LNG Research Study

Testing of a Flammable Vapor Ignition Resistant (FVIR) Water Heater

Prepared for
The Southern California Gas Company

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Disclaimer

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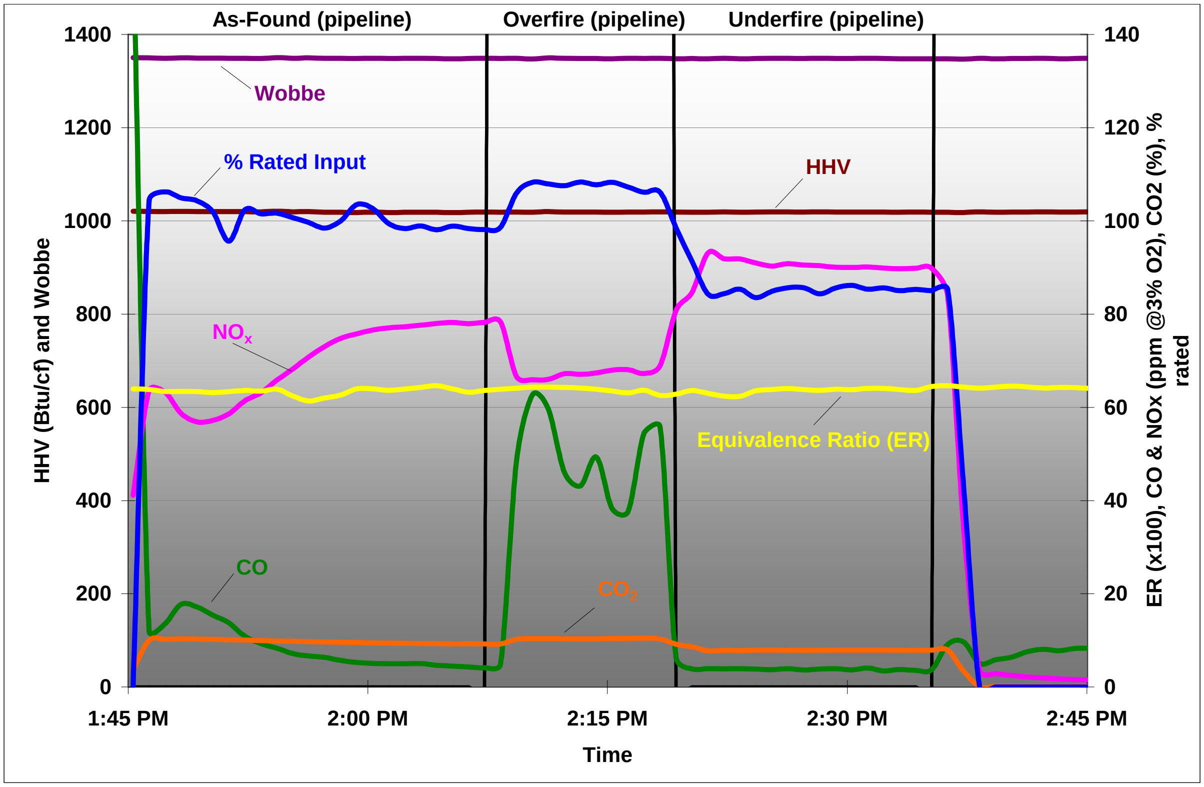
RESULTS SUMMARY

The residential flammable vapor ignition resistant water heater (FVIR-WH) was tested over a wide range of operating conditions, gas properties and composition and did not show significant sensitivities to the gas blends tested with regard to safety, performance or 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.

As-Found, Overfired, and Underfired Test

NO_x emissions during the test sequence, corrected to 3% oxygen, ranged from 70 ppm (overfired) to 89 ppm (underfired). CO emissions were all below 5 ppm, except for the overfired condition, where the corrected CO concentration averaged 40 ppm. The as-found firing rate was 98.5% of the rated input. A summary of the continuous test data and calculations for the as found, overfired, and underfired test is shown in Figure 1.

Figure 1 – Summary of FVIR –WH As-Found, Overfired, and Underfired Testing



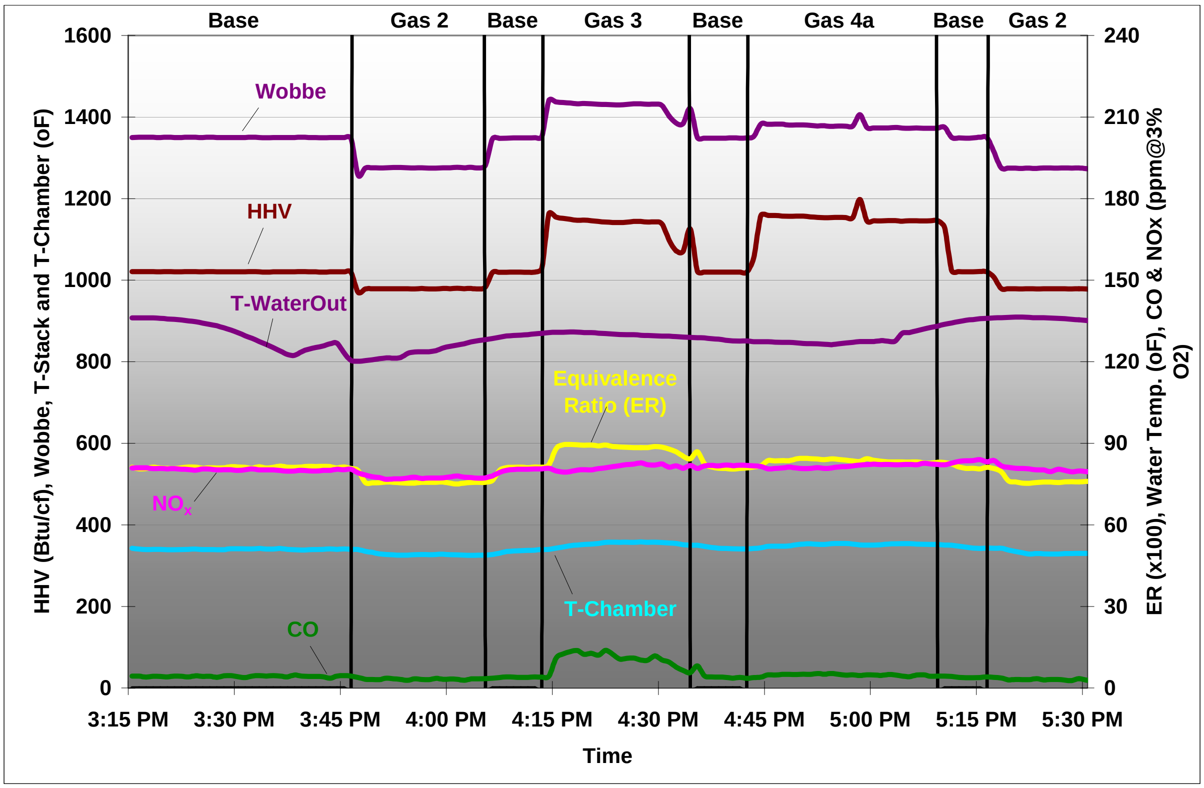
[1] Emission test results are for information purposes. They were not the result of certified tests.

Performance Test

NO_x emissions during the test sequence, corrected to 3% oxygen, ranged from 79 ppm (Gas #2) to 82 ppm (Gas #3, Gas #4a). CO emissions were all below 5 ppm, except for Gas #3, where the corrected CO concentration averaged 11 ppm. The initial baseline firing rate was 97.8% of the rated input, slightly below the 98% called for in the test protocol.

Stack temperatures and combustion chamber temperatures were slightly higher when operating on high Btu fuel (Gas #3 and Gas #4a), but remained well below temperatures that would pose an operating concern. A summary of the continuous test data and calculations for the performance test is shown in Figure 2.

