LNG Research Study

Testing of a Condensing Hot Water Boiler

Prepared for
The Southern California Gas Company

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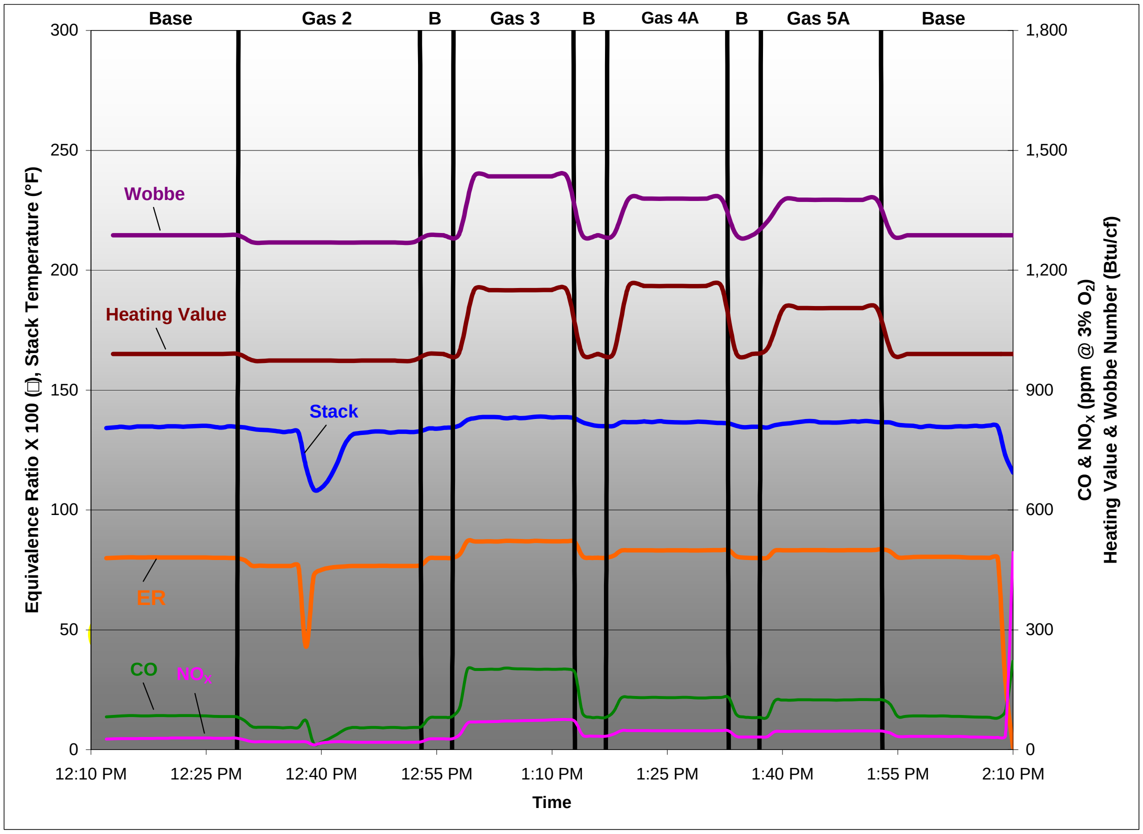
RESULTS SUMMARY

The condensing hot water boiler was tested over a wide range of operating conditions, gas properties and composition and showed some variations in emissions. A summary of results for each of these tests is provided below, with more detailed analyses in the Results section. Tables of average measured and calculated values are presented in Appendix F.

Performance Test

The average baseline NO_X emissions during the test sequence, corrected to 3% oxygen, was 30.9 ppm. Corrected NO_X emissions during the gas blend performance testing ranged from 19.3 ppm (Gas #2) to 72.8 ppm (Gas #3). The average baseline CO emissions (corrected to 3% O_2) were 82.1 ppm. The Gas blends resulted in corrected CO emissions from 55.6 ppm (Gas #2) to 201.7 ppm (Gas #3). The as-found firing rate was 79.6% of the rated input*. A summary of the continuous test data and calculations for the performance test is shown below.

Figure 1 – Summary of Condensing Boiler Performance Testing



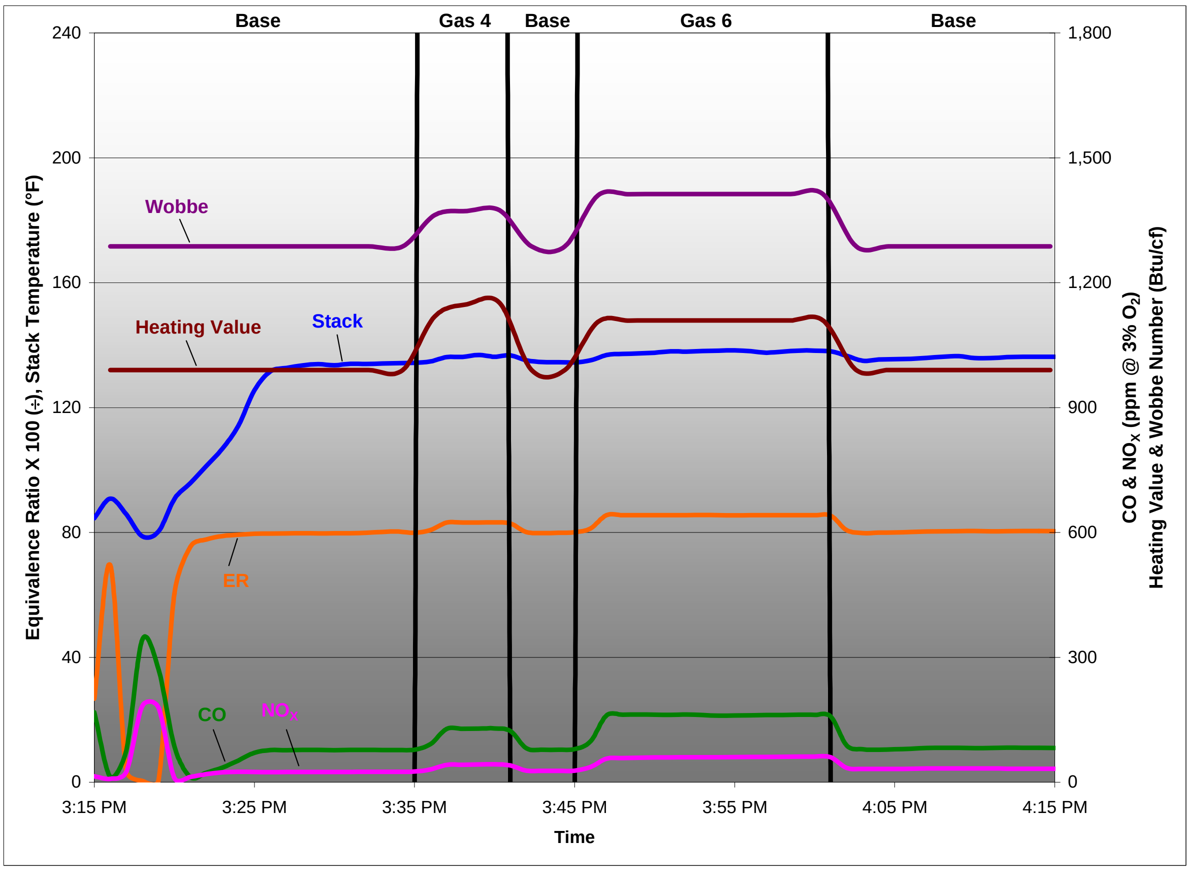
Emission test results are for information purposes. They were not the result of certified tests.

* With the burner control configuration shipped with the unit, the input rate could not be adjusted above 80% nameplate firing rate. The burner control system uses a zero-pressure manifold with induced gas flow via the pre-mix blower. The blower was set to operate at the highest speed allowed by the controller. This configuration precluded operation at rated or overfired conditions.

Performance Test – Additional Gases
Average baseline gas NO_X emissions during the test sequence, corrected to 3% oxygen, were 28.5 ppm. Corrected NO_X emissions during gas blending ranged from 42.2 ppm (Gas #4) to 60.5 ppm (Gas #6). Average baseline gas CO emissions during the test sequence, corrected to 3% O2, were 79.8 ppm. Corrected CO concentrations for the gas blends ranged from 128.7 ppm (Gas #4) to 161.3 ppm (Gas #6). The average baseline firing rate was 78.5% of the rated input, which was below the 100% +/- 2% called for in the test protocol (see note above).

A summary of the continuous test data and calculations for the performance testing with the additional gases is shown in Figure 2.

