited resources and time restrictions, input from manufacturers and consultants was requested to determine simplified test alternatives.

Before every test, the following steps were performed:

- All emissions analyzers were calibrated and checked for linearity.
- Data logger was enabled 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 manual 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.

### Rated Input Test

Using Baseline Gas, the manifold pressure was adjusted to achieve a rated input of 500,000 Btu/hr ± 2%. Once readings were stable, data collection was started and the gases were run continuously in the following order.

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

### At Various Input Rates Using Baseline Gas Test

The manifold pressure was adjusted to achieve a rated input of 500,000 Btu/hr ± 2% to begin the test. Once this condition was met, the boiler was operated with Baseline Gas was run continuously in the following manner:

- At Rated Input for 10 minutes
- 6% Under Fire Adjustment (8 minutes)
- At 470,000 Btu/hr ± 2% (6% Under Fire) 10 minutes
- 6% Over Fire Adjustment (7 minutes)
- At 530,000 Btu/hr ± 2% (6% Over Fire) 10 minutes
- Rated Input Adjustment (3 minutes)
- At Rated Input for 10 minutes to conclude testing

### Cold Ignition Test

Using Baseline Gas, manifold pressure was adjusted to achieve a rated input of 500,000 Btu/hr ± 2%. The following steps were followed:

- The gas delivery system was purged with Gas 3 (Highest-Wobbe Number).
- The commercial water boiler was ignited (using Gas 3) from a cold start and data was collected for one minute. For each time the boiler was ignited, visual observations of the flame and ignition delays were documented. This test was repeated 2 more times, allowing the boiler to reestablish cold start conditions in between each ignition.
- The gas delivery system was purged with Gas 2 (Lowest-Wobbe Number).
- The commercial water boiler was ignited (using Gas 2) from a cold start and data was collected for one minute. For each time the boiler was ignited, visual observations of the flame and ignition delays were documented. This test was repeated 2 more times, allowing the boiler to reestablish cold start conditions in between each ignition.

### Hot Ignition Test

Using Baseline Gas, manifold pressure was adjusted to achieve a rated input of 500,000 Btu/hr ± 2%. The following steps were followed:

- The gas delivery system was purged with Gas 3 (Highest-Wobbe Number).
- The commercial water boiler was ignited (using Gas 3) and data was collected for one minute. For each time the boiler was ignited, visual observations of the flame and ignition delays were 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 (Lowest-Wobbe Number).
- The commercial water boiler was ignited (using Gas 2) and data was collected for one minute. For each time the boiler was ignited, visual observations of the flame and ignition delays were documented. This test was repeated 2 more times with no more than one minute elapsing between tests.

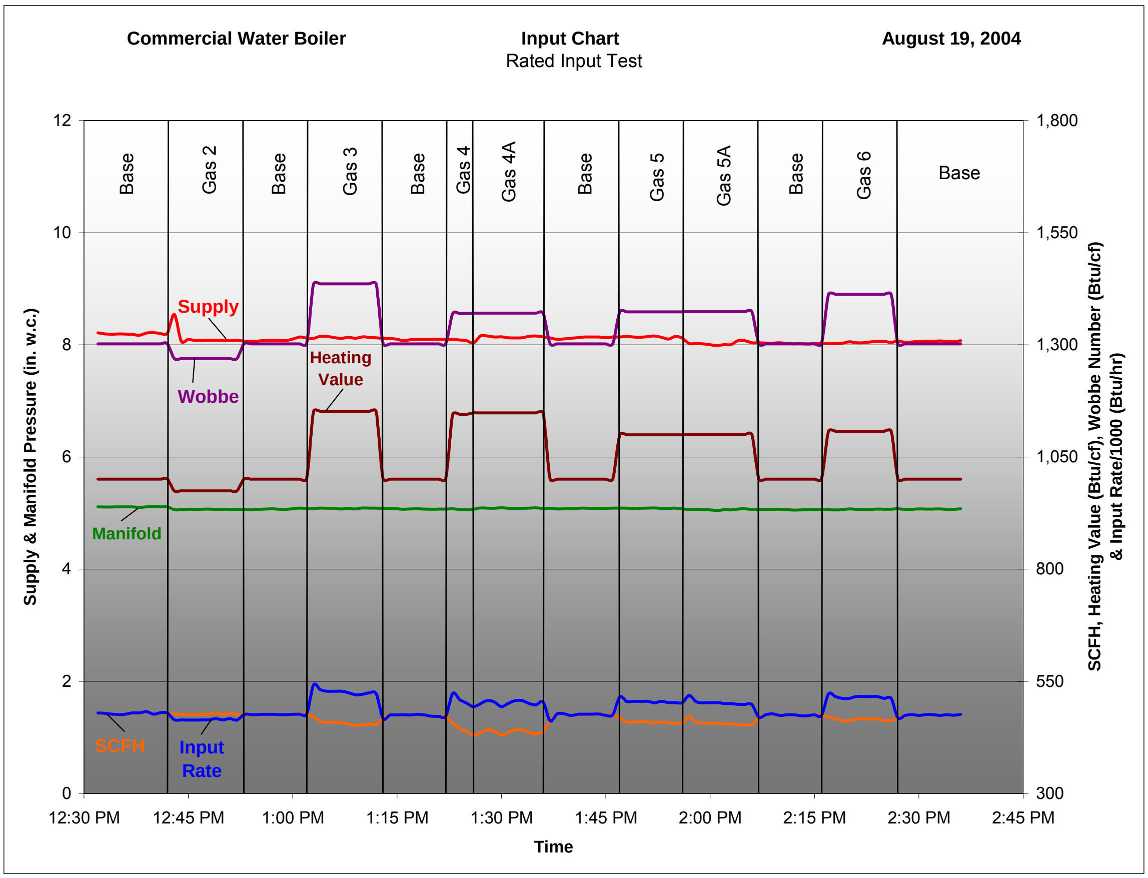
## Results[1, 2]

### Rated Input Test

*Input*

During the 1st Baseline Gas run, the commercial water boiler operated at approximately 478,000 Btu/hr; 4.4% below rated input. Both manifold and supply pressures remained within the limits set by the test protocol despite slight fluctuations in supply pressure.

The gas flow rate varied due to different gas compositions and the presence of heavier components in some of the gases tested. Baseline Gas achieved the highest flow rate (478 scfh - 1st run) and Gas 4A experienced the lowest flow rate (446 scfh) among all gases tested. The highest input rate was experienced with Gas 3 (526,659 Btu/hr), while the lowest input rate occurred with Gas 2 (464,211 Btu/hr).