Figure 2 – Summary of FVIR-WH Performance Testing

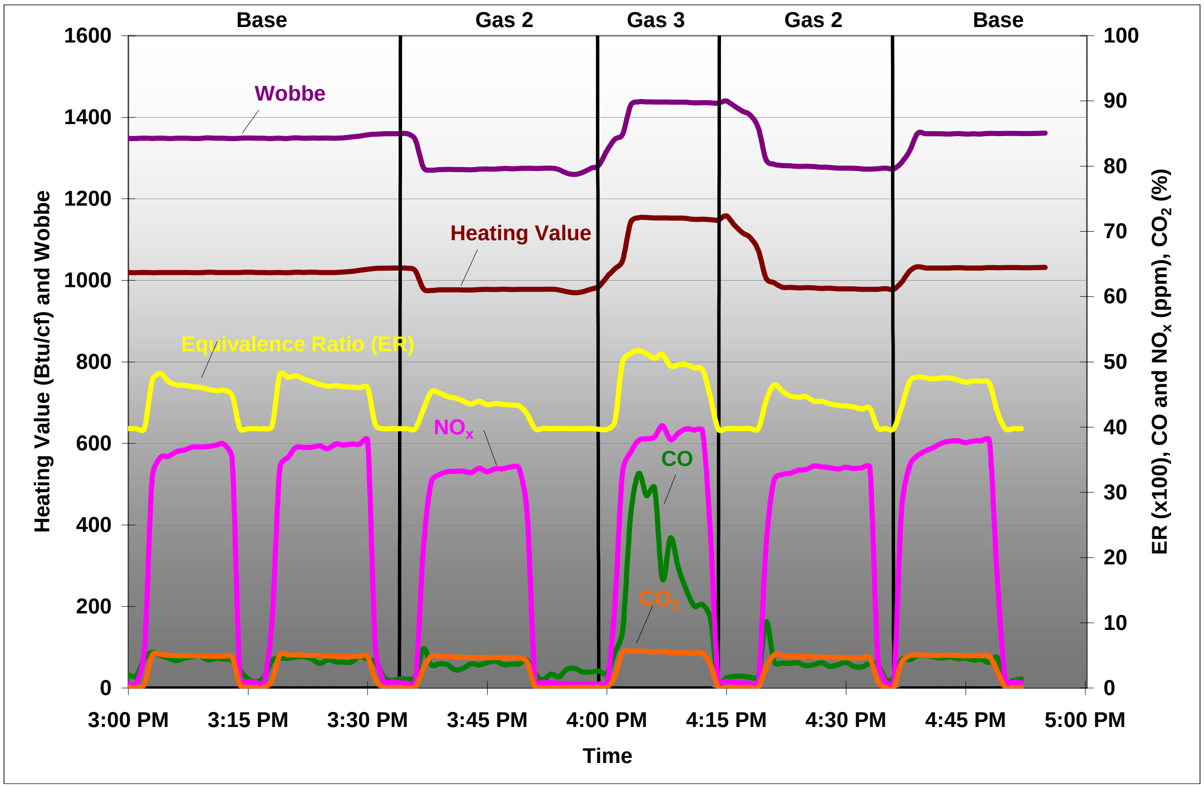


[1] Emission test results are for information purposes. They were not the result of certified tests

Emissions Test

All tests (including baseline gas) yielded NO_x emission factors that were higher than anticipated. CO emissions, corrected to 3% oxygen, were all below 10 ppm, except for Gas #3, where the corrected CO concentration averaged 44.9 ppm. The average baseline firing rate was 100.4% of the rated input. A summary of the continuous test data and calculations for the emissions test is shown in Figure 3.

Figure 3 – Summary of FVIR-WH Emissions Testing



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

EQUIPMENT SELECTION CRITERIA

The particular features of this water heater that make it important to study is that it represents modern technology that has recently come into widespread residential use. New regulations are designed to limit flammable vapor fires that take place where the water heater is located. The flammable vapor resistant technologies incorporate a flame arrestor to prevent flames from leaving the combustion chamber of the water heater. By design, this flame arrestor has a smaller combustion air opening than traditional water heaters, and could potentially decrease air/fuel ratio when fueled with rich gases. The protocol development was guided by the ANSI standard and the regulations of the South Coast Air Quality Management District.

EQUIPMENT SPECIFICATIONS

Description: Gas-fired flammable vapor ignition resistant residential water heater
Burner Type: Radial atmospheric with combustion air cutoff
Input rating: 36,000 Btu/hr
Storage tank volume: 40 U.S. gal.
Type of fuel: Natural gas
Required fuel inlet supply pressure: 5.0 – 10.5” W.C.
Gas manifold pressure: 4.0” W.C.

STANDARDS

A test protocol was developed based on the following standards:

- ANSI Z21.10.1-2001, Standard for Gas Water Heaters, Volume I.
- South Coast Air Quality Management District Rule 1121, Control of NOX Emission from Residential Type Natural Gas-Fired Water Heaters, last amended December 10, 1999.
- South Coast Air Quality Management District Protocol for Rule 1121, 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 FVIR-WH 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, water heater base, flue gas, combustion chamber, and several locations in the storage tank. Pressure transducers were installed to measure supply, gas meter, manifold, atmospheric, and water pressures. A schematic of the instrumented FVIR-WH is shown in Appendix B (Figure B2).

Installation specific to Initial Tests and 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 (upstream of the vent cap). For these tests, there was no additional vent pipe installed beyond the vent cap.

Installation Specific to Emissions Tests
For emissions testing, an integrated sampling probe was installed in a four-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 1121 protocol.

Once instrumentation was installed, the FVIR-WH was operated on pipeline gas to verify that the water heater 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

Four types of tests were conducted in evaluating the FVIR-WH:

1) As-found, overfired, and underfired
2) Performance
3) Emissions
4) Ignitions

Testing the FVIR-WH 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 heater 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 Figure 3 below. 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.

As-Found, Overfired, and Underfired Tests
The water heater was fired from a cold (ambient) condition, with the thermostat set to the highest level to ensure continuous firing throughout the test period. This series consisted of a continuous test run, with three distinct operating conditions:

1) “As-Found” condition, where the heater was operated at the manufacturer’s gas supply specifications
2) “Overfired” condition, where the manifold pressure was increased to a point approximating 106.25% rated input
3) “Underfired” condition, where the main gas supply pressure was reduced to 4” W.C. (from normal supply pressure of 7.0” W.C.)

Performance Tests

The water heater was set to maintain a constant 130 ^{o}F outlet water temperature via adjustment of the water outlet control valve. The gas supply was set to within 2% of the manufacturer’s rated input on baseline gas. The water heater was operated for approximately 15 minutes at this condition, followed by 15-minute segments using Gas #2, Gas #3, and Gas #4a. The unit was returned to baseline gas for a five-minute period between gas each gas blend switch.

Emissions Tests

The emissions tests consisted of batch draws of 10.7 gallons over a three-minute period from a stable operating condition. Emissions measurements for calculation purposes were based on the last three minutes of burner operation prior to cutout for each gas tested. Emissions tests were conducted using baseline gas, Gas #2 (low heating value, low Wobbe), and Gas #3 (High heating value, high Wobbe).

Ignition Tests

The FVIR-WH was tested for pilot and ignition performance with various gas blends under a number of different conditions, including ignitions at rated manifold pressure, at reduced manifold pressure, with pilot turndown, and with a repetitive sequence. For each of the ignition sequences, visual observations were made to determine any ignition delays, flame carryover, flashback and/or other flame phenomena.