Figure 2 – Summary of Cond. Boiler Performance Testing – Additional Gases

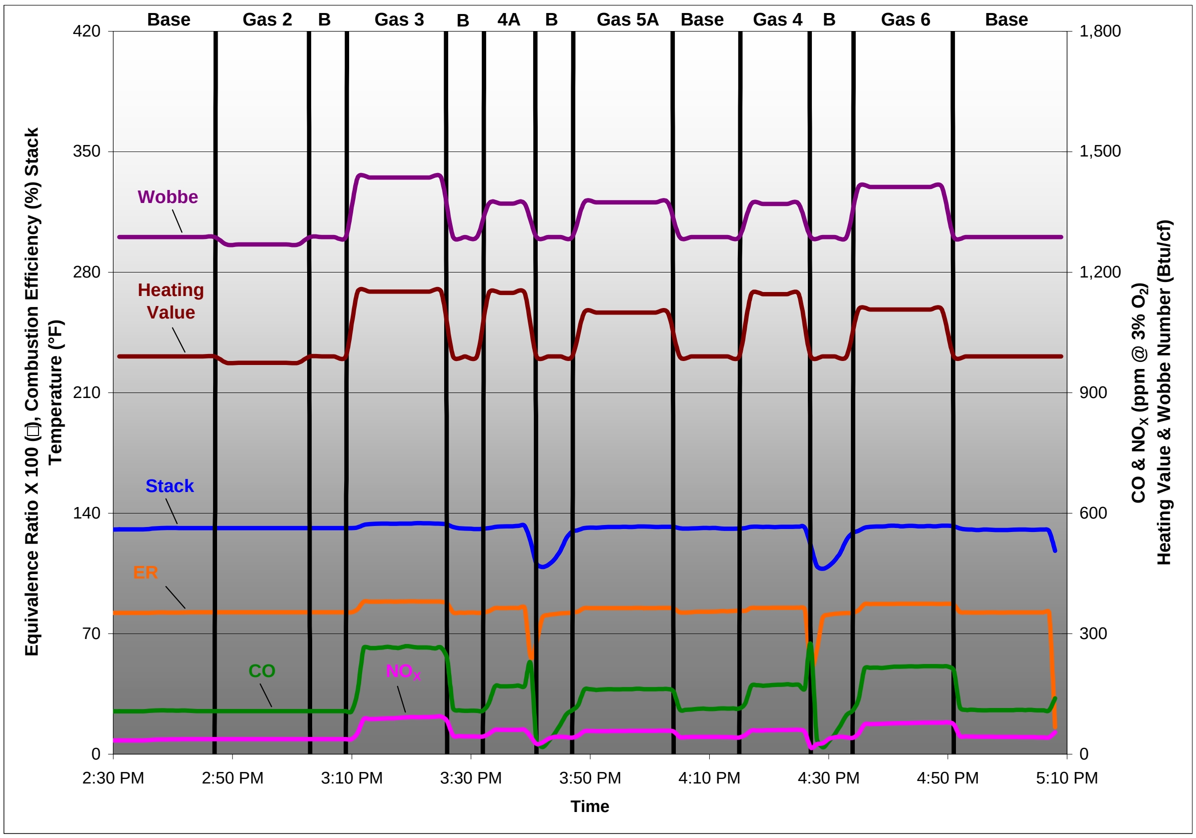


Emission test results are for information purposes. They were not the result of certified tests.

*Emissions Test**

NO_x emissions ranged from 37.3 ppm (Gas #2) to 90.6 ppm (Gas #3). CO emissions, corrected to 3% oxygen, ranged from 107.3 ppm (Gas #2) to 265.5 ppm (Gas #3). The average baseline firing rate was 88.0% of the rated input. This rate is higher than was achieved during the performance tests, due to less restriction in the ventilation duct. A summary of the continuous test data and calculations for the emissions test is shown in Figure 3. After switching to base gas after Gas #4a and Gas #4, the blower control system reset to start-up mode (see Figure 3).

Figure 3 – Summary of Cond. Boiler Emissions Testing



* Emission test results are for information only. They are not the results of certified tests

EQUIPMENT SELECTION CRITERIA

The manufacturer of this condensing boiler in his response to our survey indicated a great deal of concern regarding adverse changes in the operation and emissions generation of this unit with the rich gases. This was corroborated in our discussions with our field technicians and consultants. Overall it was agreed that this unit should be tested because:

1. Is a new unit in the market and it utilizes new technologies
2. The induced gas pre-mix burner system with a zero-pressure regulator could be very sensitive
3. The unit is very compact and high efficiency

EQUIPMENT SPECIFICATIONS

Description: Gas-fired condensing hot water boiler utilized for hydronic heating
Type of burner: Induced pre-mix
Input rating: 199,000 Btu/hr
Type of fuel: Natural gas
Required fuel inlet supply pressure: 3.5 – 14.0" W.C.
Gas manifold pressure: -0.01" W.C.

STANDARDS

A test protocol was developed based on the following 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 NOX from Large Water Heaters and Small Boilers, adopted January 9, 1998.
- South Coast Air Quality Management District Protocol, NOX Compliance Testing for Natural Gas-fired Water Heaters and Small Boilers, last amended January 1998.

A detailed description of the protocol and rationale is presented in Appendix A.

INSTALLATION

The overall setup of the equipment included a number of sub systems, including gas supply, gas composition blending and analysis, gas appliance, flue gas monitoring, and data acquisition. A schematic of the overall test system is shown in Appendix B (Figure B1).

The condensing boiler was installed and instrumented in a laboratory test cell according to the manufacturer's specifications and the test protocol. Thermocouples were installed to measure process temperatures, including water in and out, flue gas, gas supply, and ambient. Pressure transducers were installed to measure supply, gas meter, manifold, atmospheric, and water pressures. A schematic of the instrumented condensing boiler is shown in Appendix B (Figure B2).

Installation specific to Performance tests
For performance testing (including as found, overfired, underfired, and gas blending tests), a single point emissions sampling probe was installed directly in the flue outlet. The vent pipe consisted of an elbow at the vent collar, a short horizontal section, another elbow and a vertical section, the top of which was five feet above the draft relief opening.

Installation Specific to Emissions Tests
For emissions testing, an integrated sampling probe was installed in a five-foot section of vent pipe, one foot below the exit. The vent pipe was attached to the outlet of the vent cap, per the SCAQMD Rule 1146.2 protocol.

Once instrumentation was installed, the condensing boiler was operated on pipeline gas to verify that the boiler and all instrumentation operated properly. Manifold and supply pressures were not adjusted during setup.

TEST GASES

Several sources of gases were used for the project, including pipeline gas and special blends of gases either prepared by a provider of specialty gases or on site.

The project required testing the range of gas compositions shown in Appendix C (Table C1). As indicated in the Table, there were primary, secondary, and tertiary gases. The primary gases included the baseline or set up gas and others that outlined the boundary conditions for compositions determined by SCG. Secondary gases were intermediate gases within the boundary conditions and were used for processes that exhibit sensitivities to primary gases. Tertiary gas compositions depended on results from the secondary gases and had properties that were incremental changes in heat content or Wobbe number, depending on results from the secondary gas.

TEST PROCEDURES

Three types of tests were conducted in evaluating the Condensing Boiler:

1) Performance
2) Emissions
3) Ignitions

Testing the condensing boiler for this project followed the protocol shown in Appendix A. The test protocol was designed to discriminate changes in the operation of the gas equipment for the range of gas properties and compositions in the study. In the interest of time and applicability to the scope of this work, some simplified procedures were developed from existing test standards. These simplified procedures were developed in consultation with the manufacturer and other technical parties to ensure applicability

While each test adhered to the protocol, generally each day followed a similar sequence of steps as outlined below.

1. All emissions analyzers were calibrated.
2. The water boiler was turned “on” and allowed to heat up to an “idle” steady state condition while running on baseline or pipeline gas.
3. Data loggers were synchronized and temperatures, pressures and gas flow readings were inspected.
4. Data recording was started while running with baseline/pipeline or test gas.
5. Each test was run for approximately 20 minutes with the burner at a specified power level and gas with all temperature, emissions and composition monitors being data logged. During the test, visual and photographic observations were made of the flame in order to determine yellow tipping and flame lifting phenomena or lack of same.
6. Drift inspections were performed on all emissions analyzers
7. Steps 5 and 6 were repeated for other firing rates and for the range of test gases in the matrix as indicated in Appendix C. High-speed transitions (~14 seconds) were made from baseline gas to substitute gas while recording observations. Phenomena of interest included: flame color change, flame lifting, flashback or rollout, pilot burner instability or outage, etc.

Performance Tests

The condensing boiler was set to maintain a constant 120 ^{o}F inlet water temperature and a 140 ^{o}F outlet water temperature via adjustment of the water outlet control valve. The gas supply was set to within 2% of the shipped rated input on baseline gas. The boiler was operated for approximately 15 minutes at this condition, followed by 15-minute segments using Gas #2, Gas #3, Gas #4a, and Gas #5a. The unit was returned to baseline gas for a five-minute period between each gas blend switch. A supplementary performance test was performed separately following the same procedures using gas 4 and gas 6

Emissions Tests

The boiler was operated as described above, with a five-foot vent stack for emissions testing. Emissions tests were conducted using baseline gas, Gas #2, Gas #3, Gas #4a, Gas #5a, Gas #4 and Gas #6.

Ignition Tests

The condensing boiler was tested for ignition performance with various gas blends under a number of different conditions, including cold and hot ignitions at rated inlet pressure, reduced inlet pressure, and with a repetitive sequence. Ignition tests were conducted using baseline gas, Gas #2, and Gas #3. For each of the ignition sequences, visual observations were made to determine any ignition delays, flame carryover, flashback and/or other flame phenomena.