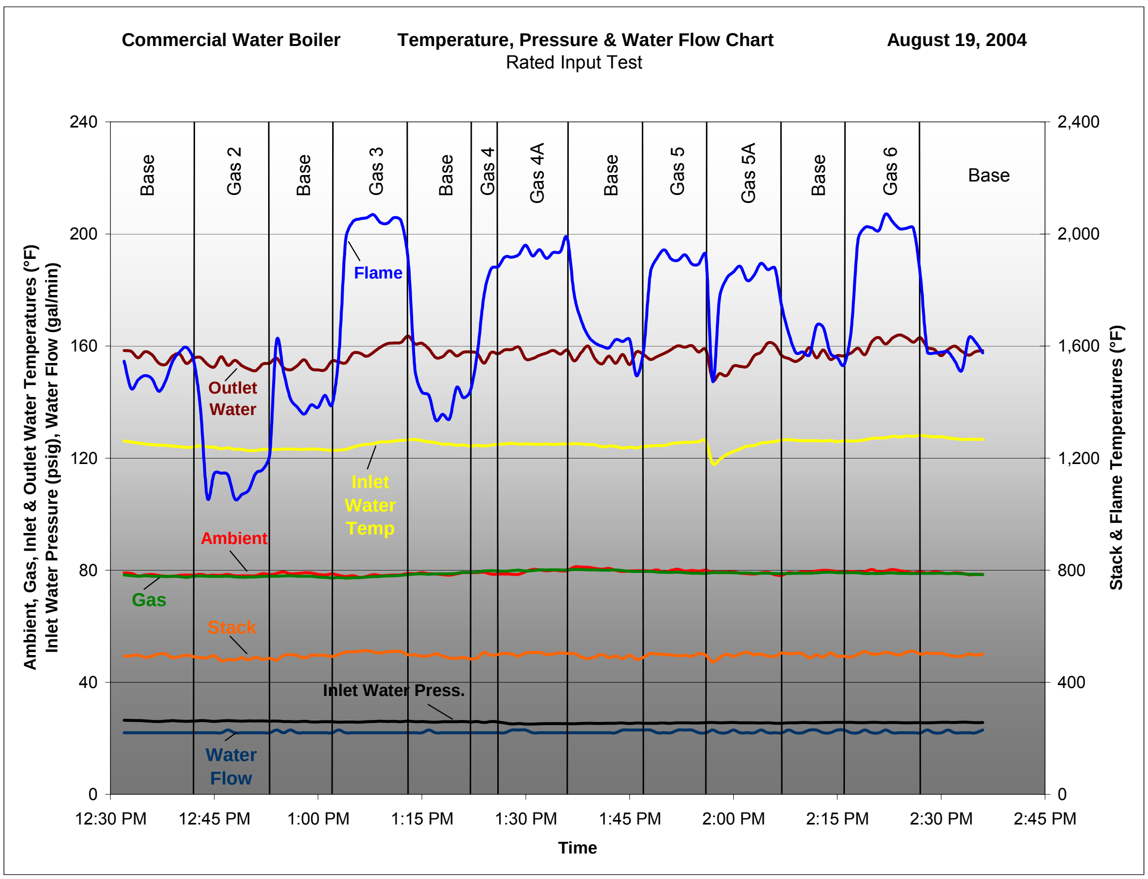

[1] All emissions, temperature and input values mentioned throughout the results section are average values.
[2] CO, HC & $NO_X$ emissions data are corrected to 3% $O_2$.

*Temperatures*

The highest flame temperature was reached with Gas 3 (1,996°F), followed by Gas 6 (1,986°F) and Gas 4A (1,941°F). Furthermore, Gas 2 (1,138°F) held the lowest flame temperature. 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 (508°F), followed by Gas 6 (503°F) and Gas 4A (502°F). Gas 2 held the lowest stack temperature at 485°F.

The inlet water and outlet water temperatures were highest with Gas 6 at temperatures of 127°F and 161°F.Both ambient and gas temperatures remained stable at 78 ± 3°F for the entire test period.