RESULTS

As-Found, Overfired, and Underfired Test

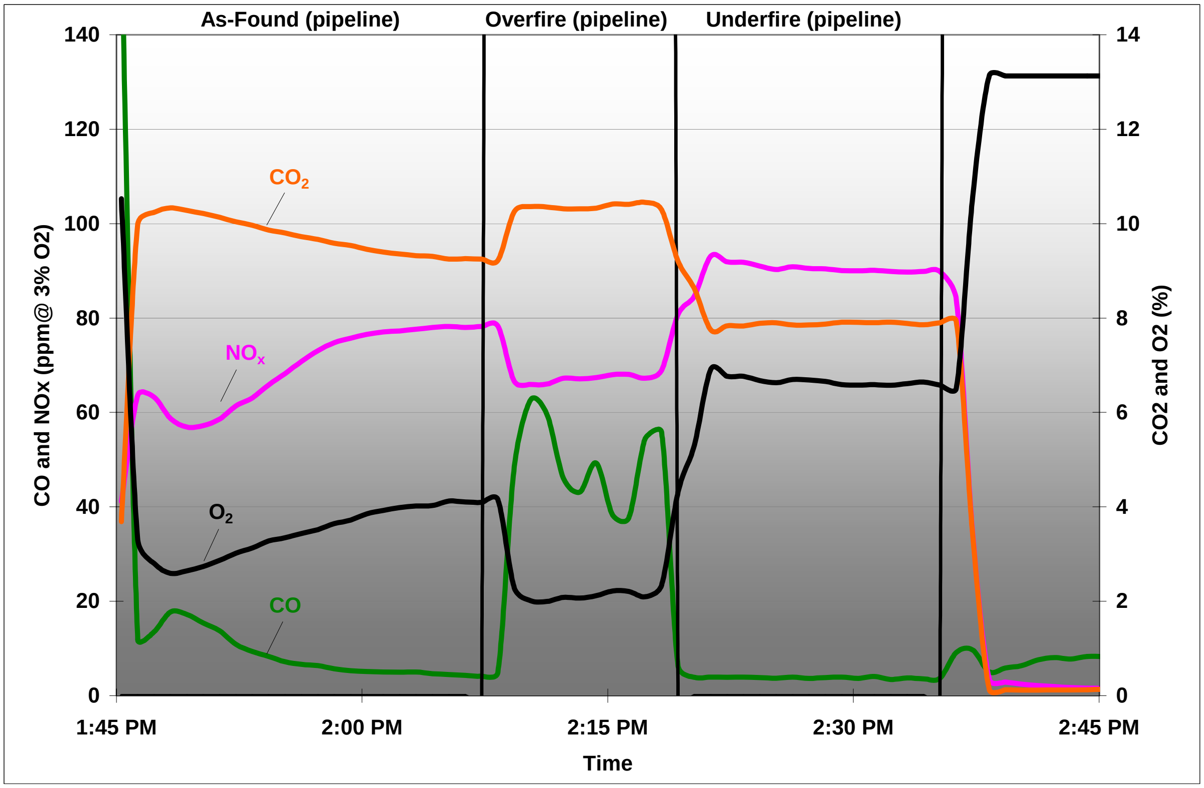
Emissions

NO_x emissions concentrations for the as-found condition averaged 78 ppm (corrected to 3% O_2). The average NO_x concentration decreased to 70 ppm (@ 3% O_2) after switching to the overfired condition. The highest levels of NO_x, measured during the test sequence [89 ppm (@ 3% O_2)], were seen during the underfired test.

CO emissions for the as-found and underfired conditions were below 5 ppm (@ 3% O_2). CO emissions for the overfired condition averaged 40 ppm (@ 3% O_2).

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

Figure 4 – Emissions Data (As-found, Overfired, and Underfired Test)



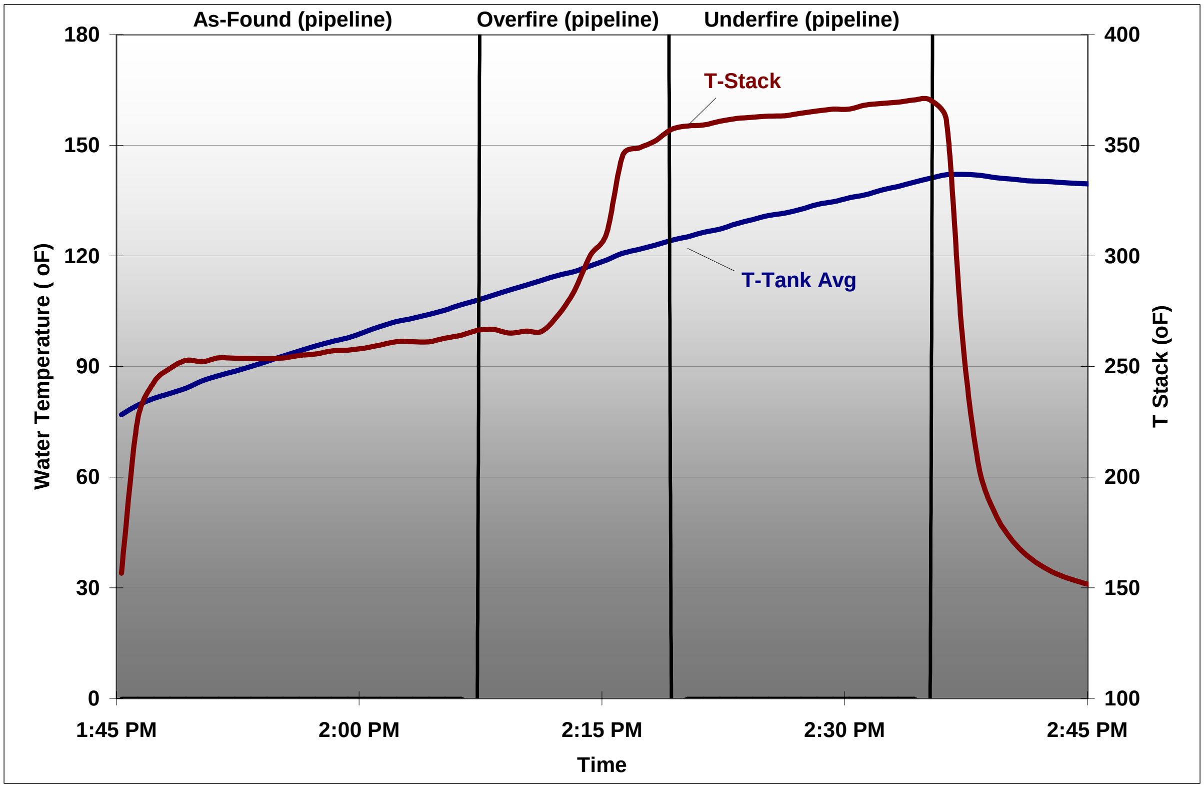
Emission test results are for information purposes. They were not the result of certified tests.

Temperatures
As expected, the mean tank temperature shows a gradual increase over the course of the test sequence (the testing began with the tank temperature at ambient conditions, and the thermostat set to the highest setting). The tank temperature levels off following the final (underfired) sequence, indicating burner cutout at the thermostat set point.

While the stack temperature shows the same general "warm-up" trend as the mean tank temperature over the test sequence, the trend appears to be accelerated by the overfire condition.

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

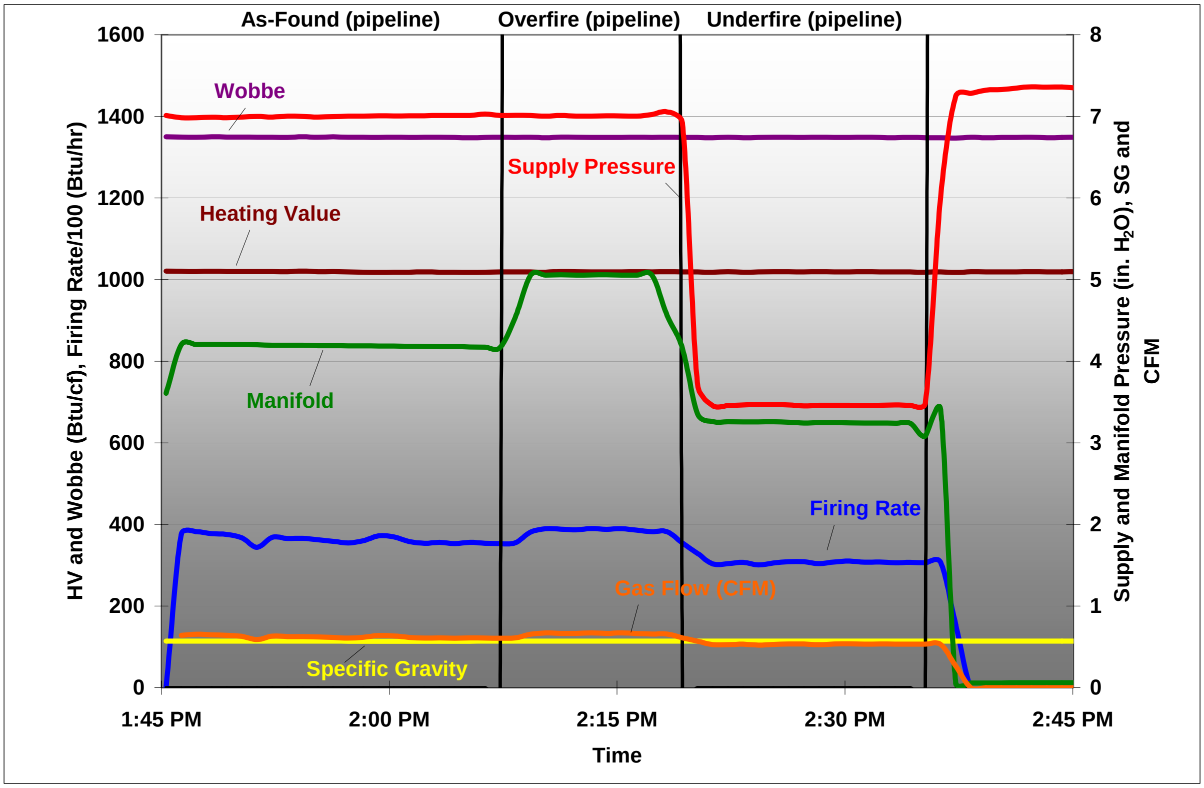
Figure 5 – Temperature Data (As-Found, Overfired, and Underfired Test)