RESULTS

Performance Test

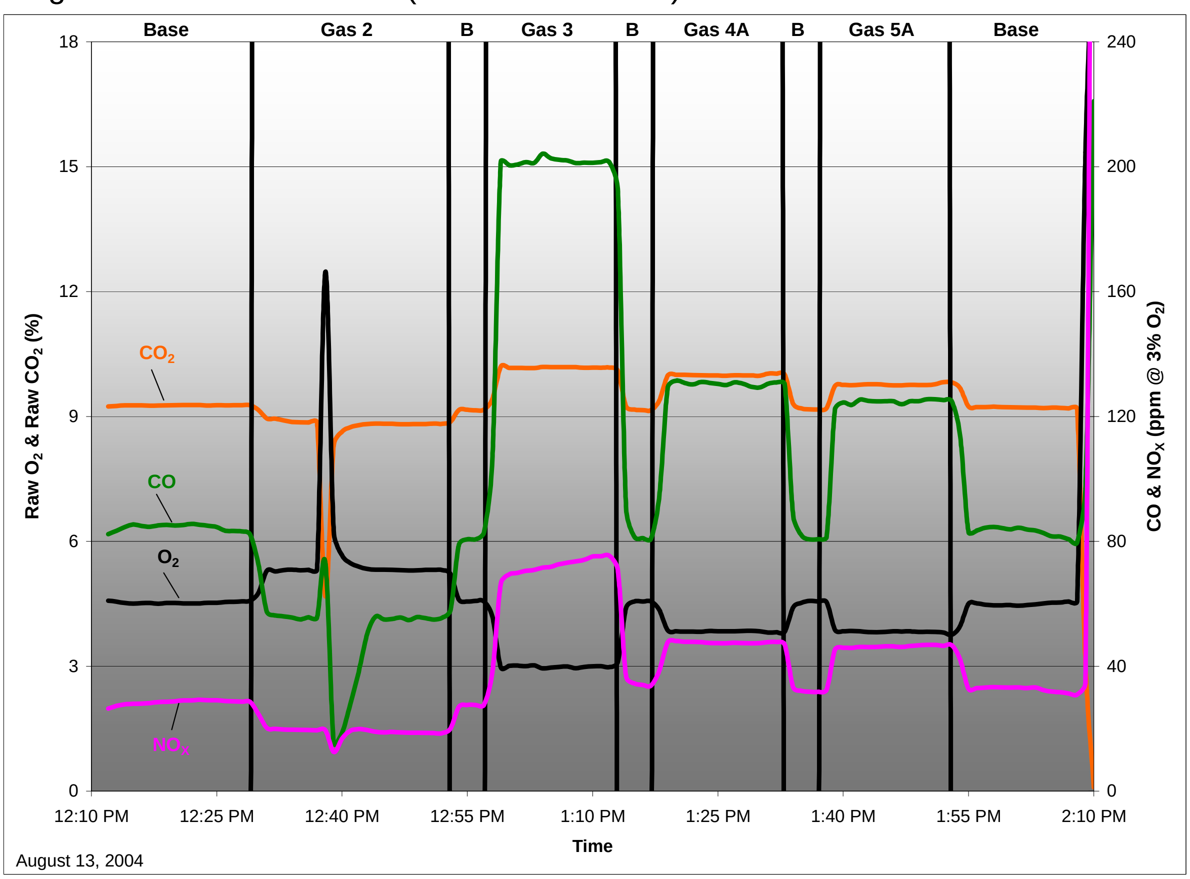
Emissions

NO_x emissions concentrations for the as-found (baseline) condition averaged 30.9 ppm (corrected to 3% O_2). The average NO_x concentration decreased to 19.3 ppm (@ 3% O_2) after switching to Gas #2. The highest levels of NO_x, measured during the test sequence [72.8 ppm (@ 3% O_2)], were seen after switching to Gas #3. The intermediate gases (Gas #4a and Gas #5a) showed corrected NO_X emissions of 47.6 ppm and 46.3 ppm, respectively.

CO emissions for the as-found (baseline) condition averaged 82.1 ppm (@ 3% O_2). CO emissions decreased to 55.6 ppm (@ 3% O_2) after switching to Gas #2. The highest levels of CO [201.7 ppm @ 3% O_2)] were seen after switching to Gas #3. The intermediate gases (#4a and #5a) resulted in corrected CO emissions of 130.4 ppm and 124.7 ppm, respectively.

Figure 4 presents the continuous raw emissions concentration measurement data for this test sequence.

Figure 4 – Emissions Data (Performance Test)



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

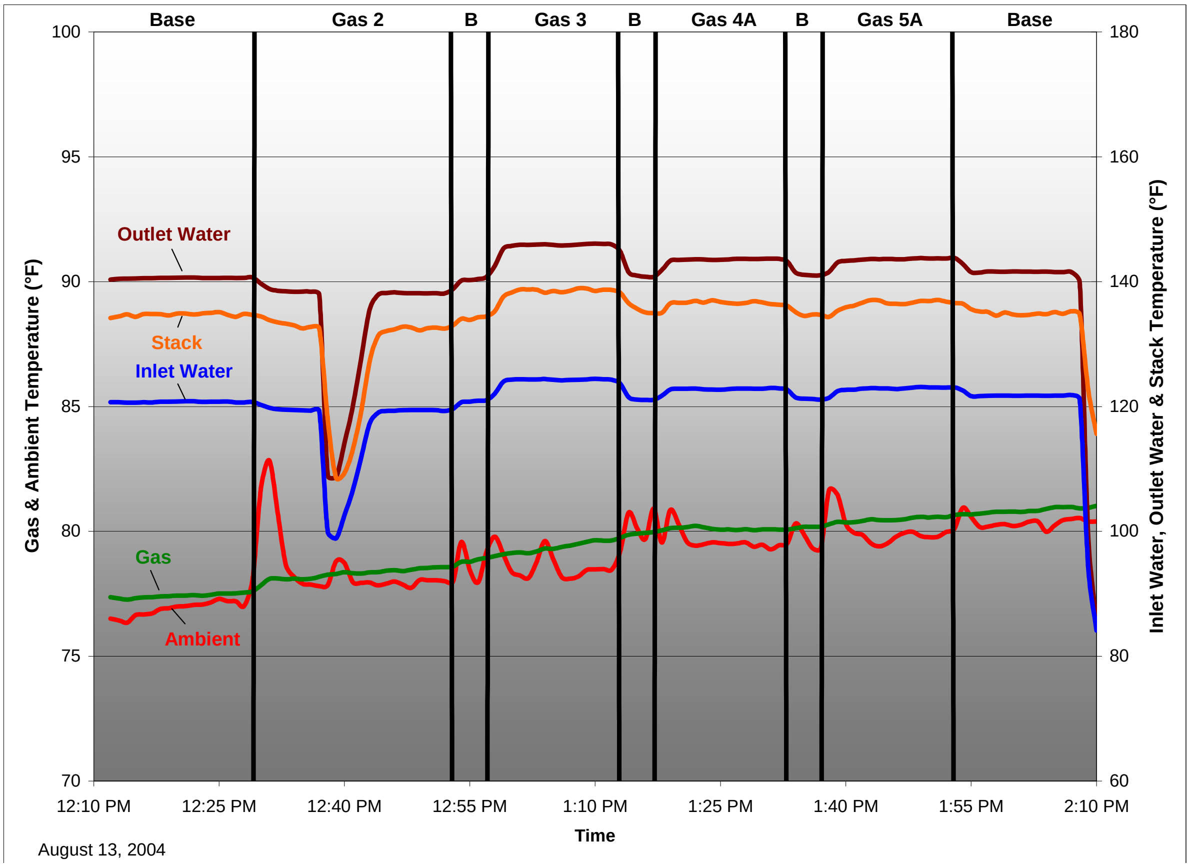
Temperatures

The temperature rise across the boiler for the baseline tests averaged 19.7 ^oF. The temperature differential decreased slightly to 18.9 ^oF after switching to Gas #2. The differential was highest when operating on Gas #3 (21.6 ^oF). Gas #4a and Gas #5a both resulted in average temperature differentials of 20.7 ^oF.

Stack temperatures fell within a narrow band over the test sequence, ranging from 132.7 ^oF (Gas #2) to 138.6 ^oF (Gas #3).

Figure 5 presents the continuous temperature measurement data for this test sequence.

Figure 5 – Temperature Data (Performance Test)

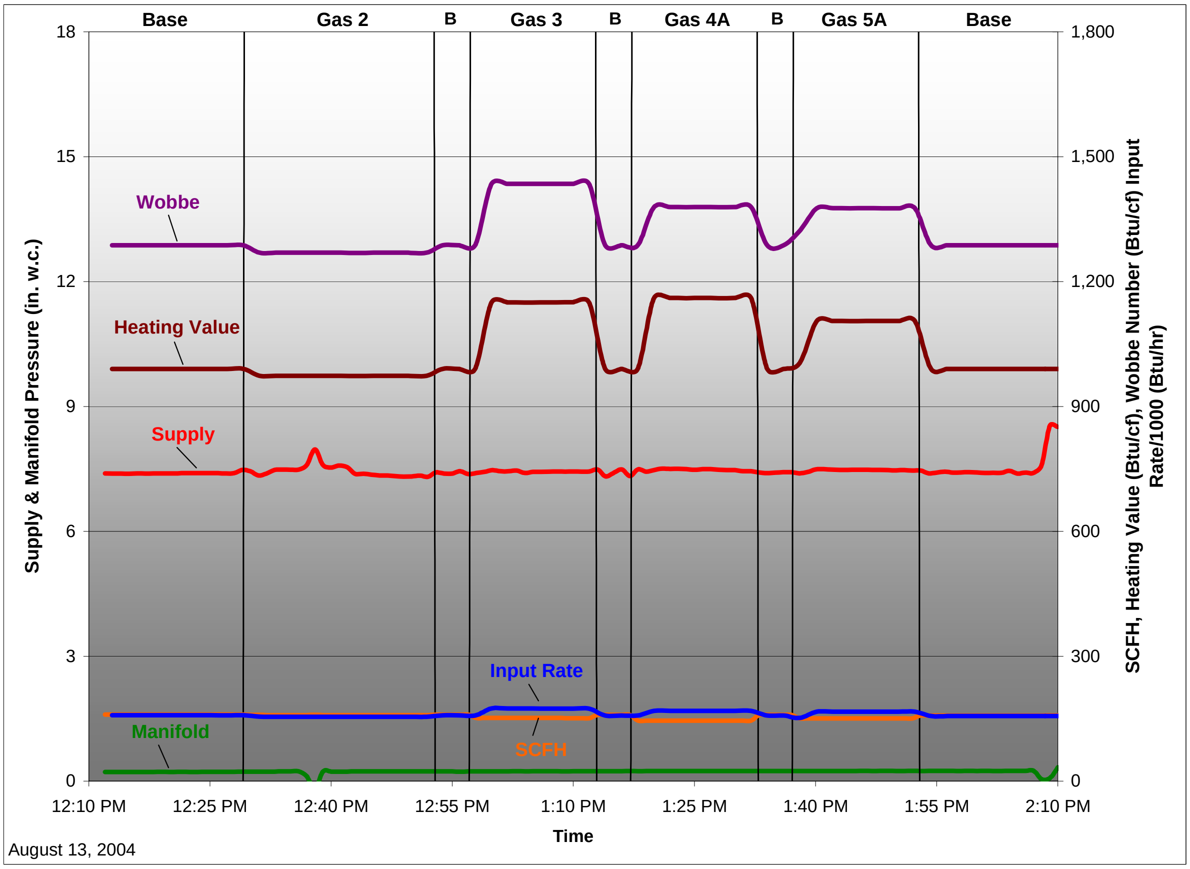


Gas Input

The condensing boiler was set to operate at the highest input condition allowed by the burner control system using baseline gas for this test sequence. The average baseline condition yielded a firing rate of 79.1% of the nameplate rating. Firing rates for the performance testing with different gas blends ranged from 77.6% (Gas #2) to 87.6% (Gas #3) of nameplate rating. Fuel gas analyses show a steady heating value and Wobbe over the course of the test sequence.