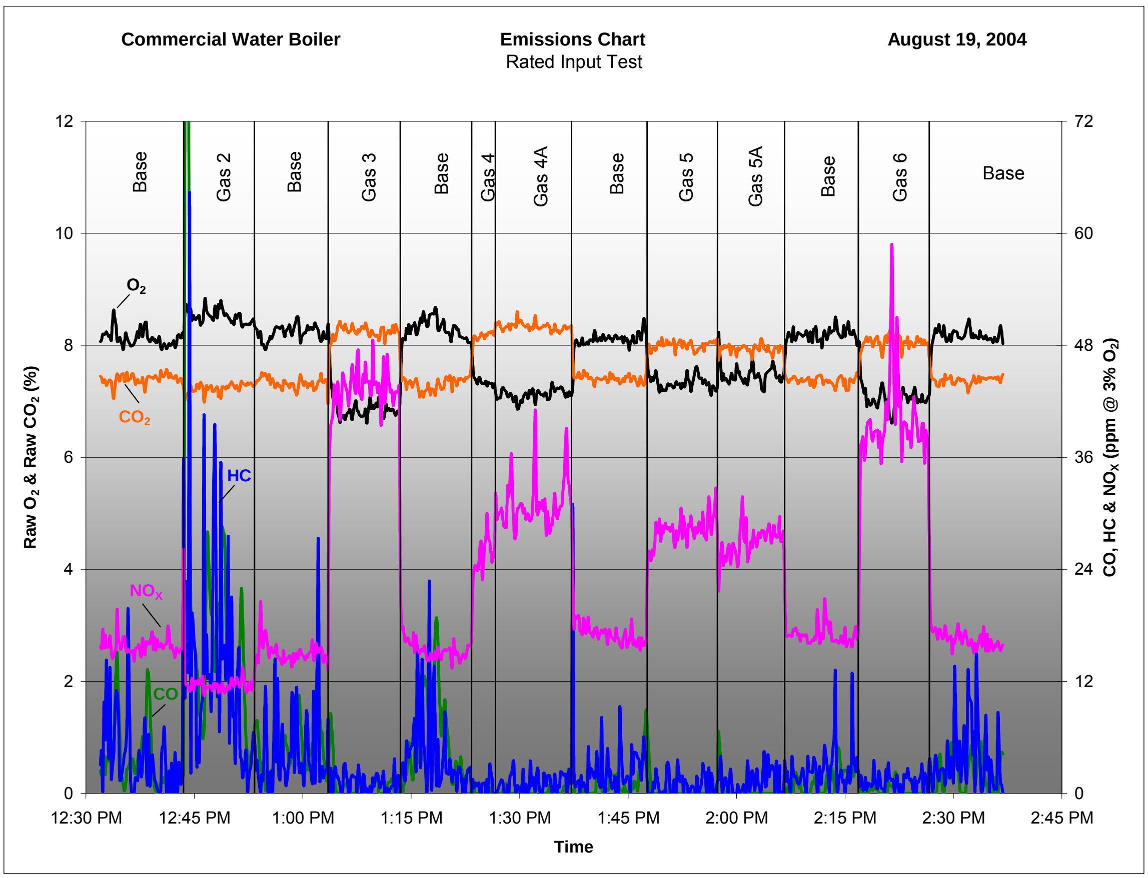


*Emissions*

$NO_x$ emissions values were highest with Gas 3 (43 ppm) followed by Gas 6 (38 ppm). $NO_X$ emissions values for Gases 2, 4, 4A, 5 and 5A did not exceed 31 ppm, with the lowest observed $NO_X$ emissions value occuring with Gas 2 (12 ppm). Baseline Gas $NO_x$ emissions ranged between 15 and 17 ppm.

CO emissions values did not exceed 15 ppm, with the highest and the lowest values being observed with Gas 2 (15 ppm) and with Gas 5A (<0.5 ppm). Also, HC emissions followed the same patterns as CO emissions throughout the test period.

The Gas 4 run was short because there was insufficient gas supply, thus, no comparisons could be made with Gas 4A. The only noticeable differences between results for Gas 5 and Gas 5A were slight decreases in $NO_X$, flame temperature, and input rate during the Gas 5A run.



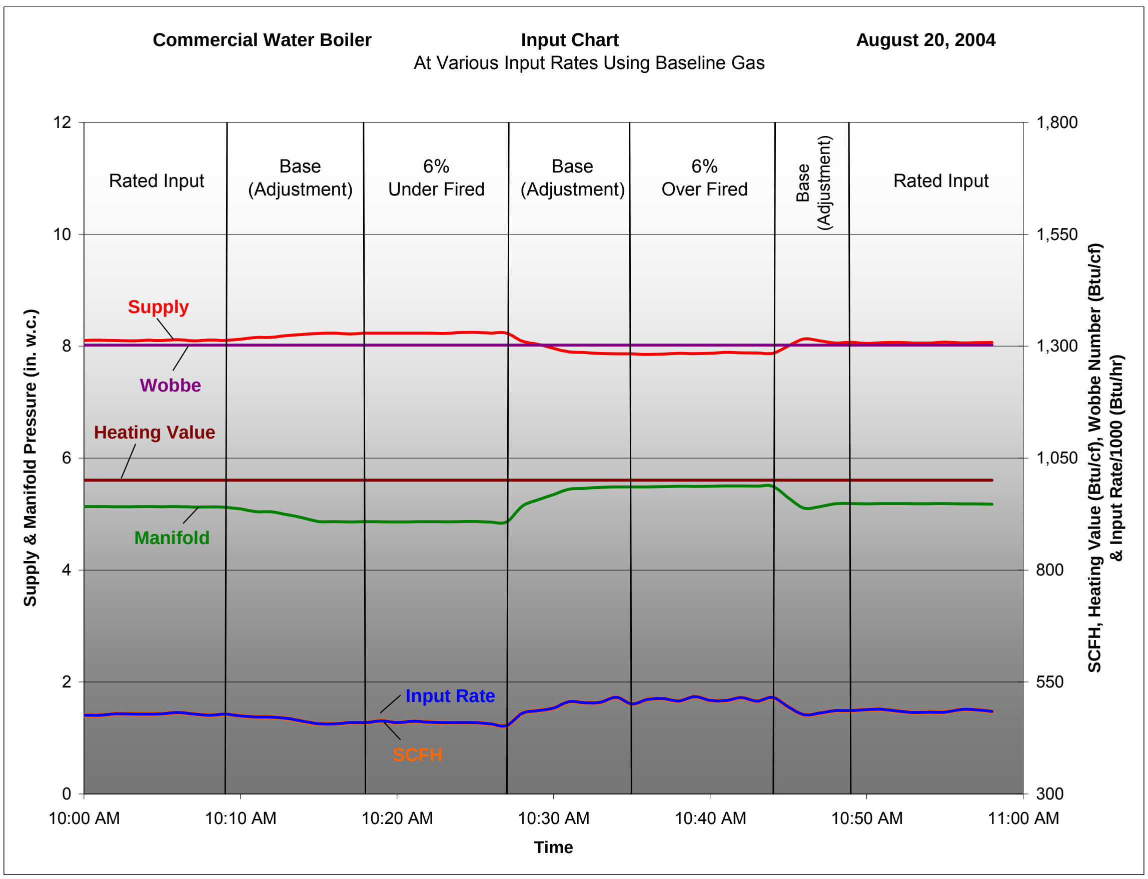

**NOTE:** Emission test results are for information purposes. They were not the result of certified tests.

### At Various Input Rates Using Baseline Gas Test

*Input*

The commercial water boiler operated at approximately 4.4% below rated input when the manifold pressure was adjusted to manufacturer specifications. The boiler was adjusted to operate at three conditions: Rated Input (500,000 Btu/hr ± 2%), 6% Under Fired (470,000 Btu/hr ± 2%) and 6% Over Fired (530,000 Btu/hr ± 2%). At each of the three conditions, the boiler did not stay within the ± 2% range required for each firing rate.

The gas flow was highest during the 6% over fired run with a flow of 510 scfh. Supply and manifold pressure varied throughout all runs due to regulator adjustments on the appliance to achieve the appropriate input rate.