Gas Input
The FVIR-WH was operated at three distinct gas supply conditions using baseline gas for this test sequence. The as-found condition yielded a firing rate of 98.5% of the nameplate rating. The overfired condition (achieved by increasing gas manifold pressure from 4.2 in. to 5.0 in W.C.) resulted in a firing rate of 105.7% of the nameplate. The underfired condition (achieved by reducing the gas supply pressure from 7.0 in. to 3.5 in. W.C.) resulted in a firing rate of 85.2% of the nameplate. Fuel gas analyses show a consistent 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 (As-Found, Overfired, and Underfired Test)



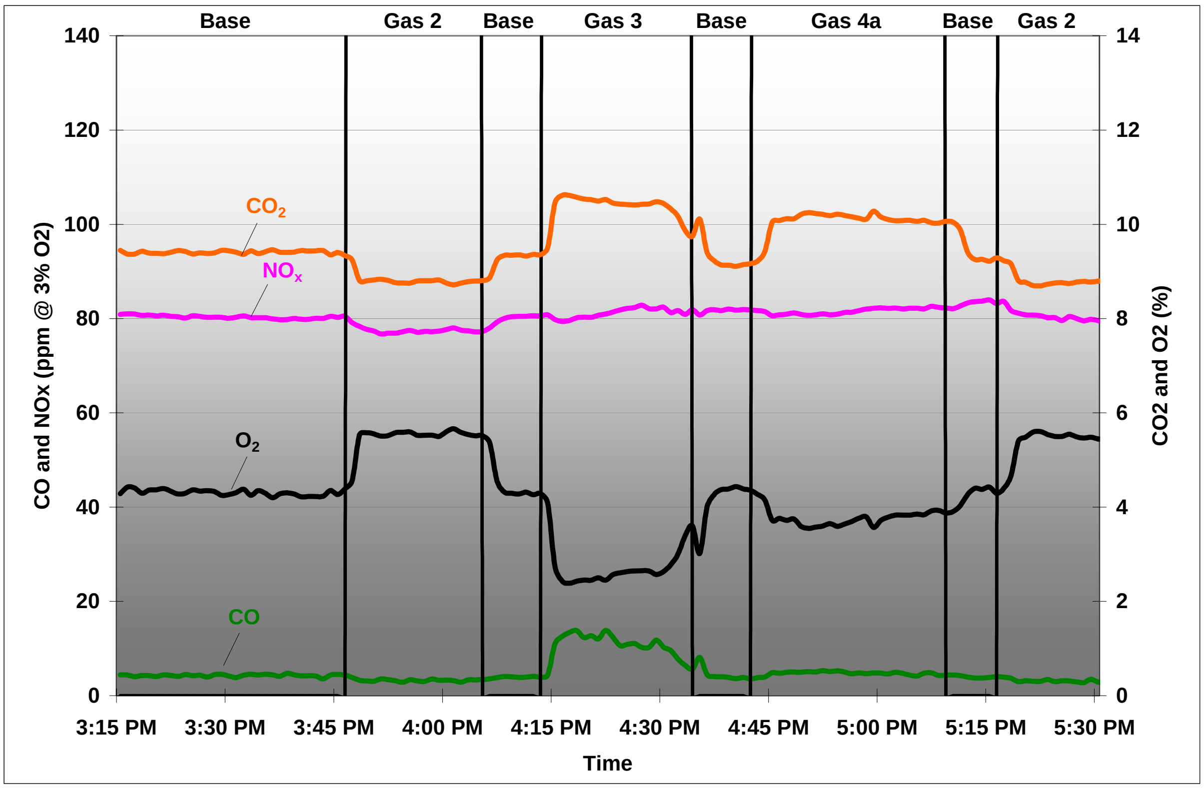
Performance Test

Emissions

NO_x emissions during the performance test fell within a narrow range of corrected concentrations over a large range of gases tested. NO_x emissions concentrations for the base gas condition averaged 81 ppm (corrected to 3% O_2). The average NO_x concentration decreased to 79 ppm (@ 3% O_2) after switching to Gas #2. The average NOx concentration (@ 3% O_2) using both Gas #3 and Gas #4a was 82 ppm.

CO emissions over the range of gases tested were below 5 ppm (@ 3% O_2), except for Gas #3, where average CO emissions were 11 ppm (@3% O_2). Figure 7 presents the continuous emissions measurement data for this test sequence.

Figure 7 – Emissions Data (Performance Test)



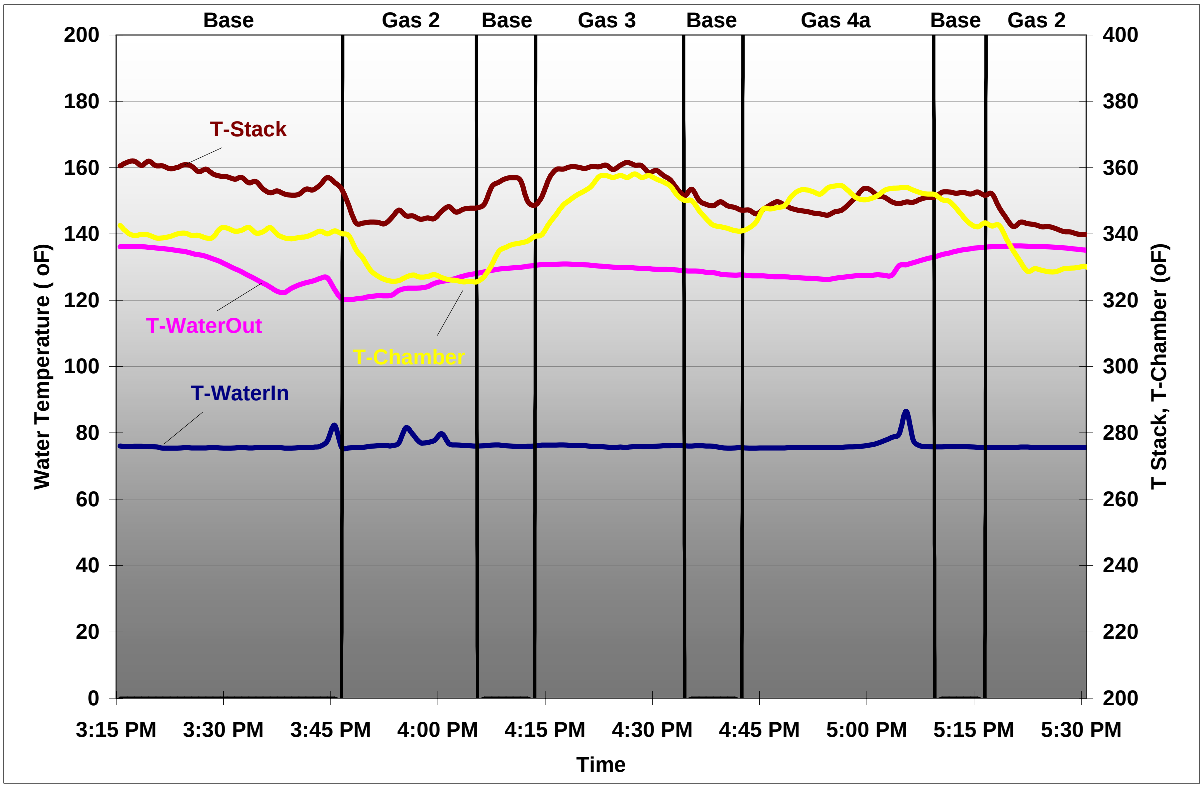
Emission test results are for information purposes. They were not the result of certified tests.