Figure 6 presents the continuous gas input measurement data for this test sequence.

Figure 6 - Gas Input Data (Performance Test)



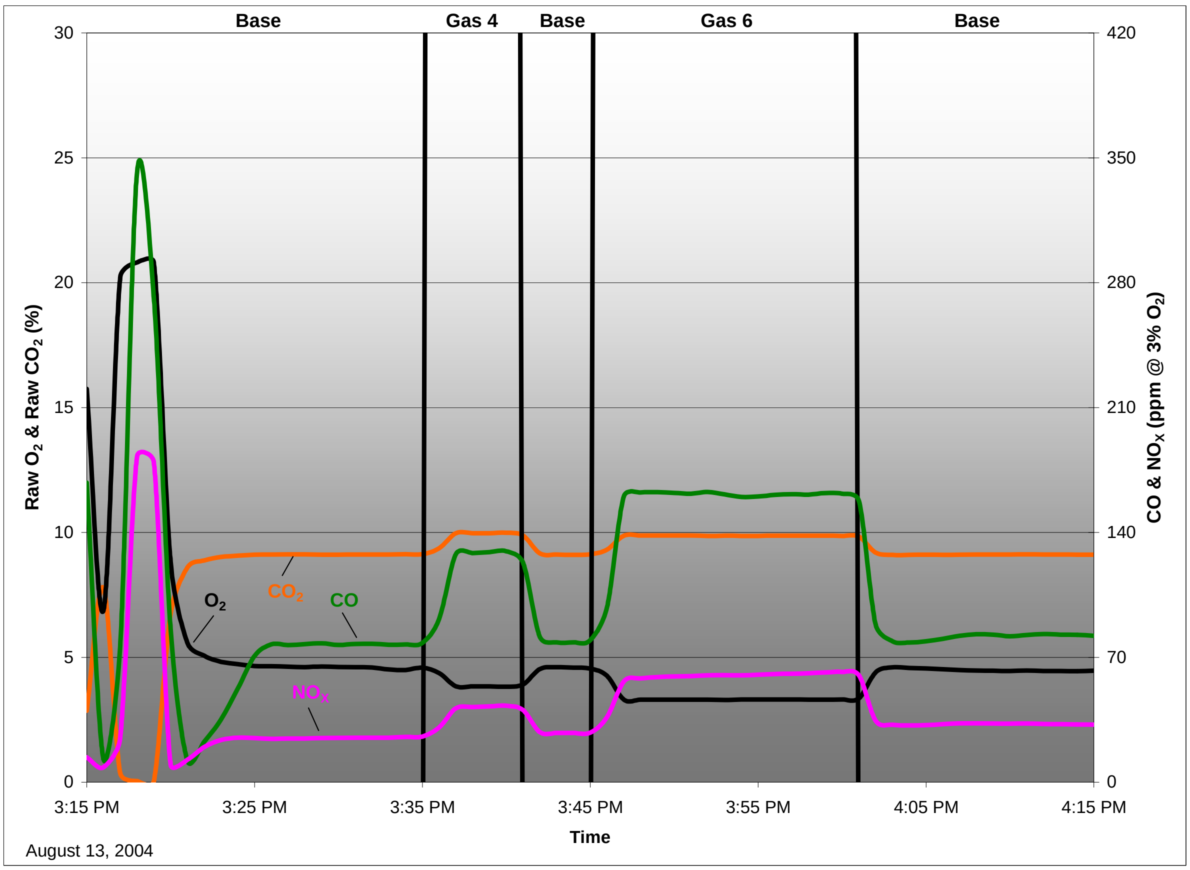
Performance Test – Additional Gases

Emissions

NO_x emissions concentrations for the as-found (baseline) condition averaged 28.5 ppm (corrected to 3% O_2). The average NO_x concentration for Gas #4 was 42.2 ppm (@ 3% O_2), compared with 47.6 ppm (@3% O_2) for Gas #4a, above. The average NO_X concentration for Gas #6 was 60.5 ppm @3% O_2).

CO emissions for the as-found (baseline) condition averaged 79.8 ppm (@ 3% O_2). The average CO concentration for Gas #4 was 128.7 ppm (@ 3% O_2), compared with 130.4 ppm (@3% O_2) for Gas #4a, above. The average NO_X concentration for Gas #6 was 161.3 ppm (@3% O_2). Figure 7 presents the continuous emissions measurement data for this test sequence.

Figure 7 – Emissions Data (Performance Test – Additional Gases)



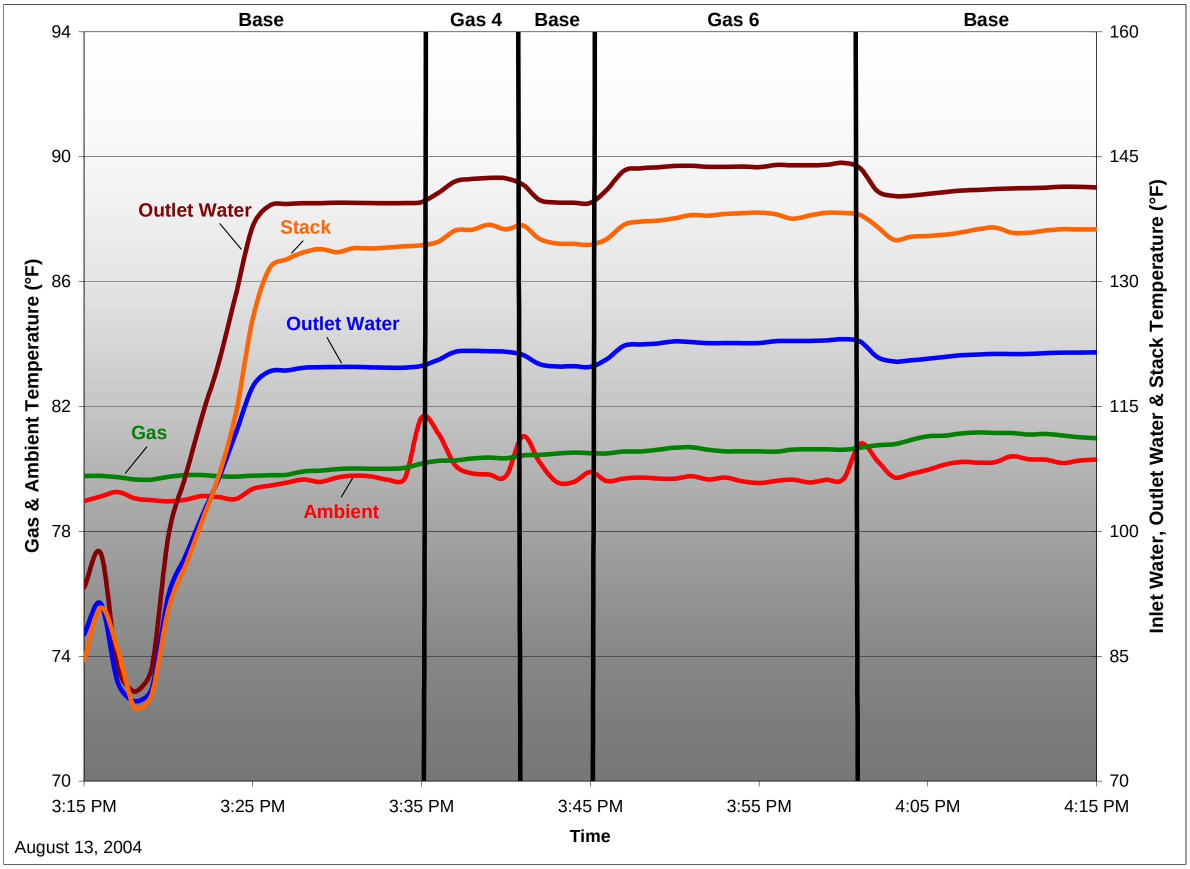
Emission test results are for information purposes. They were not the result of certified tests.

Temperatures
The temperature rise across the boiler for the baseline tests averaged 19.8 ^{o}F. The temperature differential increased slightly to 20.7 ^{o}F after switching to Gas #4. The differential was 21.1 ^{o}F when operating on Gas #6.

Stack temperatures fell within a narrow band over the test sequence, ranging from 133.6 ^{o}F (Baseline Gas) to 137.8 ^{o}F (Gas #6).

Figure 8 presents the continuous temperature measurement data for this test sequence.