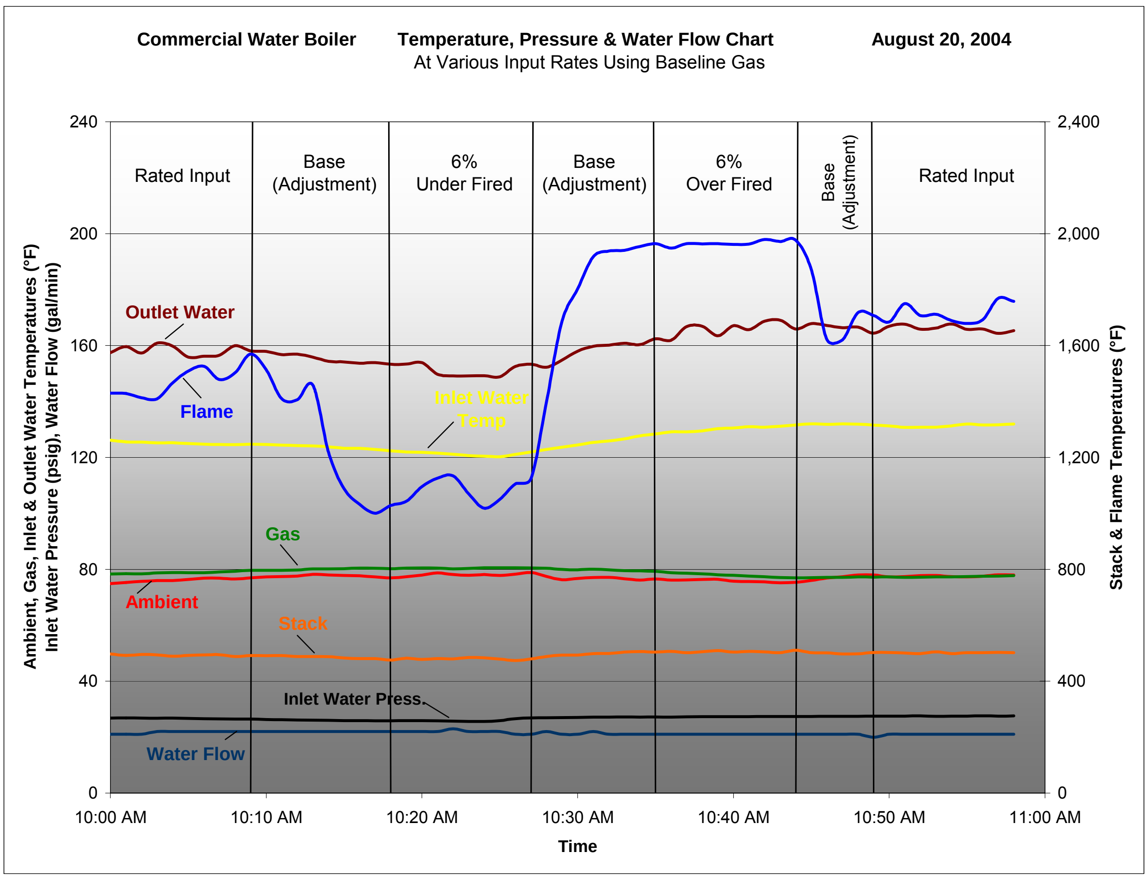


Temperature

The highest flame temperature occurred when the commercial water boiler was over-fired by 6% with a value of 1,966°F. The lowest flame temperature occurred when the boiler was under-fired by 6% with a value of 1,080°F. The first run at rated input reached a flame temperature of 1,473°F, increasing during the last rated input run to 1,704°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 when the boiler was over fired by 6% with a value of 506°F and lowest during the 6% under-fire run with a value of 480°F. At rated input, a stack temperature of 493°F was observed for the 1st run, but increased to 502°F for the last run at rated input.

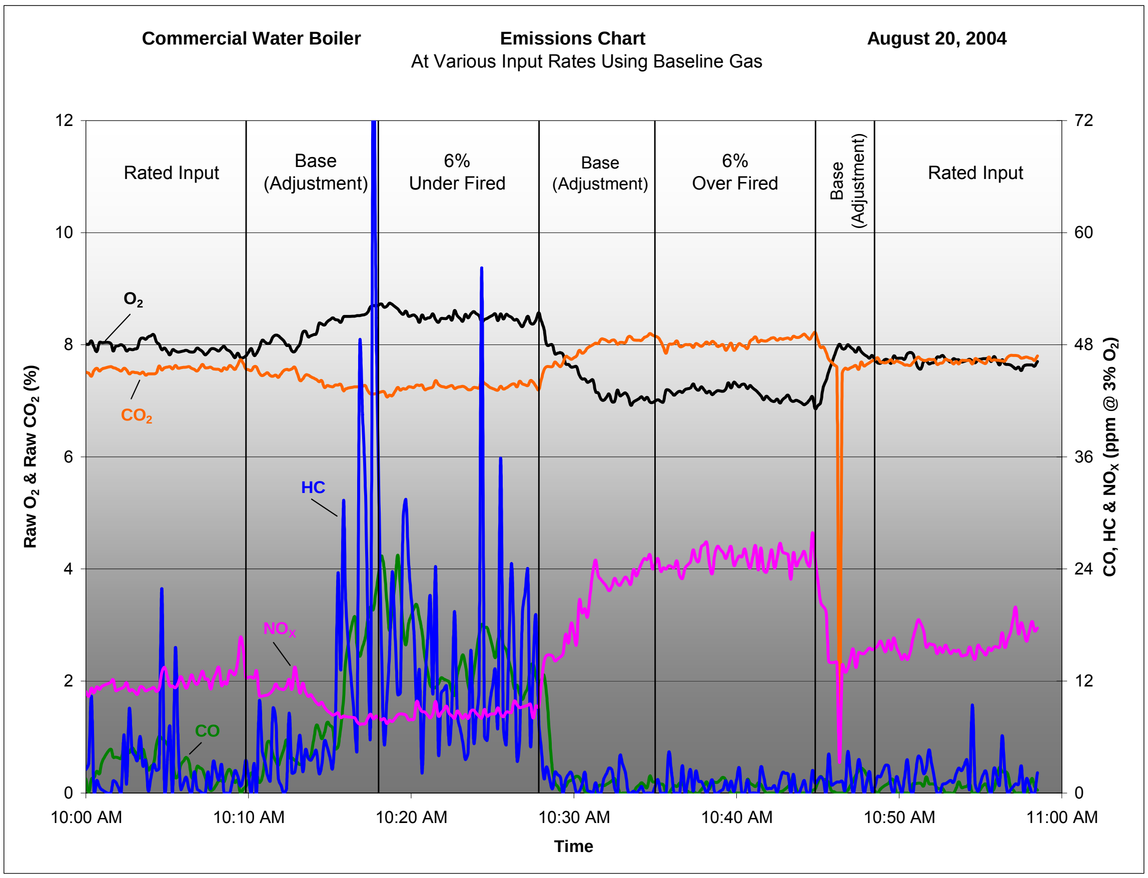
The outlet water temperature was highest when the boiler was over fired by 6% at a temperature of 167°F. The inlet water temperature was highest for the last rated input run with a temperature of 131°F, followed by the 6% over-fired run with a temperature of 130°F.