Temperatures

As expected, stack temperatures and combustion chamber temperatures were slightly higher when operating on high Btu fuel (Gas #3 and Gas #4a), but remained well below temperatures that would pose an operating concern.

Figure 8 presents the continuous temperature measurement data for this test sequence. “T-Chamber” temperature refers to thermocouple located in the combustion chamber.

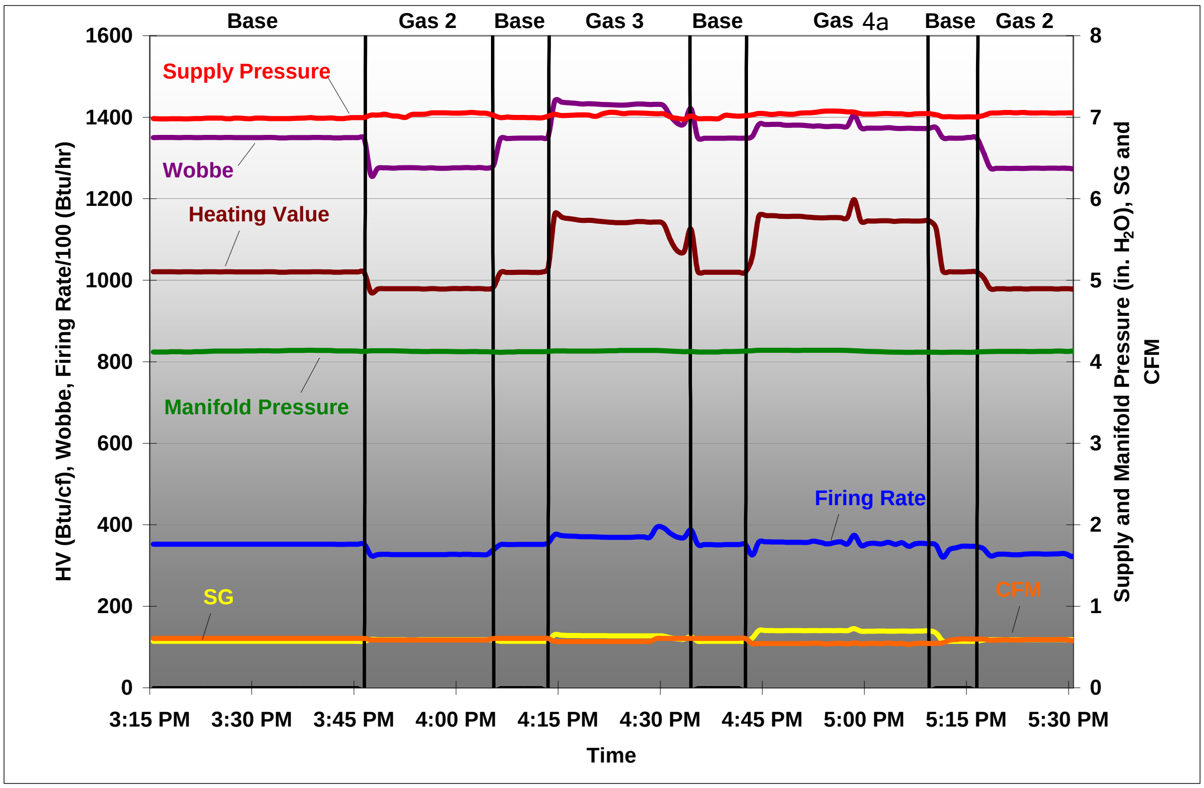
Figure 8 – Temperature Data (Performance Test)



Gas Input
The average Base gas firing rate (4 tests) was 97.8% of the nameplate rating, except for the last run, which fell to 94.7%. The Gas #2 firing rate averaged 90.9% of the nameplate. The Gas #3 firing rate averaged 102.6% of the nameplate firing rate. Gas #4a yielded a 98.2% of the firing rate. Fuel gas analyses show a consistent heating value and Wobbe over the course of the test sequence, except for a spike during operation of Gas 4a. In this case, the test was extended to provide a minimum of 15 minutes of steady state data.

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

Figure 9 – Gas Input Data (Performance Test)



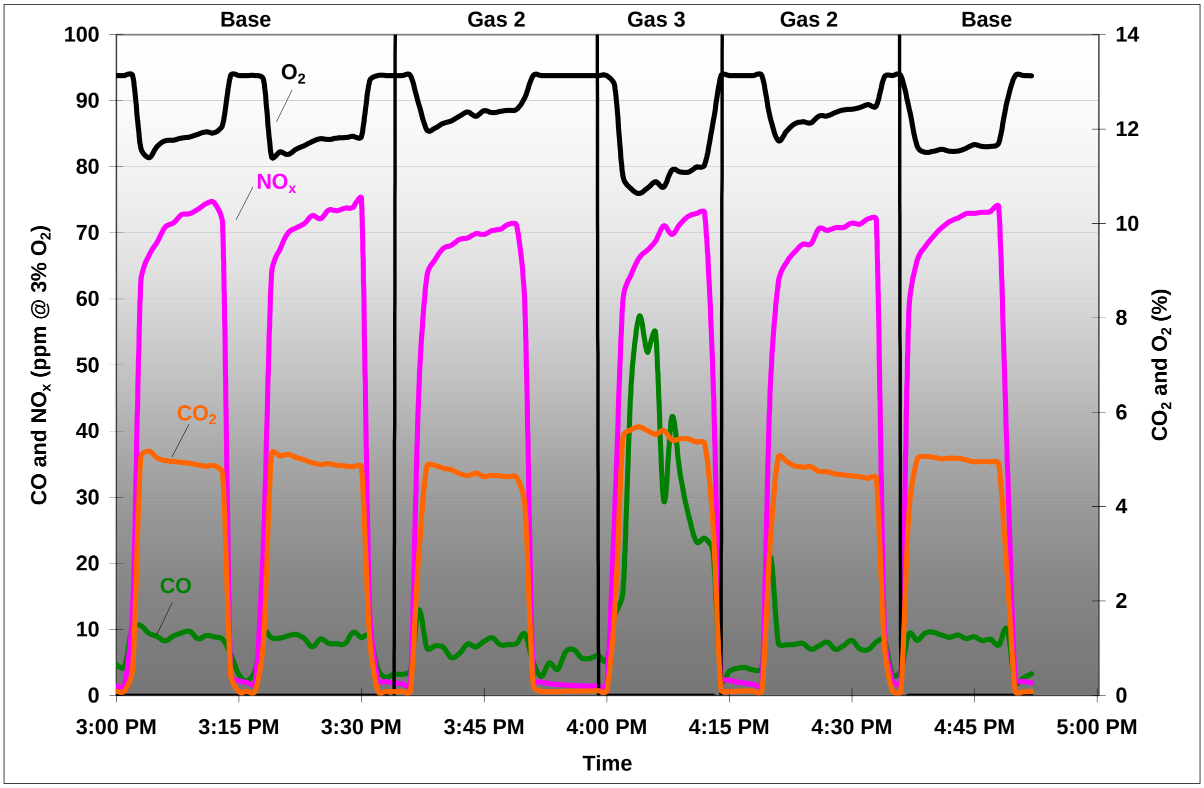
Emissions Test

Emissions

For the FVIR water heater tested, results indicate that NO_x emission concentrations and heat output-based emission factors are not affected by the gas compositions used in this study. As observed with the performance test, NO_x emissions during this test fell within a narrow range of corrected concentrations over a large range of gases tested. The corrected NO_x concentrations, however, were lower during the emissions test than the performance test. This is expected, as the performance test was conducted with the emissions probe in the flue outlet without a vent pipe, and the emissions test probe was installed in the four-foot long vent pipe and that allowed more air dilution. NO_x emissions concentrations for the base gas condition averaged 72 ppm (corrected to 3% O_2). The average NO_x concentration decreased to 70.5 ppm (@ 3% O_2) after switching to Gas #2. The average NOx concentration (@ 3% O_2) using Gas #3 was 69 ppm.

CO emissions over the entire test ranged from 7.7 ppm (@ 3% O_2) for Gas #2 to 45 ppm (@3% O_2) for Gas #3. Figure 10 presents the continuous emissions measurement data for this test sequence.