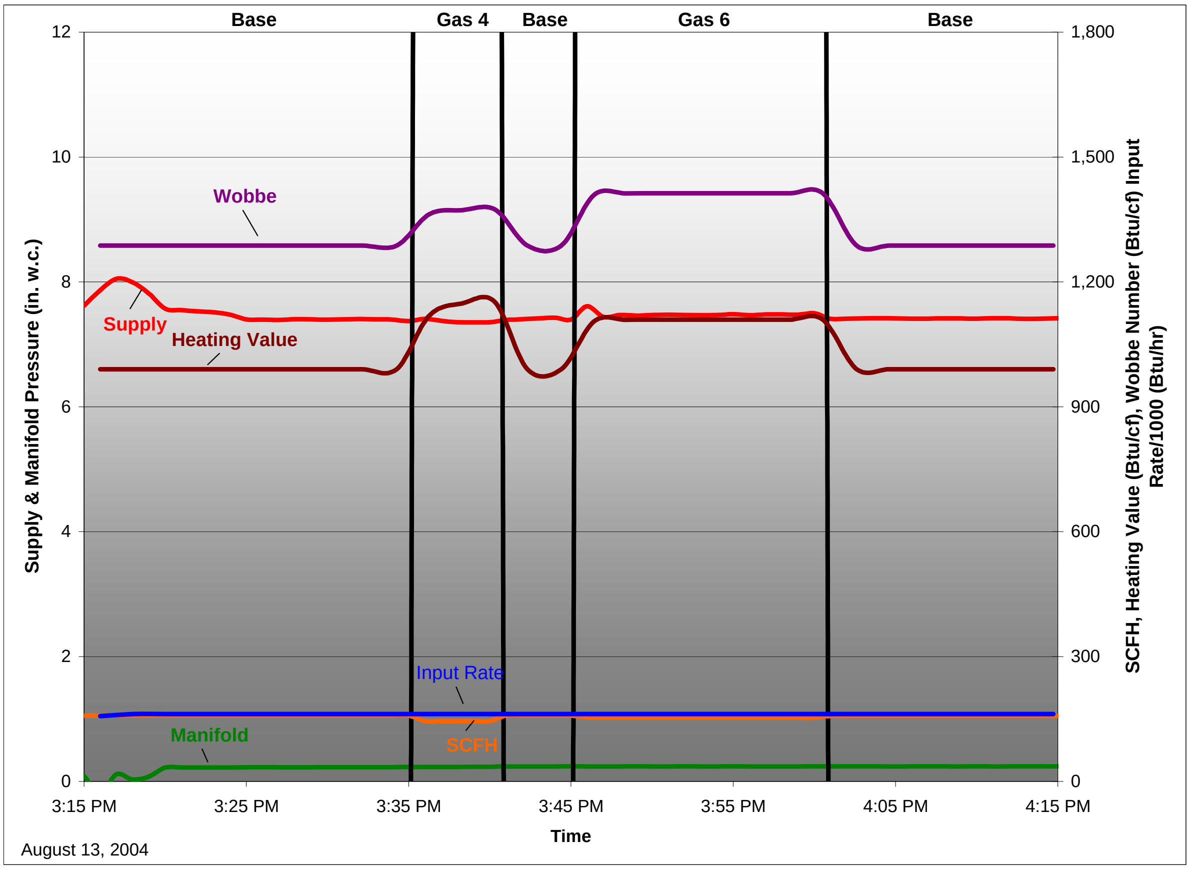
Figure 8 – Temperature Data (Performance Test – Additional Gases)



Gas Input
As above, the condensing boiler was set to operate at the highest input condition allowed by the burner control system using baseline gas for this test sequence. The average baseline condition yielded a firing rate of 78.5% of the nameplate rating. Firing rates for the performance testing with different gas blends ranged from 82.9% (Gas #4) to 85.4% (Gas #6) of nameplate rating. Fuel gas analyses show a steady heating value and Wobbe over the course of the test sequence.

Figure 9 presents the continuous gas input measurement data for this test sequence.

Figure 9 – Gas Input Data (Performance Test – Additional Gases)



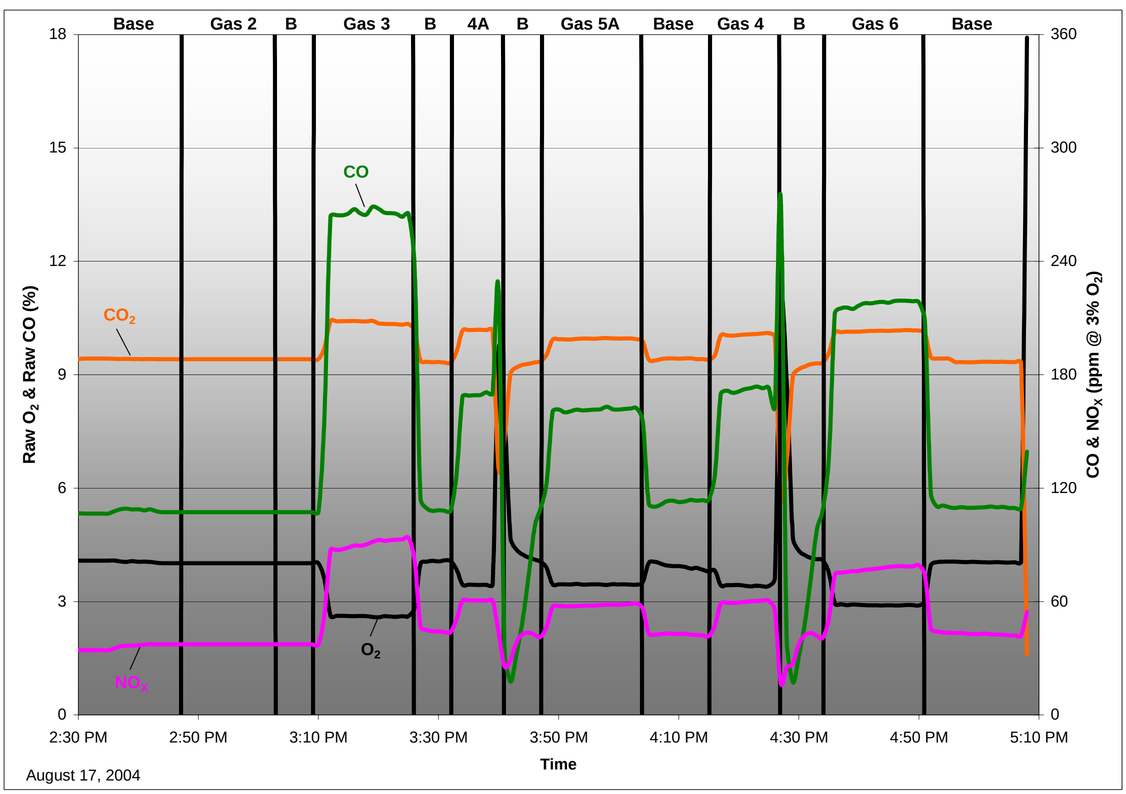
Emissions Test

Emissions

For the condensing boiler tested, results indicate that CO and NO_x emission concentrations are affected by the gas compositions used in this study. As observed with the performance test, CO and NO_x emissions during this test increased with increasing Wobbe. The measured concentrations, however, were higher during the emissions test than the performance test. This is expected, as the emissions test was conducted with a five foot exhaust duct, providing less vent restriction and increased blower speed (higher firing rate).

NO_x emissions concentrations for the base gas condition averaged 41.6 ppm (corrected to 3% O_2). The average NO_x concentration decreased to 37.3 ppm (@ 3% O_2) after switching to Gas #2. The highest average NO_X concentration (@ 3% O_2) was observed using Gas #3 was 90.6 ppm. Intermediate gas blends resulted in corrected NO_X concentrations ranging from 58 ppm (Gas #5a) to 77.2 ppm (Gas #6). CO emissions concentrations for the base gas condition averaged 109.9 ppm (corrected to 3% O_2). The average CO concentration decreased to 107.3 ppm (@ 3% O_2) after switching to Gas #2. The highest average CO concentration (@ 3% O_2) observed while using Gas #3 was 265.5 ppm. Intermediate gas blends resulted in corrected CO concentrations ranging from 161.5 ppm (Gas #5a) to 217.3 ppm (Gas #6). Figure 10 presents the continuous emissions measurement data for this test sequence.

Figure 10 – Emissions Data (Emissions Test)



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

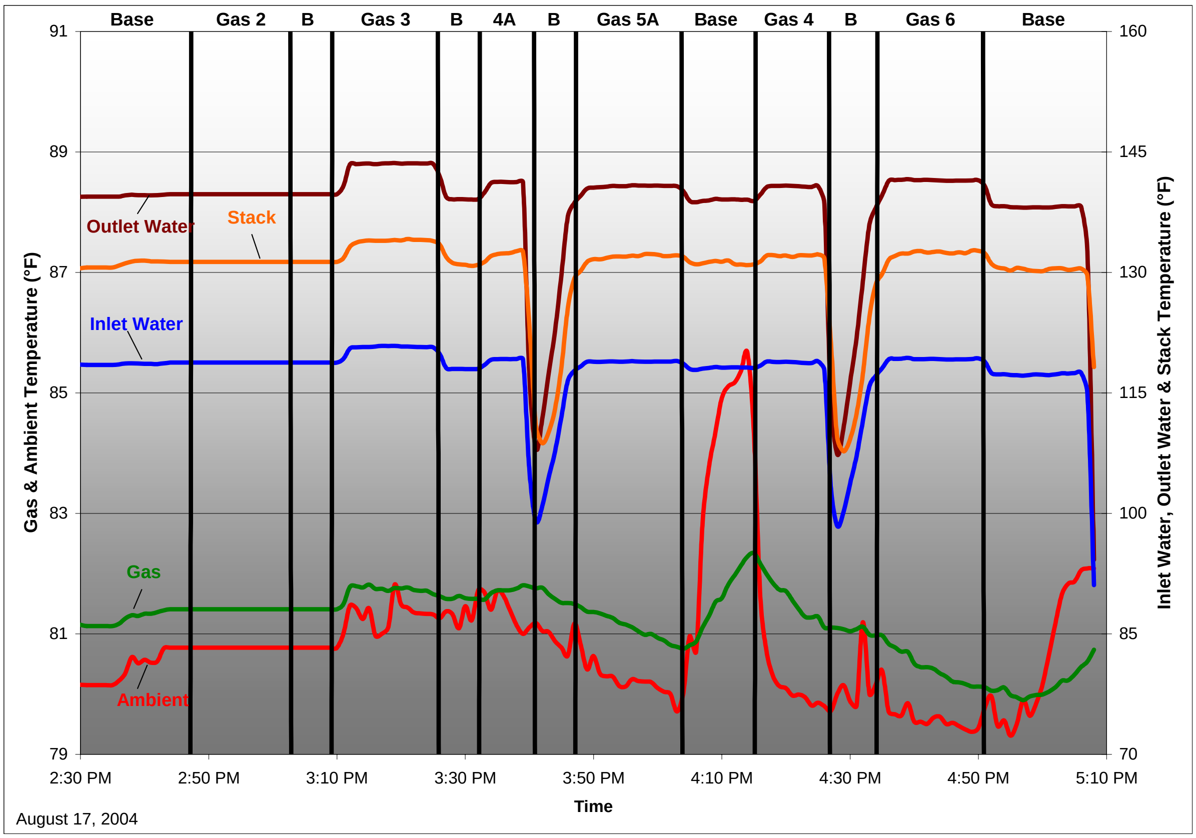
Temperatures

The temperature rise across the boiler for the baseline emissions tests averaged 21.0 ^{o}F. The temperature differential was identical to baseline (21.0 ^{o}F) after switching to Gas #2. The differential was highest when operating on Gas #3 (22.8 ^{o}F). The intermediate gas blends resulted in temperature differentials that ranged from 21.7 ^{o}F (Gas #4 to 22.3 ^{o}F (Gas #6).