*Emissions*

The highest $NO_X$ emissions value was observed when the boiler operated at 6% over-fired conditions, achieving a value of 25 ppm. The $NO_X$ emissions value during the 6% under-fired run was lowest with a value of 9 ppm. During the first run at rated input, the $NO_X$ value was 12 ppm and increased to 15 ppm for the last run.

The highest CO emissions value was observed during 6% under-fired conditions with a value of 13 ppm. At 6% over-fired conditions, the lowest CO value was achieved (<1 ppm). During the first run at rated input, the CO emissions value was 3 ppm and decreased to less than 1 ppm for the last run. Also, HC emissions followed the same patterns as CO emissions.




**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 | 1 | Some orange tipping, good blue flame near burner surface<br>Flame covered the entire burner surface |
| | | 2 | Some orange tipping, good blue flame near burner surface<br>Flame covered the entire burner surface |
| | | 3 | Some orange tipping, good blue flame near burner surface<br>Flame covered the entire burner surface |
| 2 | Normal | 1 | Flame did cover entire burner surface, some orange tipping was noticed<br>Flame flickered at burner surface |
| | | 2 | Flame did cover entire burner surface, some orange tipping was noticed<br>Flame flickered at burner surface |
| | | 3 | Flame did cover entire burner surface, Flame flickered at burner surface |

## 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 | 1 | Flame puffing was noticed<br>Flame did not cover the entire burner surface |
| | | 2 | Flame puffing was noticed<br>Flame did not cover the entire burner surface |
| 3 | Normal | 1 | No puffing was noticed; flame more stable<br>Flame covered the entire burner surface<br>Longer flame size and orange colored flame were noticed. |
| | | 2 | No puffing was noticed; flame more stable<br>Flame covered the entire burner surface<br>Longer flame size and orange colored flame were noticed |

**Appendix A:** Protocol

## 1. Standards

- 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.

## 2. Boiler Data

- **Description:** Space heating commercial water boiler with tube type heat exchanger
- **Burner:** Gas fired premix surface burner operating on a blue flame mode
- **Maximum input rating:** ~500,000 BTU/hr
- **Minimum input rating:** ~250,000 BTU/hr
- **Type of fuel:** Natural gas
- **Required gas supply pressure:** 5" w.c. - 14" w.c.

## 3. Test Arrangement

3.1. **Basic setup** – The boiler is to be tested on a leveled concrete surface. Fuel gas, electrical power, and water are to be provided at rates and conditions required by the test standards and manufacturer specifications. Combustion products are to be sampled in a vent stack constructed per emission measurement standards.

3.2. **Water flow and piping** – Provide water at the flow rate and temperature required by the test standards and manufacturer specifications. If necessary, provide a supply water pump, a recirculation pump, and valves necessary to adjust water flow rate and temperatures. Maintain water pressure at a level sufficient to ensure proper boiler operation.

3.3. **Vent pipe -** For all testing, a straight vertical vent pipe, five 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, ten inches from the bottom of the vent pipe. Six inches from the bottom of the pipe, provide a three-point thermocouple grid, wired as a thermopile.

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 on the boiler rating plate ± 1%.

3.6. **Temperatures** - In addition to data required for firing rate, provide thermocouples in inlet and outlet water piping as prescribed in Figure 8 of the AQMD protocol, as close to the boiler as possible. Also provide a thermocouple for measurement of the test ambient temperature – at 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.

3.7. **Instrumentation** – All instrumentation is to be per the SCAQMD Protocol for Rule 1146.2.

3.8. **Special measures** – 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 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)

## 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 combination of gas orifice size and manifold pressure required to deliver rated input with Baseline Gas. Manifold pressure is to be 5" w.c. ± 10% of that specified on the rating plate. The firing rate generally will not be at rated input with gases other than Baseline Gas.

5.4. **Water flow, temperature and pressure -** Adjust outlet temperature as close as possible to 165 ± 5°F and do not make any adjustments after starting the test. Adjust inlet temperature to obtain the required outlet temperature while following manufacturer's recommended installation procedures for a boiler utilized in space heating. The inlet water should be 125 ± 5°F.

## 6. Testing

6.1. **Startup Run -** Operate boiler on Baseline Gas for one-half hour at maximum input, as-received – i.e. with gas orifices received in the boiler and manifold pressure at the rating plate value ± 0.2" w.c.. Fifteen minutes after starting, check firing rate and record emissions data. Also record ambient temperature, gas pressures, gas temperatures, gas flow, water temperatures, water supply pressure, and stack temperature and flame temperatures.

Experiment with the boiler water temperature controls to determine what procedures should be used to start and operate the boiler at various firing rates.

Verify proper operation of all equipment and instrumentation.

6.2. **Base case at rated input -** Adjust boiler to operate at the rating plate input, maintaining manifold pressure within ±10% of that specified on the rating plate and changing gas orifices if necessary. This establishes and defines the "basic firing setup" referred to in Section 5.3 above. Record input rate and combustion data and verify that the firing rate is within ± 2% of the rated input.

During the testing observe flames and note yellow tipping and flame lifting or flashback phenomena or lack of it. 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. Steady operation testing

### 7.1. Steady operation tests – Baseline and substitute gases at rated input

7.1.1. **Steady operation with Baseline Gas -** Starting with Baseline Gas, operate the boiler at basic operating condition. Verify that firing rate is at ± 2% of the rated input and record combustion data ($NO_X$, $CO_2$ & CO) as required by the AQMD Protocol. Do not conduct "over-fire" test.

Continue operation to establish that 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 3.6.

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

7.1.2. **Gas changeover and steady operation with substitute gases -** Continue steady boiler operation with Baseline Gas and conduct a high-speed switch to Gas 2. 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:** The firing rate is not to be adjusted and the boiler controls must not be allowed to adjust firing rate in response to a water temperature change.)

Record all operating data including firing rate, stack temperature, and other temperatures per section 7.1.1. Continue operation and record combustion data ($NO_X$, $CO_2$ & CO) 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.

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, 4, 5, and 6. Omit the high-speed switch sequence to Baseline Gas between Gases 4 and 4A and between Gases 5 and 5A.