Figure 10 – Emissions Data (Emissions Test)

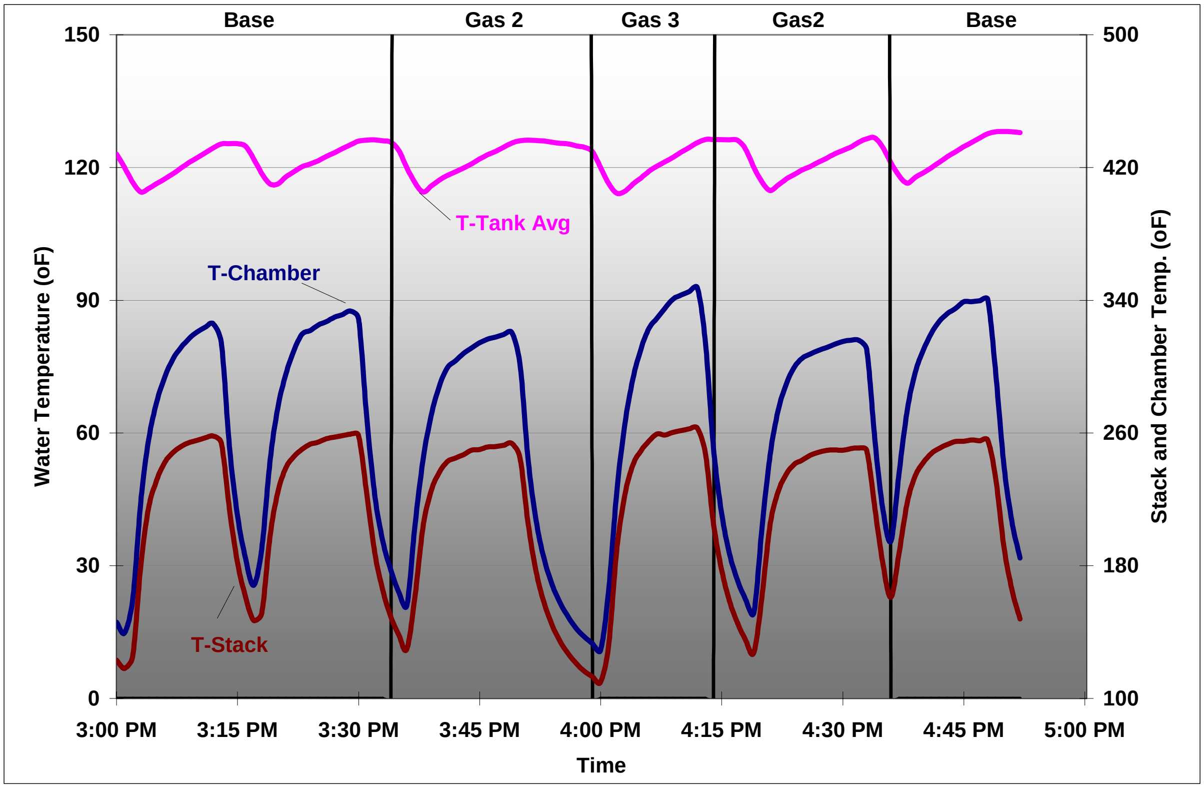


Emission test results are for information purposes. They were not the result of certified tests.

Temperatures
Maximum stack temperatures ranged from 248 °F (Gas #2) to 254 °F (Gas #3). Likewise, maximum combustion chamber temperatures ranged from 310 °F (Gas #2) to 322 °F (Gas #3).

Figure 11 presents the continuous temperature measurement data for this test sequence. "T-Chamber" temperature refers to thermocouple located in the combustion chamber. The mean tank temperatures, combustion chamber temperatures, and stack temperatures all show the effects of the burner cycling on and off.

Figure 11 – Temperature Data (Emissions Test)

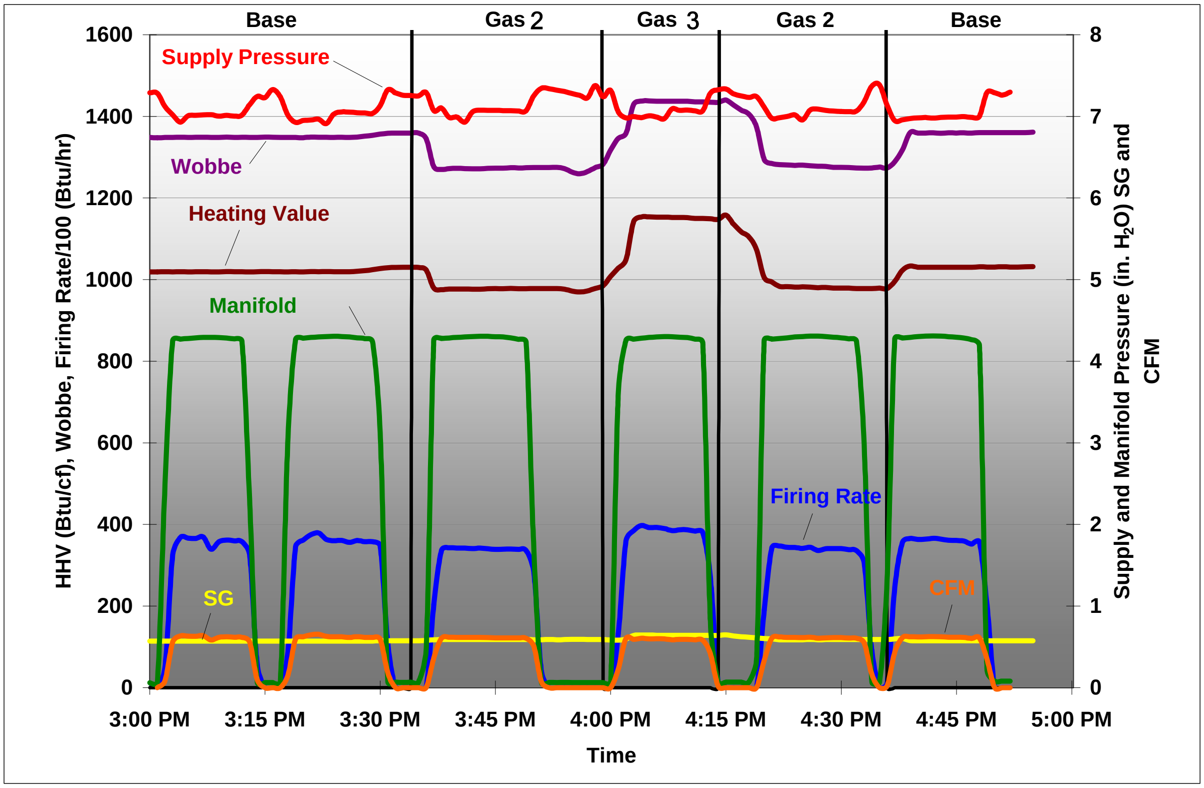


Gas Input

The average Base gas firing rate (2 tests) was 100.4% of the nameplate rating. The Gas #2 firing rate averaged 94.4% nameplate. Gas #3 resulted in a 108.5% of the nameplate firing rate. 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 FVIR water heater according to the protocol detailed in Appendix A. These included hot and cold ignitions conducted at standard gas supply pressure, reduced gas supply pressure, and with maximum pilot turndown. 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 FVIR water heater with different gas compositions.

Table 1 – Ignition Test Observations

Gas	Input Condition	Conclusion	Comments and Observations
Base	rated	normal	
Base	underfired	normal	slight delay in ignition
2	rated	normal	
2	underfired	normal	slight delay in ignition
3	rated	normal	
3	undefired	normal	slight delay in ignition
4a	rated	normal	
4a	underfired	normal	slight delay in ignition
base	rated, repetitive ignition	normal	
base	underfired, repetitive ignition	normal	slight delay in ignition
2	rated, repetitive ignition	normal	slow to extinguish during "off" portion of cycle
2	underfired, repetitive ignition	normal	slight delay in ignition
3	rated, repetitive ignition	normal	slow to extinguish during "off" portion of cycle
3	underfired, repetitive ignition	normal	slight delay in ignition
Base	rated, pilot turndown	normal	
Base	underfired, pilot turndown	normal	slight delay in ignition
2	rated, pilot turndown	normal	
2	underfired, pilot turndown	normal	slight delay in ignition
3	rated, pilot turndown	normal	
3	underfired, pilot turndown	normal	slight delay in ignition

Appendix A

Test Protocol – Flammable Vapor Ignition Resistant Water Heater

1. Objectives and General Approach

This protocol specifies procedures for conducting and reporting tests of flammable vapor ignition resistant water heaters (FVIR water heaters or FVIR-WH) with respect to their operation with re-gasified natural gas. The study is to evaluate the ability of a heater to operate through a change to or from LNG and the effect of LNG on the operation, safety, combustion emissions or other aspects of heater 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 heater 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 of April 22, 2004.