Stack temperatures fell within a narrow band over the test sequence, ranging from 131.0 ^{o}F (Baseline Gas) to 133.9 ^{o}F (Gas #3).

Figure 11 presents the continuous temperature measurement data for this test sequence.

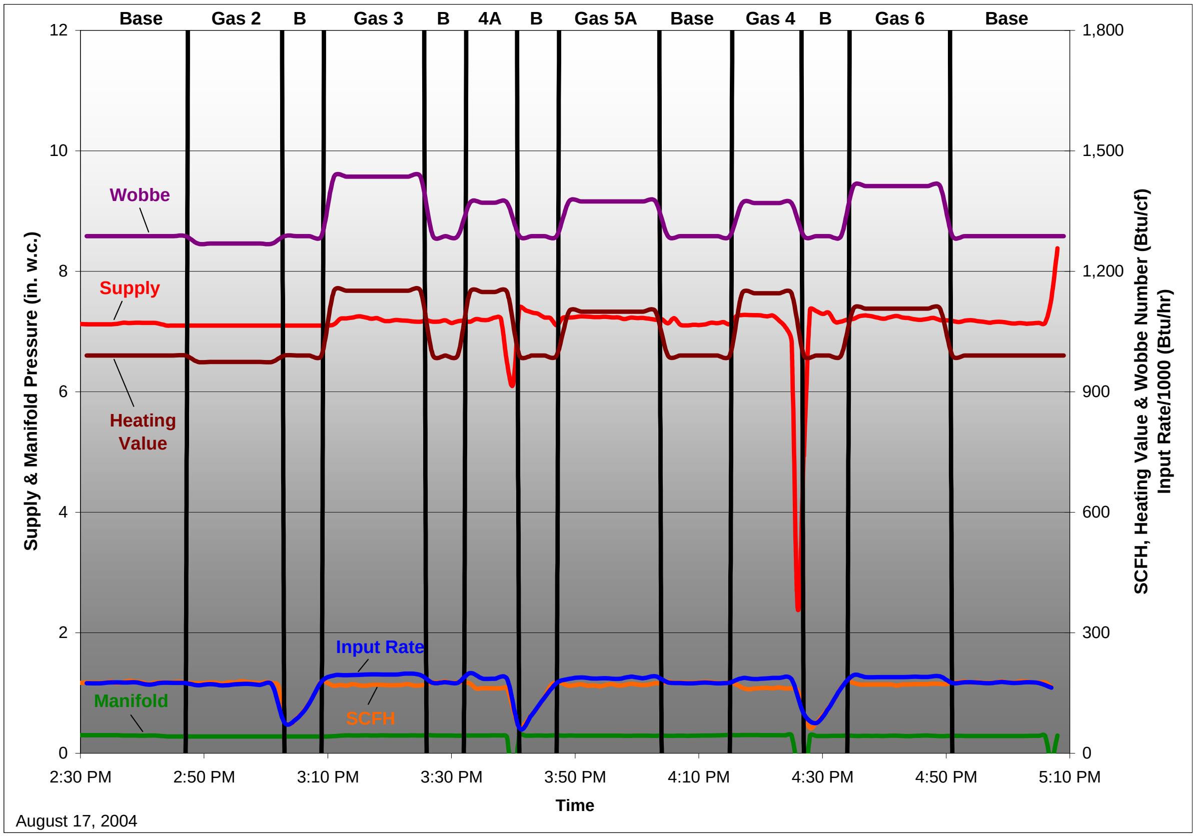
Figure 11 – Temperature Data (Emissions Test)



Gas Input
The condensing boiler was set to operate at the highest input condition allowed by the burner control system using baseline gas for this test sequence. The average baseline condition yielded a firing rate of 88.0% of the nameplate rating (compared with 79.1% firing rate during the performance tests, as noted above). Firing rates for the emissions testing with different gas blends ranged from 85.9% (Gas #2) to 98.3% (Gas #3) of nameplate rating. Fuel gas analyses show a consistent heating value and Wobbe over the course of the test sequence.

Figure 12 presents the continuous gas input measurement data for this test sequence.

Figure 12 – Gas Input Data (Emissions Test)



Ignition Testing

A series of ignition tests was performed on the condensing boiler according to the protocol detailed in Appendix A. These included hot and cold ignitions conducted at standard gas supply pressure and reduced gas supply pressure. These tests were conducted with pipeline gas, Gas #2 (lean gas), and Gas #3 (rich gas). In all cases, there was smooth flame carryover and no flashback observed during ignition. Results suggest that there are no issues related to ignition of this condensing boiler with different gas compositions.

Table 1 – Ignition Test Observations

Start Temp.	Gas	Input Pressure	Conclusion	Comments and Observations
COLD	Base	rated	normal	immediate carryover, slight lifting (yellow pulse) at first, then smooth ignition
	Base	reduced	normal	smaller, single pulse, no yellow tip, immediate carryover
HOT	Base	rated	normal	three pulse, yellow tipping on first pulse, immediate carryover
	Base	reduced	normal	one slow pulse, yellow-orange flame tips, smooth carryover
	Gas 2	reduced	normal	one slow pulse, yellow-orange flame tips, smooth carryover
	Gas 2	rated	normal	large first pulse, followed by two smaller pulses with yellow tipping, immediate carryover
	Gas 3	rated	normal	three pulse, yellow tipping on first pulse, immediate carryover
	Gas 3	reduced	normal	one slow pulse, yellow-orange flame tips, smooth carryover

Appendix A

Test Protocol – Condensing Boiler

1. Objective and General Approach

This protocol specifies procedures for conducting and reporting tests of gas-fired gas-fired hot water boilers with respect to their operation with liquefied natural gas (re-gasified). The study is to evaluate the ability of a boiler to operate through a change to or from LNG and the effect of LNG on the operation, safety, combustion emissions or other aspects of boiler performance.

The project is to be conducted by the Center for Environmental Research and Technology of the University of California, Riverside under contract with the Southern California Gas Company. The overall approach is to evaluate boiler operation successively with a “baseline” gas and gas mixtures of high and low heat content and Wobbe Number. The gases and the sequence of their introduction are specified in the LNG Research Study White Paper developed in Phase I of the study.

2. 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 NOX 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.

3. Boiler Data

Record descriptive and technical data, including the following:

3.1 Boiler rating plate data
Model number
Serial number
Rated input
Rated output
For boilers with less than 300 kBtu/h input, the AFUE rating per the FTC label. For boilers with greater input, the rated steady state efficiency.
Manifold pressure

3.2 Component data (to the extent it can be observed)
- Gas valve manufacturer & model number

- Pilot burner or igniter manufacturer & model number. For a pilot burner, record the gas orifice diameter if marked.
- Flame sensor manufacturer & model number and a written description
- Ignition control type, manufacturer & model number
- Inducer manufacturer, model number and significant rating label data
- Diameter (or drill number) of main burner orifices

3.3 Copy installation instructions/ other information shipped with the boiler.

3.4 Photograph the boiler and significant design/construction features.

4. Test Arrangement

4.1 Basic setup

The boiler is to be tested on the concrete laboratory floor. 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.

4.2 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 recirculating pump and valving necessary to adjust water flow rate and temperatures. Maintain water pressure at a level sufficient to assure proper boiler operation.

4.3 Vent pipe

For performance testing, the maximum allowable vent pipe (elbows and straight runs) per manufacturer's specifications. Provide the pipe with insulation of resistance rating 4 hr-ft-^{o}F/Btu or greater. Provide a single point sample probe in the vent pipe, approximately 1 ft. from the appliance vent outlet.

For emissions testing, a straight vertical vent pipe, five feet in length and of the diameter of the boiler vent collar, is to be provided. If necessary for laboratory ceiling & exhaust hood clearance, the height may be reduced to four feet. Provide the pipe with insulation of resistance rating 4 hr-ft-^{o}F/Btu or greater. Provide an integrated sampling probe, constructed per the AQMD protocol, six inches from the top of the vent pipe. Twelve inches from the bottom of the pipe, provide a nine-point thermocouple grid, wired as a thermopile.

4.4 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.

4.5 Electrical power

Electrical power is to be provided at the voltage specified on the boiler rating plate ± 1%.

4.6 Instrumentation

Instrumentation is to be per the SCAQMD Protocol for Rule 1146.2.

4.7 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 room 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.

4.8 Instrumentation

Instrumentation is to be per the SCAQMD Protocol for Rule 1146.2.

4.9 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.

5. Test Gases

Gas composition is specified in Appendix B of the Phase II Scope of Work:

- #1 Baseline gas
- #2 Low-Wobbe low-heat content gas
- #3 High-Wobbe high-heat content gas
- #4a Medium-Wobbe high-heat content gas
- #5a Medium-Wobbe medium-heat content gas
- #4 Medium-Wobbe high-heat content gas
- #6 Medium-Wobbe medium-heat content gas

Additional gases, consistent with the Phase II protocol are to be used when results of testing with the preceding gases indicate additional investigation is necessary.

6. Basic Operating Condition

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

6.1 Room temperature

Hold between 65 and 85^oF. Room temperature is to be measured as specified in Sections 7.4.1.6 & 7.1.6 of the AQMD Protocol.

6.2 Gas supply pressure

7.0” WC ± 0.3” WC, measured during steady operation.

6.3 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 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.

6.4 Water flow, temperature and pressure

Maintain outlet water temperature at 140^oF ± 2^oF. Maintain inlet water temperature to provide the maximum permissible temperature rise required by the Manufacturer. If a temperature rise is not specified, maintain inlet water temperature at 120^oF ± 2^oF. Maintain adequate water pressure to assure proper operation of the boiler.