When testing has been conducted with all gases, shut down boiler and examine emission analyzers accuracy by performing a linearity test, then check for calibration drift by zeroing and spanning the instruments.

7.1.3. **Under-fire & Over-fire Testing**

7.1.3.1. **Under-fire Testing -** Using Baseline Gas, adjust manifold pressure to fire at 94% of rated input. For ten minutes record all operating data including firing rate, stack temperature, and other temperatures per section 7.1.1. Also, record combustion data ($NO_X$, $CO_2$ & CO) 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.

7.1.3.2. **Over-fire Testing -** Using Baseline Gas, adjust manifold pressure to fire at 106% of rated input. For ten minutes record all operating data including firing rate, stack temperature, and other temperatures per section 7.1.1. Also, record combustion data ($NO_X$, $CO_2$ & CO) 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.

## 8. Ignition Tests

### 8.1. Cold Ignition

Using Baseline Gas, adjust the manifold pressure to allow for a rated input of 500,000 Btu/hr $\pm$ 2%. Purge the gas delivery system of Baseline Gas with Gas 3. Using Gas 3, ignite the boiler 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 boiler 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, adjust the manifold pressure to allow for a rated input of 500,000 Btu/hr $\pm$ 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 boiler 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 and $NO_X$ emissions (ppm, Corrected to 3% $O_2$) are to be calculated per the AQMD protocol for Rule 1146.2.

**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 factory de-rate practices 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:

ANSI Standard Z21.13 specifies that the vent pipe consist of an elbow at the vent collar, a short horizontal section, another elbow and a vertical section, the top of which is to be 5 ft. above the vent collar or draft relief opening, whichever is lower. The AQMD protocol and ASHRAE Standard 103-1993 (the latter applying to boilers with less than 300,000 Btu/hr input) require a 5 ft. vertical vent pipe.

To minimize test time the vent pipe height is specified at 5 ft. for all testing and is allowed to be as short as 4 ft. 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 at 80 ± 10°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 by mixing outlet and supply water to meet the manufacturer's specification.

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.

ASHRAE Standard 103-1993 (applying to boilers with input less than 300,000 Btu/hr) specifies a water temperature rise of 19°F to 24°F and an inlet water temperature of 120°F to 124°F.

In the belief that the differences in these specifications do not have significant effect on safety and emission performance and in the interest of testing economy water temperatures are specified at the same values for all testing. Outlet water temperature is to be 180°F ± 2°F. Water temperature rise is specified at the maximum permissible stated by the manufacturer. If a maximum rise is not stated by the manufacturer, inlet/supply water is specified at 75 ± 5°F.

**Appendix B:** Table of Averages

At Rated Input

| **Table of Averages**<br>Commercial Water Boiler<br>Rated Input Test<br>August 19, 2004 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Gases** | **Base** | **2** | **Base** | **3** | **Base** | **4** | **4A** | **Base** | **5** | **5A** | **Base** | **6** | **Base** |
| HHV (Btu/cf) | 1,001 | 974 | 1,001 | 1,152 | 1,001 | 1,145 | 1,148 | 1,001 | 1,099 | 1,100 | 1,001 | 1,107 | 1,001 |
| Wobbe (Btu/cf) | 1,302 | 1,269 | 1,302 | 1,436 | 1,302 | 1,370 | 1,371 | 1,302 | 1,373 | 1,374 | 1,302 | 1,412 | 1,302 |
| Input Rate (Btu/hr) | 478,221 | 464,211 | 475,820 | 526,659 | 473,224 | 510,844 | 501,008 | 474,487 | 504,782 | 502,309 | 474,166 | 514,685 | 474,049 |
| Corrected SCFH | 478.1 | 476.4 | 475.5 | 455.0 | 474.2 | 446.1 | 437.2 | 475.6 | 458.3 | 455.1 | 473.8 | 465.1 | 474.5 |
| **Emissions** (not from certified tests) | | | | | | | | | | | | | |
| Raw $O_2$ (%) | 8.1 | 8.5 | 8.3 | 6.8 | 8.3 | 7.4 | 7.1 | 8.1 | 7.3 | 7.5 | 8.2 | 7.1 | 8.2 |
| Raw $CO_2$ (%) | 7.4 | 7.2 | 7.3 | 8.2 | 7.3 | 8.2 | 8.3 | 7.4 | 8.0 | 7.9 | 7.4 | 8.1 | 7.4 |
| CO (ppm @ 3% $O_2$) | 2.3 | 14.8 | 4.3 | 0.5 | 5.4 | 0.1 | 0.2 | 1.1 | 0.1 | 0.1 | 1.4 | 0.3 | 1.9 |
| HC (ppm @ 3% $O_2$) | 3.9 | 12.1 | 4.1 | 1.2 | 4.2 | 1.0 | 1.1 | 2.3 | 1.0 | 1.3 | 2.2 | 1.2 | 2.8 |
| $NO_X$ (ppm @ 3% $O_2$) | 16.0 | 11.6 | 14.8 | 43.2 | 15.5 | 25.5 | 30.1 | 17.1 | 28.2 | 26.8 | 16.7 | 38.5 | 16.5 |
| Ultimate $CO_2$ (%) | 12.1 | 12.2 | 12.1 | 12.3 | 12.1 | 12.6 | 12.6 | 12.1 | 12.3 | 12.3 | 12.1 | 12.2 | 12.1 |
| Equivalence Ratio (Φ) | 0.64 | 0.62 | 0.58 | 0.69 | 0.58 | 0.67 | 0.68 | 0.64 | 0.67 | 0.67 | 0.63 | 0.69 | 0.64 |
| **Temperatures (°F)** | | | | | | | | | | | | | |
| Ambient | 78.3 | 78.2 | 78.8 | 78.1 | 78.8 | 79.0 | 79.4 | 80.4 | 79.9 | 79.0 | 79.3 | 79.6 | 78.9 |
| Flame | 1,512 | 1,138 | 1,408 | 1,996 | 1,400 | 1,745 | 1,931 | 1,627 | 1,875 | 1,817 | 1,612 | 1,986 | 1,604 |
| Gas | 77.9 | 77.7 | 77.7 | 77.6 | 78.8 | 79.6 | 79.9 | 80.0 | 79.2 | 79.0 | 79.0 | 78.9 | 78.8 |
| Stack | 494.4 | 484.7 | 492.2 | 508.1 | 492.2 | 496.5 | 502.1 | 491.4 | 497.4 | 494.6 | 497.9 | 502.6 | 499.3 |
| Inlet Water | 124.8 | 123.4 | 123.1 | 124.8 | 125.4 | 124.5 | 125.0 | 124.3 | 125.1 | 124.8 | 126.2 | 127.1 | 127.2 |
| Outlet Water | 156.1 | 153.6 | 153.1 | 158.0 | 158.7 | 156.3 | 157.6 | 156.0 | 158.1 | 154.2 | 156.5 | 161.0 | 158.8 |
| **Pressures** | | | | | | | | | | | | | |
| Supply (in. w.c.) | 8.2 | 8.1 | 8.1 | 8.1 | 8.1 | 8.1 | 8.1 | 8.1 | 8.1 | 8.0 | 8.0 | 8.0 | 8.1 |
| Manifold (in. w.c.) | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 |
| **Flow** | | | | | | | | | | | | | |
| Water Flow (gpm) | 22.0 | 22.1 | 22.2 | 22.1 | 22.1 | 22.0 | 22.3 | 22.3 | 22.5 | 22.3 | 22.5 | 22.2 | 22.3 |