This protocol applies to residential type vertical-tank water heaters within the scope of ANSI Standard Z21.10.1, with water connections and vent on top of the heater. It is also limited to heaters with a single firing rate, standing pilot burner and snap-action main burner gas control.

2. Standards

- ANSI Z21.10.1-2001, Standard for Gas Water Heaters, Volume I.
- South Coast Air Quality Management District Rule 1121, Control of NOX Emission from Residential Type Natural Gas-Fired Water Heaters, last amended December 10, 1999.
- South Coast Air Quality Management District Protocol for Rule 1121, last amended January 1998.

3. Water Heater Data

Record descriptive and technical data, including the following:

3.1 Heater rating plate data

a. Model number
b. Serial number
c. Rated input
d. Recovery rating
e. Storage vessel capacity
f. Manifold pressure

3.2 Energy Factor rating per FTC label

3.3 Component data (to the extent it can be observed)

a. Gas control manufacturer & model number
b. Pilot burner or igniter manufacturer & model number. For a pilot burner, record the gas orifice diameter if marked.
c. Diameter (or drill number) of main burner orifice(s)

3.4 Copy installation instructions and other information shipped with the heater.

3.5 Photograph the water heater and significant design/construction features.

4. Test Arrangement

4.1 Basic setup

Operate the heater in open laboratory without closet or alcove, on a square base of ¾" plywood. The sides of the square are to be 8" greater than the water heater casing diameter. The plywood is to be displaced ¾" from the floor by means of edge runners 1" wide and a 4" X 4" block is to be placed at the center of the base. The top of the base is to be painted flat black, and the space between the base and the floor is to be filled with fiberglass insulation of at least 1.5 lb/ft^3 density.

4.2 Water supply

Building water supply is to be blended with stored/heated water as necessary to provide required flow rates and temperature. Blending is to be accomplished with a commercial mixing valve.

4.3 Water piping and temperature measurement

4.3.1 Water piping

Water piping and temperature measurement sites are to be per Figure 4 of the SCAQMD Protocol for Rule 1121 except that the horizontal portions of the water connections are not to be 24" above the heater as specified therein. Because much of the other testing is to be done per the ANSI standard (without a vent pipe) connections are to be made close to the top of the heater in a manner that will assure that combustion products do not contact the piping.

4.3.2 Stored water temperature

A six-thermocouple assembly for internal tank temperature measurement is to be provided as required by section 7.1.5 of the AQMD Protocol.

4.4 Ambient temperature

A thermocouple for ambient temperature measurement is to be provided per section 7.1.6 of the SCAQMD Protocol for Rule 1121.

4.5 Draw rate control

Supply water pressure is to be regulated and a throttling valve and ball-type shutoff valve are to be provided in the outlet piping. The arrangement is to be such that water draw can be started or stopped without affecting a pre-set flow rate.

4.6 Vent pipe immersion

4.6.1 Combustion and burner & pilot operational tests

Per section 2.1.8 of Standard ANSI Z21.10.1, no vent pipe is to be provided. In tests with this setup, combustion product samples are to be taken with a single-point probe in the heater flue passage just before the draft hood. Provide a single thermocouple junction 3” below flue tube outlet (before draft hood).

4.6.2 Flue temperature test

Provide a two-foot insulated vent pipe with thermocouple grid per section 2.17 of ANSI Standard Z21.10.1.

4.6.3 NOX emission tests

Provide a vent pipe constructed, except for length, per AQMD Protocol for Rule 1121, section 7.1.9, with integrating sample probe per sections 5.8.4.1.1 and 6.3.1.1 and Figure 3. Because of ceiling height restriction, the length (height) of the stack is to be four feet instead of the five-foot length specified.

4.7 Base & floor temperature

Three or four thermocouples are to be placed between the base of the heater and the plywood on which the heater is supported. Locate the thermocouples at places most likely to be hot. If possible obtain manufacturer’s advice as to where the thermocouples should be located.

4.8 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 heater gas control if available, or at a tee in the gas piping at the heater connection.

4.9 Instrumentation

Instrumentation is to be per the SCAQMD Protocol for Rule 1121.

4.10 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 heater 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

#4 High-Wobbe medium-heat content gas

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

6. Basic Operating Condition

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

6.1 Room temperature

Room temperature is to be maintained between 65 and 85^{o}F.

6.2 Water supply temperature and pressure

Water is to be supplied at 72^{o}F ± 4^{o}F per section 4.2.1 of the SCAQMD Protocol for Rule 1121. Water pressure is to be adequate for maintenance of the water draw rates required in this protocol.

6.3 Water outlet temperature at steady state

When not specified otherwise in the procedure, steady state outlet water temperature is to be 130^{o}F ± 5^{o}F.

6.4 Gas supply pressure

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

6.5 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.

7. Testing – Startup run

With gas supply pressure at 7.0" WC, operate heater as received for one hour on baseline gas. The purpose of this run is to burn off manufacturing process oils, to verify instrumentation operation and to determine approximate firing rate and emission. Use the gas orifice received in the heater and verify manifold pressure at the rating plate value ± 0.2" WC. Do not draw water initially, but when the stored water temperature reaches 130^{o}F, draw at a rate that will maintain outlet temperature at 130 ± 5^{o}F. At the end of this break-in run, stop firing with the thermostat and continue to draw water to bring tank water temperature to 70^{o}F, ± 2^{o}F.

Approximately one-half hour after last firing the burner, adjust the thermostat as high as it can be set to start the heater. Fifteen minutes after starting, record firing rate data, CO_2 and carbon monoxide emission. Immediately after obtaining this data, reduce the heater supply gas pressure to 3.5” WC. Allow the heater to operate for five minutes at this condition and again record firing rate and combustion data. During this test, draw water when the stored water temperature reaches 130°F and adjust flow as necessary to hold outlet water flow at 130°F ± 5°F.

After this run cool the heater and remove burner assembly. Wipe inside of combustion chamber and burner and pilot assembly with a clean white cloth. Be sure to remove any residual dirt or soot.

8. Operating tests – water heating

8.1 Base case at rated input

With gas supply pressure at 7.0” WC, adjust heater to operate at the rating plate input, holding manifold pressure within 10% of that specified on the rating plate and changing the gas orifice if necessary. This establishes and defines the “basic firing setup” referred to in section 6.5 above.

Starting with tank water temperature at 70°F ± 2°F, operate heater for 15 minutes and record input and combustion data (CO_2 & CO). 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 five minutes at this condition record input and combustion data (CO_2 & CO). Immediately thereafter return manifold pressure to that required for rated input and then reduce gas supply pressure to 3.5” WC. After 5 minutes at this condition record input and combustion data. Thereafter re-adjust supply pressure to 7.0” WC.

Before further testing remove burner assembly and wipe inside of combustion chamber with a clean white cloth. Record results, noting specific location and appearance of any deposits. Thoroughly clean all surfaces so that subsequent soot deposition can be identified.

8.2 Water heating with gas changeover

8.2.1 Steady operation with baseline gas

Operate heater at the basic firing setup. Draw water when the stored water temperature reaches 130°F and adjust draw rate to maintain outlet water temperature at 130 ± 5°F. Verify that the firing rate is at rated input ± 2% and establish steady state operation, based on the flue gas thermocouple, requiring that it change no more than 5°F in a 15-minute period. Record all combustion and operating data.

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

8.2.2 Gas changeover and steady operation with substitute gases

Continue steady operation with baseline gas and conduct a high-speed switch to the substitute gas. Do not adjust firing rate. 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.

When steady state is achieved record firing rate and all operating data.

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

With the heater 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 heater, remove burner assembly and examine combustion chamber for presence of soot by means of the white cloth technique specified in section 8.1. If soot is found, clean chamber and repeat testing with suspect gas blend(s), selected on the basis of earlier yellow tipping observations. Establish which gas(es) tends to burn with soot deposition.