7. Testing – Startup Run

Operate boiler on baseline gas for one 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” WC. Fifteen minutes after starting, record firing rate data, CO_2 and carbon monoxide emission. 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 “startup” 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 both maximum and minimum firing rates.

Verify proper operation of all equipment and instrumentation.

8. Steady operation testing

8.1 Base case at rated input

Adjust boiler to operate at the rating plate input, holding 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 6.3 above.

From a cold start record input and combustion data (CO_2 & CO) at 15 minutes and verify that the firing rate is within 2% of rated input. Immediately thereafter adjust manifold pressure to fire at 106.25% of rated input. After 15 minutes record input and combustion data (CO_2 & CO). Thereafter re-adjust manifold pressure to the basic firing setup. Then reduce the gas supply pressure to 4.0” WC and record firing rate and combustion data. After obtaining this data, return supply pressure to 7.0” WC.

Without stopping boiler, adjust water and temperature controls and water flow as necessary to operate boiler at minimum firing rate with inlet water temperature at the original value ± 5^oF. Determine the firing rate and record combustion data (CO_2 & CO).

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

8.2 Steady operation tests – baseline and substitute gases

8.2.1 Full input

8.2.1.1 Steady operation with baseline gas

Starting with the 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 (CO_2 & CO). Do not conduct “overfire” test.

Continue operation to establish that stack temperature changes by no more than ± 5^oF 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 4.7 preceding.

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 same.

8.2.1.2 Gas changeover and steady operation with substitute gases: Continue steady boiler operation with baseline gas and conduct a high-speed switch to 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 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 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 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 8.1. 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.

9. Burner and ignition operating characteristics

9.1 Operation with baseline gas

9.1.1 Full input

9.1.1.1 Cold operation

Verify or adjust boiler operation to the basic operating condition with baseline gas. Allow boiler to cool to room temperature and initiate burner operation by means of the boiler controls. Allow the burners to operate at normal manifold pressure for five seconds and turn them off. Repeat three times. Observe and record operation with respect to:

- Immediate ignition and carryover to all burners

- Flashback. If flashback is noted, allow burners to operate for 30 seconds to determine if clearing occurs.
- Flame rollout
- Instability of the main or pilot burner flames
- Repeat the sequence with supply pressure at 4.0” WC.
-

Note: For the purpose of conserving overall test time, cold operation data may be gathered at startup in other parts of the test protocol.

9.1.1.2. Hot operation
Repeat the testing of the previous section at both supply pressure conditions, starting with the boiler at steady state operation. Observe and record the same phenomena.

9.1.2 Minimum input
9.1.2.1 Cold operation
Repeat the tests of section 9.1.1.1 at minimum firing rate.

9.1.2.2 Hot operation
Repeat the tests of section 9.1.1.2 at minimum firing rate.

9.2 Operation with substitute gases
Without adjustment of boiler, return to the full input condition and switch to gas #2. When steady state conditions are achieved, turn the burners off and on three times. Observe and record observations per preceding section. In particular, note variation from operation with baseline gas and behavior with respect to areas that were of concern with the baseline gas. Repeat the sequence for gas #3.

If unusual phenomena are noted with either of the gases, conduct cold operation testing with that gas, per sections 9.1.1.1 and 9.1.2.1.

10. 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.

11. 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.

12. Calculations

NO_X emission is to be calculated per the AQMD protocol for Rule 1146.2 in terms of PPM at 3% oxygen.

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 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 five feet 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 kBtu/h input) require a five foot vertical vent pipe.

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

Water temperature:
ANSI Standard Z21.13 specifies inlet water at 80^{o}F ± 10^{o}F and outlet temperature of 180^{o}F ± 2^{o}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. For this specific case, water inlet temperature is set to 120 ^oF with a temperature rise of 20 ^oF.

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 140^oF ± 2^oF. Water temperature rise is specified at the maximum permissible stated by the manufacturer.

Appendix B

Equipment Schematics

Overall Setup for the Test Cell

The overall setup of the equipment included a number of sub systems, including gas supply, gas composition blending and analysis, gas appliance, flue gas monitoring, and data acquisition. The overall schematic is shown in Figure B1 below. Gas analysis was accomplished with a Gas Chromatograph. A schematic of the fully instrumented Condensing Boiler is shown in Figure B2.

Figure B1 – Overall Equipment Layout

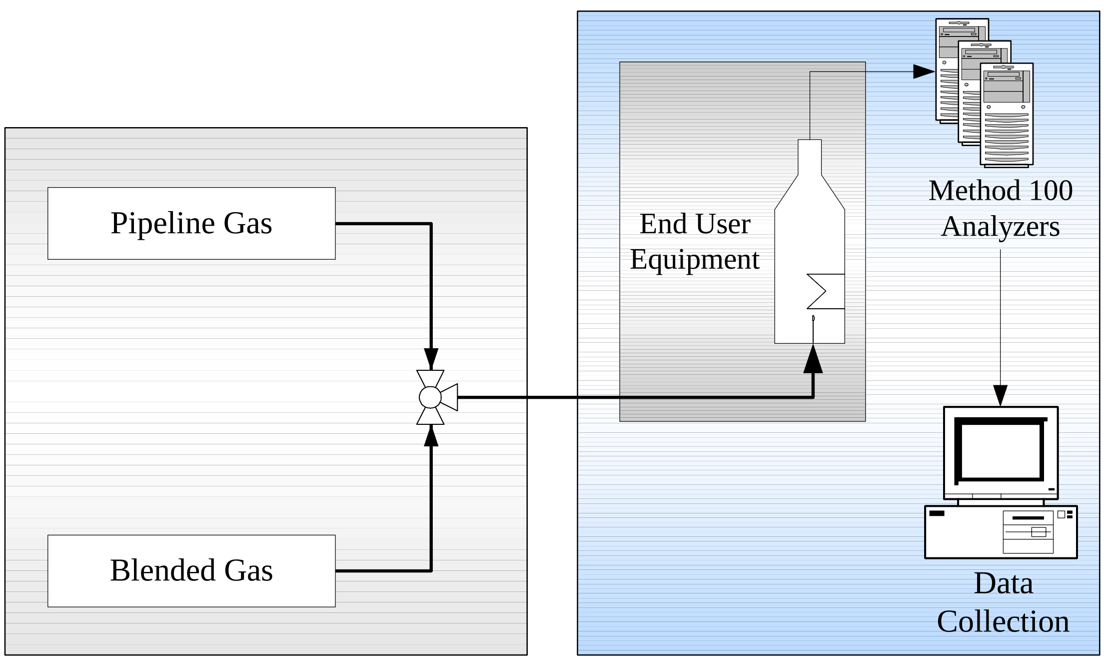
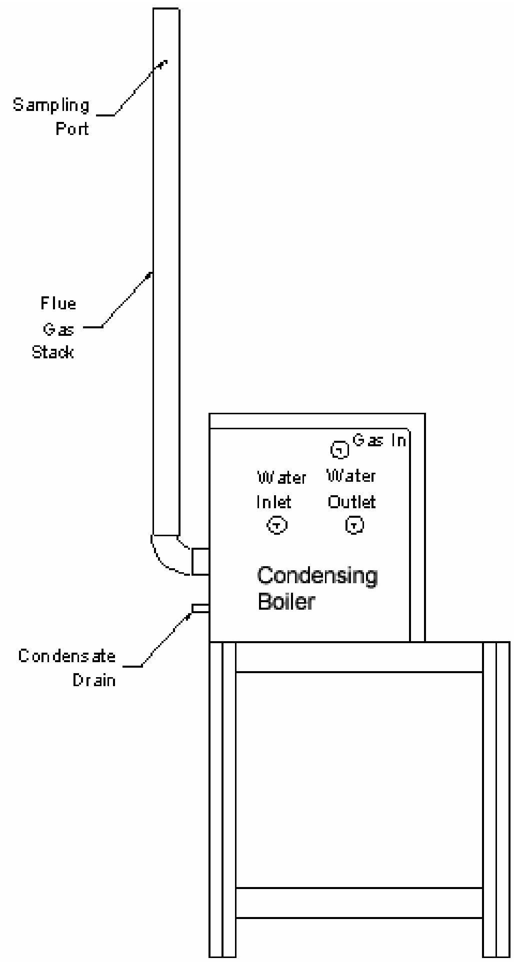


Figure B2 – Condensing Boiler Schematic with Instrumentation



Appendix C

Gas Composition and Blending

The project required testing the range of gas compositions shown in Table C1. As indicated in the Table, there were primary, secondary and tertiary gases. The primary gases included the baseline or set-up gas and others that outlined the boundary conditions for compositions determined by SCG. Secondary gases were intermediate gases within the boundary conditions and were used for processes that exhibit sensitivities to primary gases. Tertiary gas compositions depended on results from the secondary gases and had properties that were incremental changes in heat content or Wobbe number, depending on results from secondary gas.