At Various Input Rates Using Baseline Gas

| **Table of Averages**<br>Commercial Water Boiler<br>At Various Input Rates Using Baseline Gas<br>August 20, 2004 | | | | |
|---|---|---|---|---|
| **Gases** | **500,000 Btu/hr ± 2%** | **470,000 Btu/hr ± 2%** | **530,000 Btu/hr ± 2%** | **500,000 Btu/hr ± 2%** |
| HHV (Btu/cf) | 1,001 | 1,001 | 1,001 | 1,001 |
| Wobbe (Btu/cf) | 1,302 | 1,302 | 1,302 | 1,302 |
| Input Rate (Btu/hr) | 478,128 | 459,192 | 510,679 | 485,769 |
| Corrected SCFH | 477.81 | 458.89 | 510.34 | 485.45 |
| **Emissions** (not from certified tests) | | | | |
| Raw $O_2$ (%) | 7.9 | 8.5 | 7.1 | 7.7 |
| Raw $CO_2$ (%) | 7.6 | 7.2 | 8.0 | 7.7 |
| CO (ppm @ 3% $O_2$) | 2.8 | 13.4 | 0.5 | 0.7 |
| HC (ppm @ 3% $O_2$) | 1.3 | 11.2 | 0.9 | 1.7 |
| $NO_X$ (ppm @ 3% $O_2$) | 11.7 | 8.6 | 25.1 | 15.4 |
| Ultimate $CO_2$ (%) | 12.2 | 12.2 | 12.2 | 12.2 |
| Equivalence Ratio (Φ) | 0.65 | 0.62 | 0.68 | 0.66 |
| **Temperatures (°F)** | | | | |
| Ambient | 76.1 | 78.0 | 75.9 | 77.7 |
| Flame | 1,473 | 1,080 | 1,966 | 1,704 |
| Gas | 78.8 | 80.4 | 78.0 | 77.4 |
| Stack | 493.2 | 479.7 | 505.6 | 501.9 |
| Inlet Water | 125.1 | 121.3 | 130.9 | 131.4 |
| Outlet Water | 158.2 | 151.3 | 166.7 | 166.0 |
| **Pressures** | | | | |
| Supply (in. w.c.) | 8.1 | 8.2 | 7.9 | 8.1 |
| Manifold (in. w.c.) | 5.1 | 4.9 | 5.5 | 5.2 |
| **Flow** | | | | |
| Water Flow (gpm) | 21.7 | 21.9 | 21.0 | 20.9 |

**Appendix C:** Test Gases

| Gas Analysis<br>Sample Date | Baseline<br>8/4/04 | 2<br>8/5/04 | 3<br>7/27/04 | 4<br>8/5/04 | 4A<br>7/27/04 | 5<br>8/18/04 | 5A<br>7/19/04 | 6<br>8/7/04 |
|---|---|---|---|---|---|---|---|---|
| **COMPONENTS** | **MolPct** | **MolPct** | **MolPct** | **MolPct** | **MolPct** | **MolPct** | **MolPct** | **MolPct** |
| C6 + 57/28/14 | 0.0200 | 0.0307 | 0.0297 | 0.1858 | 0.0406 | 0.0737 | 0.0435 | 0.0000 |
| NITROGEN | 1.9100 | 1.0866 | 0.0609 | 1.0608 | 1.0782 | 0.8003 | 0.7777 | 0.0000 |
| METHANE | 94.3900 | 95.8713 | 86.7978 | 84.9713 | 84.3951 | 88.8139 | 90.8094 | 91.6800 |
| CARBON DIOXIDE | 1.2400 | 2.9973 | 0.0000 | 3.0005 | 3.0516 | 1.4074 | 1.4130 | 0.0000 |
| ETHANE | 1.6600 | 0.0000 | 9.3416 | 4.7846 | 0.0220 | 5.2987 | 0.0230 | 5.5300 |
| PROPANE | 0.3100 | 0.0141 | 2.7663 | 2.4015 | 11.3998 | 2.6048 | 6.9175 | 1.7500 |
| i-BUTANE | 0.0600 | 0.0000 | 1.0037 | 1.1936 | 0.0094 | 0.0022 | 0.0113 | 0.5200 |
| n-BUTANE | 0.0500 | 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 | 0.0200 | 0.0000 | 0.0000 | 0.5944 | 0.0000 | 0.1567 | 0.0000 | 0.0000 |
| n-PENTANE | 0.0100 | 0.0000 | 0.0000 | 0.6001 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| OXYGEN | 0.3300 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **TOTAL** | **100.000** | **100.000** | **100.000** | **100.000** | **100.000** | **100.000** | **100.000** | **100.000** |
| | | | | | | | | |
| Compressibility Factor | 0.9980 | 0.9980 | 0.9972 | 0.9969 | 0.9969 | 0.9974 | 0.9974 | 0.9975 |
| **HHV (Btu/real cubic foot)** | **1000.66** | **974.40** | **1151.62** | **1145.13** | **1148.33** | **1099.38** | **1099.82** | **1107.06** |
| LHV (Btu/real cubic foot) | 901.62 | 877.27 | 1041.31 | 1035.92 | 1039.51 | 993.10 | 993.61 | 999.82 |
| Specific Gravity | 0.5906 | 0.5895 | 0.6434 | 0.6989 | 0.7018 | 0.6407 | 0.6410 | 0.6143 |
| **WOBBE Index** | **1302.13** | **1269.12** | **1435.73** | **1369.72** | **1370.73** | **1373.49** | **1373.72** | **1412.47** |