Table C1 - Range of Some Properties and Gas Compositions for This Study

Test Gas

Primary		CH_4	C_2H_6	C_3H_8	iso-C_4H_{10}	n-C_4H_{10}	iso-C_5H_{12}	n-C_5H_{12}	C_6 plus	CO_2	O_2	N_2	Wobbe#	HHV
1	Baseline, Line Gas	96.08	1.78	0.37	0.06	0.06	0.01		0.03	1.18		0.44	1339	1022
2	970 Btu Gas	96.00								3.00	0.00	1.00	1271	974
	or 1000 Btu Gas	97.00	0.75	0.10						2.00		0.15	1315	1000
3	1150 Btu Gas, Hi Wobbe	87.03	9.23	2.76	0.99					0.00	0.00	0.00	1437	1150
4	1150 Btu Gas, Lo Wobbe	84.92	4.79	2.40	1.20	1.20	0.60	0.60	0.30	3.00	0.20	0.80	1375	1150
4a	or 4 component mix	84.45		11.55						3.00		1.00	1375	1150
Secondary														
	If fails test gas 4													
5	1100 Btu Gas, Avg. Wobbe	88.88	5.28	2.61	0.34	0.50	0.11	0.06	0.06	1.40	0.00	0.75	1376	1100
5a	or 4 component mix	90.85		7.00						1.40		0.75	1376	1099
6		91.68	5.53	1.76	0.52	0.52				0.00	0.00	0.00	1413	1107

Appendix D

Equipment List

Measurement	Equipment	Technology	Range
high CO concentration	Horiba VIA-50	NDIR	0-10% programmable
low CO concentration	Horiba CMA-331A	NDIR	0-200 ppm, 0-1000 ppm
O_2 concentration	Horiba CMA-331A	para-magnetic pressure	0-10%, 0-25%
CO_2 concentration	Horiba CMA-331A	NDIR	0-5%, 0-2%
calibration gas divider	STEC SGD-710C	capillary	10% increments
gas component flow	Unit Instruments 5301, 5361	mass flow controllers	0-50 lpm (5301), 0-100 lpm (5361)
total gas input	Rockwell R-275	dry gas meter	0-200 cfm

Appendix E

Calculations

<u>Emissions Concentrations</u>

Corrected to 3% O_2

CO and NO_x conc. (at 3% O_2) = $ppm \times \left[\frac{20.9 - 3\%}{20.9 - \%O_2} \right]$

Where

ppm = measured CO or NO_x concentration, ppmv
% O_2 = measured O_2 concentration, percent by volume

<u>Ultimate CO_2</u>

Ult. CO_2 = $Raw\,CO_2\,(\%)\,x \left[\frac{20.9}{20.9 - RawO_2} \right]$

Where

Ult. CO_2 = Ultimate CO_2 (%)
Raw CO_2 = Measured CO_2 Concentration (%)
Raw O_2 = Measured O_2 Concentration (%)

Percent 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})	$i\text{-}C_4H_{10} + 6.5O_2 + 6.5(3.78)N_2 \rightarrow 4CO_2 + 5H_2O + 6.5(3.78)N_2$	31.07	28.57
n-Butane C_4H_{10})	$n\text{-}C_4H_{10} + 6.5O_2 + 6.5(3.78)N_2 \rightarrow 4CO_2 + 5H_2O + 6.5(3.78)N_2$	31.07	28.57

To determine the percent 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 the gas blends tested, 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 (e.g. methane requires 2 moles of O_2 plus 7.56 moles of N_2 = 9.56 moles of theoretical air). The theoretical flue gas 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 (e.g. combustion of 1 mole of methane produces 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 or quadropole mass spectroscopy), the % composition of each test gas is used to determine the theoretical air and theoretical flue gas values for each gas tested. Thus,

Theoretical Air = $\sum C_1P + C_2P + \ldots + C_nP$

And

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 in decimal decimal, rather than percentage form). Therefore, the % excess air is calculated as follows:

% Excess Air = $\left[Theo.FlueValue \times \frac{Ult.CO_2 - RawCO_2}{Theo.AirValue \times RawCO_2} \right]$ X 100%

Air/Fuel Ratio = $\left[Theo.AirValue \times \frac{Theor.AirValue \times \%ExcessAir}{100} \right]$

Equivalence Ratio (ϕ)

Equivalence Ratio (ϕ) = $\frac{100}{100 + \%ExcessAir}$

Corrected Fuel Flow Rate

$$SCFH = ACFH \times GMC \times \left[\frac{FP + BP}{14.62\, psia} \right] \times \left[\frac{519.67^{o}\, R}{FT + 459.67^{o}\, F} \right]$$

Where
SCFH = standard cubic feet per hour
ACFH = actual cubic feet per hour
FP = gas supply fuel pressure (psig)
BP = barometric pressure (psia)
14.62 psia = standard atmospheric pressure
519.67 ^{o}R = standard atmospheric temperature
FT = gas supply fuel temperature (^{o}F)

Input Rate

Input Rate (Btu/hr) = SCFH x HHV

Where

SCFH = standard cubic feet per hour of fuel gas
HHV = higher heating value of fuel gas (Btu/cf)

Wobbe

W_o = $\frac{HHV}{\sqrt{SG}}$

Where

W_o = Wobbe number (Btu/cf)
HHV = higher heating value (Btu/cf)
SG = specific gravity of fuel gas

Appendix F

Tabulated Results

Table of Averages Condensing Hot Water Boiler Performance Test August 13, 2004									
Gases	**Base**	**2**	**Base**	**3**	**Base**	**4A**	**Base**	**5A**	**Base**
HHV (Btu/cf)	990	974	990	1,150	990	1,160	990	1,105	990
Wobbe (Btu/cf)	1,287	1,269	1,287	1,435	1,287	1,379	1,287	1,376	1,287
Input Rate (Btu/hr)	158,414	154,507	157,888	174,311	157,550	168,566	157,469	166,788	156,189
Corrected SCFH	160.0	158.7	159.4	151.6	159.1	145.3	159.0	150.9	157.7
Emissions (not from certified tests)									
Raw O_2 (%)	4.53	5.32	4.57	2.99	4.55	3.84	4.55	3.83	4.50
Raw CO_2 (%)	9.27	8.85	9.16	10.18	9.16	9.99	9.18	9.76	9.22
CO (ppm @ 3% O_2)	84.4	55.6	80.8	201.7	81.1	130.4	81.1	124.7	83.0
NO_X (ppm @ 3% O_2)	28.5	19.3	27.4	72.8	34.1	47.6	31.9	46.3	32.6
Ultimate CO_2 (%)	11.83	11.85	11.72	11.88	11.71	12.24	11.75	11.95	11.74
Equivalence Ratio (□)	0.80	0.75	0.80	0.87	0.80	0.83	0.80	0.83	0.80
Temperatures (°F)									
Ambient	77.0	78.1	78.6	78.4	80.1	79.6	79.7	79.8	80.3
Gas	77.4	78.3	78.8	79.3	79.9	80.1	80.2	80.5	80.8
Inlet Water	120.7	119.4	120.8	124.3	121.2	122.8	121.3	122.9	121.7
Outlet Water	140.6	138.3	140.4	145.9	141.0	143.6	141.1	143.6	141.6
Stack	134.7	132.7	134.2	138.6	135.6	136.6	134.8	136.6	134.9
Pressures									
Supply (in. w.c.)	7.40	7.43	7.40	7.44	7.41	7.48	7.41	7.47	7.43
Manifold (in. w.c.)	0.22	0.23	0.23	0.24	0.24	0.24	0.25	0.24	0.24

Table of Averages Condensing Hot Water Boiler Supplementary Test August 13, 2004					
Gases	**Base**	**4**	**Base**	**6**	**Base**
HHV (Btu/cf)	990	1,150	990	1,109	990
Wobbe (Btu/cf)	1,287	1,373	1,287	1,412	1,287
Input Rate (Btu/hr)	156,628	165,009	156,389	169,987	155,728
SCFH	158.2	144.8	157.9	153.3	157.3
Emissions (not from certified tests)					
Raw O_2 (%)	4.60	3.84	4.57	3.31	4.46
Raw CO_2 (%)	9.12	9.97	9.13	9.87	9.12
CO (ppm @ 3% O_2)	77.39	128.71	79.40	161.33	82.50
NO_X (ppm @ 3% O_2)	24.87	42.25	27.79	60.53	32.74
Ultimate CO_2 (%)	11.70	12.14	11.77	11.72	11.62
Equivalence Ratio (□)	0.78	0.83	0.81	0.85	0.81
Temperatures (°F)					
Ambient	79.35	79.89	79.82	79.66	80.17
Gas	79.86	80.33	80.49	80.60	81.04
Inlet Water	119.6	121.6	119.9	122.7	121.1
Outlet Water	139.4	142.3	139.6	143.8	141.0
Stack	133.6	136.4	134.7	137.8	136.0
Pressures					
Supply (in. w.c.)	7.40	7.36	7.41	7.47	7.41
Manifold (in. w.c.)	0.23	0.23	0.24	0.25	0.24

Gas Quality and LNG Research Study
Appendix B - 1

Table of Averages
Condensing Hot Water Boiler
Emissions & Efficiency Test
August 17, 2004

Gases	**Base**	**2**	**3**	**Base**	**4A**	**5A**	**Base**	**4**	**6**	**Base**
HHV (Btu/cf)	990	974	1,152	990	1,148	1,100	990	1,145	1,107	990
Wobbe (Btu/cf)	1,287	1,269	1,436	1,287	1,371	1,374	1,287	1,370	1,412	1,287
Input Rate (Btu/hr)	174,994	170,881	195,547	175,948	189,220	187,716	175,296	186,122	190,642	174,431
SCFH	176.7	176.0	169.8	177.0	161.7	170.5	176.7	162.0	171.6	177.1
Emissions (not from certified tests)										
Raw O_2 (%)	4.1	4.0	2.6	4.1	3.4	3.5	3.9	3.4	2.9	4.0
Raw CO_2 (%)	9.4	9.4	10.4	9.3	10.2	10.0	9.4	10.1	10.2	9.4
CO (ppm @ 3% O_2)	107.6	107.3	265.5	109.3	169.4	161.5	112.7	172.0	217.3	109.9
NO_X (ppm @ 3% O_2)	36.0	37.3	90.6	44.7	60.5	58.0	42.6	59.8	77.2	42.9
Ultimate CO_2 (%)	11.7	11.6	11.9	11.6	12.2	11.9	11.6	12.0	11.8	11.6
Equivalence Ratio (□)	0.82	0.82	0.89	0.82	0.85	0.85	0.83	0.85	0.87	0.82
Temperatures (°F)										
Ambient	80.4	80.8	81.3	81.4	81.4	80.2	83.6	80.2	79.6	80.6
Gas	81.3	81.4	81.7	81.6	81.7	81.1	81.5	81.6	80.5	80.2
Inlet Water	118.7	118.8	120.7	118.0	119.2	118.9	118.1	118.7	119.2	117.3
Outlet Water	139.6	139.7	143.5	139.2	141.2	140.7	139.0	140.4	141.5	138.2
Stack	131.3	131.3	133.9	131.1	132.4	132.0	131.2	132.0	132.4	130.4
Pressures										
Supply (in. w.c.)	7.1	7.1	7.2	7.2	7.2	7.2	7.1	7.3	7.2	7.2
Manifold (in. w.c.)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3