**Appendix D:** Zero, Span and Linearity Tables

August 19, 2004 (At Rated Input)

| | Zero, Span & Linearity Data<br>Commercial Water Boiler<br>August 19, 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 - 10:08:06 AM | 0.23 | 0.04 | 0.46 | 0.44 | 0.05 |
| | Zero Drift Check - 3:05:04 PM | 0.20 | 0.08 | -2.06 | 0.27 | 0.85 |
| | **Total Drift Over Test Period** | **0.03** | **0.04** | **2.52** | **0.17** | **0.80** |
| | **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** | **84.37** |
| | **Allowable Span Drift (Less Than ± 3% of Range)** | **0.75** | **0.60** | **6.00** | **30.00** | **3.00** |
| | Span Calibration - 10:18:36 AM | 20.95 | 12.20 | 181.86 | 434.77 | 84.66 |
| | Span Drift Check - 2:55:36 PM | 20.93 | 12.25 | 182.13 | 438.25 | 84.39 |
| | **Total Drift Over Test Period** | **0.02** | **0.05** | **0.27** | **3.48** | **0.27** |
| | **Was the Span Drift Within Allowable Deviation?** | **Yes** | **Yes** | **Yes** | **Yes** | **Yes** |
| **Linearity** | **Linearity Calibration Gas (Mid-Range Values)** | **9.03** | **8.00** | **91.20** | **434.00** | **42.86** |
| | **Allowable Linearity Drift (Less Than ±1% of Range)** | **0.25** | **0.20** | **2.00** | **10.00** | **1.00** |
| | Linearity Check - 10:23:57 AM (**CO:** 11:05:34 AM) | 9.22 | 7.94 | 90.30 | 435.64 | 41.53 |
| | **Difference From Mid-Range Values** | **0.19** | **0.06** | **0.90** | **1.64** | **1.33** |
| | **Was the Linearity Within Allowable Deviation?** | **Yes** | **Yes** | **Yes** | **Yes** | **No** |
| | Linearity Check - 3:00:02 PM | 9.05 | 7.96 | 89.68 | 438.75 | 42.07 |
| | **Difference From Mid-Range Values** | **0.02** | **0.04** | **1.52** | **4.75** | **0.79** |
| | **Was the Linearity Within Allowable Deviation?** | **Yes** | **Yes** | **Yes** | **Yes** | **Yes** |

August 20, 2004 (Various Input Rated - Baseline Gas Only)

**Zero, Span & Linearity Table**
Commercial Water Boiler
August 20, 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 - 8:54:33 AM | 0.25 | 0.02 | 0.27 | -0.08 | -0.06 |
| Zero | Zero Check - 11:01:35 AM | 0.19 | 0.15 | 0.38 | 0.17 | 1.80 |
| Zero | **Total Drift Over Test Period** | **0.06** | **0.13** | **0.11** | **0.25** | **1.86** |
| Zero | **Was the Zero Drift Within Allowable Deviation?** | **Yes** | **Yes** | **Yes** | **Yes** | **Yes** |
| Span | **Span Calibration Gas (High-Range Values)** | **20.90** | **12.20** | **182.50** | **434.00** | **84.37** |
| Span | **Allowable Span Drift (Less Than ± 3% of Range)** | **0.75** | **0.60** | **6.00** | **30.00** | **3.00** |
| Span | Span Calibration - 8:58:59 AM | 20.82 | 12.20 | 183.01 | 436.51 | 86.50 |
| Span | Span Check - 11:05:13 AM | 20.81 | 12.46 | 184.14 | 446.32 | 86.54 |
| Span | **Total Drift Over Test Period** | **0.01** | **0.26** | **1.13** | **9.81** | **0.04** |
| Span | **Was the Span Drift Within Allowable Deviation?** | **Yes** | **Yes** | **Yes** | **Yes** | **Yes** |
| Linearity | **Linearity Calibration Gas (Mid-Range Values)** | **9.03** | **8.00** | **91.25** | **434.00** | **42.86** |
| Linearity | **Allowable Linearity Drift (Less Than ±1% of Range)** | **0.25** | **0.20** | **2.00** | **10.00** | **1.00** |
| Linearity | Linearity Check - 9:06:01 AM | 9.15 | 7.94 | 91.79 | 436.13 | 43.06 |
| Linearity | **Difference From Mid-Range Values** | **0.12** | **0.06** | **0.54** | **2.13** | **0.20** |
| Linearity | **Was the Linearity Within Allowable Deviation?** | **Yes** | **Yes** | **Yes** | **Yes** | **Yes** |
| Linearity | Linearity Check - 11:08:31 AM | 9.12 | 8.11 | 90.66 | 446.61 | 43.53 |
| Linearity | **Difference From Mid-Range Values** | **0.09** | **0.11** | **0.59** | **12.61** | **0.67** |
| Linearity | **Was the Linearity Within Allowable Deviation?** | **Yes** | **Yes** | **Yes** | **No** | **Yes** |

**Appendix E:** Calculations

**Emission Concentrations**

Corrected to $O_2$ Standard (3% $O_2$)

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

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<br>**Date:** September 22, 2004<br>**Meter Number:** 11335393<br>TESTS WERE CONDUCTED USING<br>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 |

## Barometric Pressure Correction

Using the Standard Atmosphere Data for Altitudes to 60,000 ft Table (Table 3, *ASHRAE 1989 Fundamentals Handbook*, pg. 6.12), the barometric pressure at the test facility elevation was determined by linear interpolation. This value was subtracted from the barometric pressure value at sea level (29.921 in. Hg or 14.696 psia) to obtain the correction value. The correction value was subtracted from the barometric pressure reading specific to the hour and day of testing and then it was converted to absolute pressure (psia) using the following equation:

$$\text{Baro. Press (in.Hg)} \times \left[\frac{14.696\ \text{psia}}{29.921\ \text{in. Hg}}\right] = \text{Baro. Press(psia)}$$

**SCFH (Uncorrected)**

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

Where

SCFH = Standard Cubic Feet per Hour (Uncorrected)

ACFH = Actual Cubic Feet per Hour

$P_{Fuel}$ = Gas Supply Pressure (psig)

$P_{Barometric}$ = Barometric Pressure (psia)

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

$T_{standard}$ = Standard 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% |
| 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 |
| Data Logger | Logic Beach | Hyper Logger | N/A |

**<u>Appendix G:</u>** 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.