8.3 NOx emission

Install the NOx emission stack and provide all other equipment and instrumentation as required for conduct of testing under section 8.1 of the SCAQMD protocol. Using the baseline gas, conduct test and calculations per the protocol.

Repeat the NOX emission test for gas #2 (low Wobbe–low heat content) and gas #3 (high Wobbe–high heat content). Testing is to be conducted per the AQMD protocol except that the firing rate is not to be adjusted.

Unless this testing indicates that additional NOX emission testing would be useful, do not do so.

8.4 Flue gas and base/floor temperatures

Operate heater on baseline gas at the basic firing setup. Adjust the water heater thermostat to its maximum setting and operate the heater with water draw rate adjusted to deliver water at the highest possible temperature. Then adjust water flow to establish a steady outlet temperature 10^{o}F lower. At that point sample combustion gases to determine CO_2 content.

Block the draft hood relief openings and install the two-foot insulated vent pipe with thermocouple grid as described in section 2.17.1 of

ANSI Standard Z21.10.1. Operate the heater at rated input and gradually restrict the outlet of the vent pipe until the CO_2 content of the combustion gases is reestablished at the original value. Per the preceding section, hold outlet water temperature 10^oF lower than maximum. Measure flue gas temperature per section 2.17.1 and record the base/floor temperatures at the thermocouple locations selected earlier. Also record the ambient temperature, firing rate data and combustion data (CO_2 & CO).

Without changing water draw rate, without adjustment of the heater and without stopping heater operation, switch to the first substitute gas. Allow the furnace to achieve steady state conditions and verify operation for at least 15 minutes at that condition. Record data.

Without stopping operation, successively switch to the other gas blends, repeating the procedure, observations and data recording.

9. Burner and pilot operating characteristics

9.1 Testing with baseline gas

Conduct the following tests at the basic firing setup using the baseline gas.

9.1.1 Ignition

Determine ignition behavior by conducting flashback and flame carryover testing per sections 2.5.1 and 2.5.2 of ANSI Standard Z21.10.1-2001. Record observations.

Repeat the sequence with supply pressure at 3.5” WC.

9.1.2 Pilot burner

9.1.2.1 Repetitive ignition

Conduct repetitive ignition testing per section 2.6.2 of ANSI Standard Z21.10.1-2001 and record observations.

Repeat the sequence with supply pressure at 3.5” WC.

9.1.2.2 Pilot turndown

Conduct turndown testing per section 2.6.6 of ANSI Standard Z21.10.1-2001. Use millivolt specifications provided the manufacturer to determine the degree of pilot flame turndown. Record observations. (Note: This test requires modification of the pilot gas tube and the flame-sensing thermocouple. For that reason it may be convenient to conduct it after all other testing has been completed.)

9.2 Testing with substitute gases

Repeat burner and pilot operating characteristics testing with gas #2 (low Wobbe–low heat content) and gas #3 (high Wobbe–high heat content). Testing is to be conducted per the ANSI Standard except that the firing rate is not to be adjusted.

Unless this testing indicates that additional testing would be useful, do not do so.

10. Special tests

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

11. Additional Testing

Conduct additional testing and/or testing with other gas blends, per the Phase II Scope of Work, 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

NOx emission is to be calculated per the AQMD protocol for Rule 1121. Other calculations are to be per standard practice.

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 heater will be operated "as shipped" on baseline gas. After the startup, "base case" data is to be obtained with the heater 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 subsequent testing with other gas blends.

Allowing heater operation to "float" with gas blend allows conclusion that a performance change is related only to the gas. The "as shipped" startup data provides a basis for inference as to how factory de-rate practices might have affected performance.

Plywood test base for heater:

A plywood base, displaced from the concrete floor and with fiberglass insulation between the plywood and the floor, is specified so that water heater base temperature can be measured with reasonable consistency. The plywood is spaced from the floor to minimize heat conduction away from the heater. The assembly is of minimal height because the laboratory ceiling is quite low.

Water piping connections:

The SCAQMD Protocol for Rule 1121 requires in Figure 4 that the horizontal portions of the water pipe connections be 24” above the heater. Adhering to that dimension creates problems (exhaust product impingement) during most other testing, which, per the ANSI Standard, is conducted without vent pipe. To save test setup time, lower pipe connections are to be used for all testing. The effect, if any, on NOx emission is expected to be small. Since all tests will be conducted with the same arrangement, any differences can be attributed to gas blend changes, not the water piping.

Vent stack height:

Because laboratory ceiling height is limited, space for the five-foot stack specified in the AQMD Protocol for Rule 1121 is not available. A four-foot stack is being provided instead, and a sample probe is provided six inches below the top of the pipe as specified in the Protocol. Since the function of the draft hood is to make heater operation essentially independent of the vent, the effect of this compromise is expected to be small. All tests will be conducted with the same stack.

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 residual gas analyzer (RGA), model QMS-300, from Stanford Research Systems, Inc. (Sunnyvale, CA). A schematic of the fully instrumented FVIR-WH is shown in Figure B2.

Figure B1 – Overall Equipment Layout

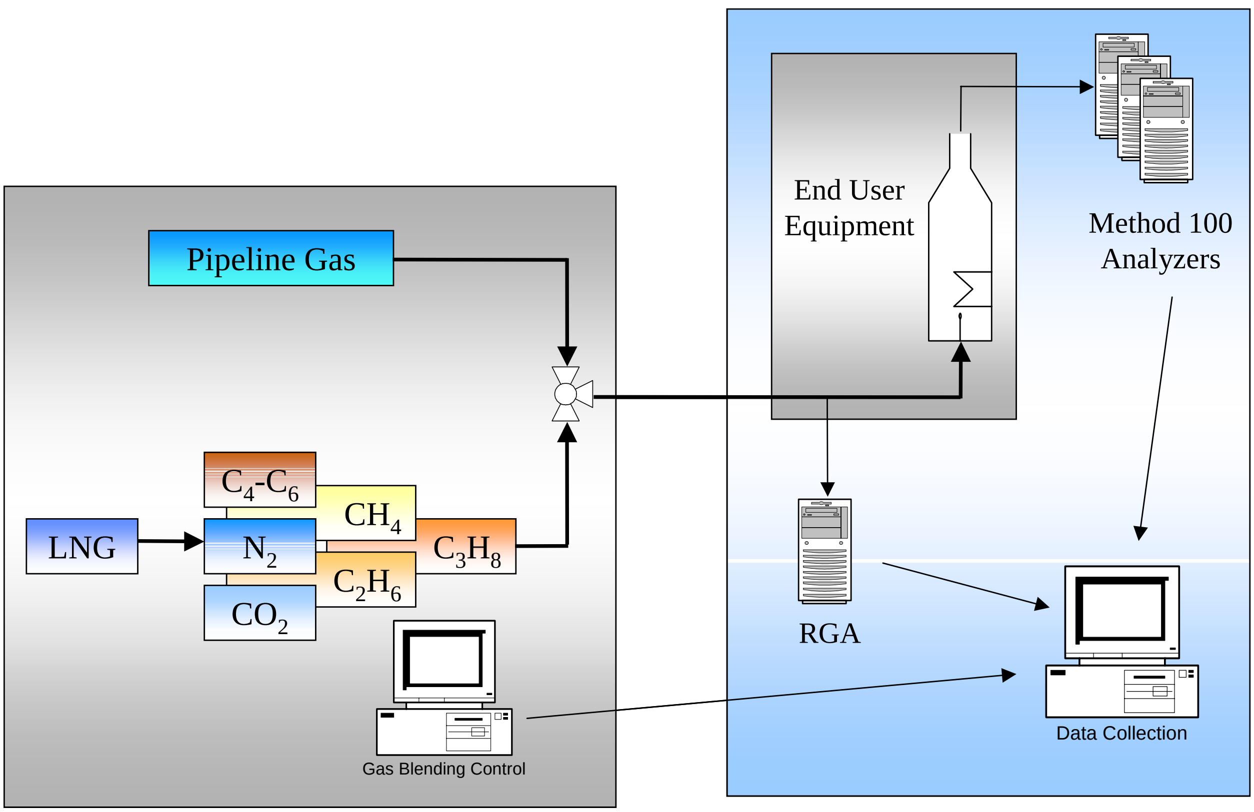
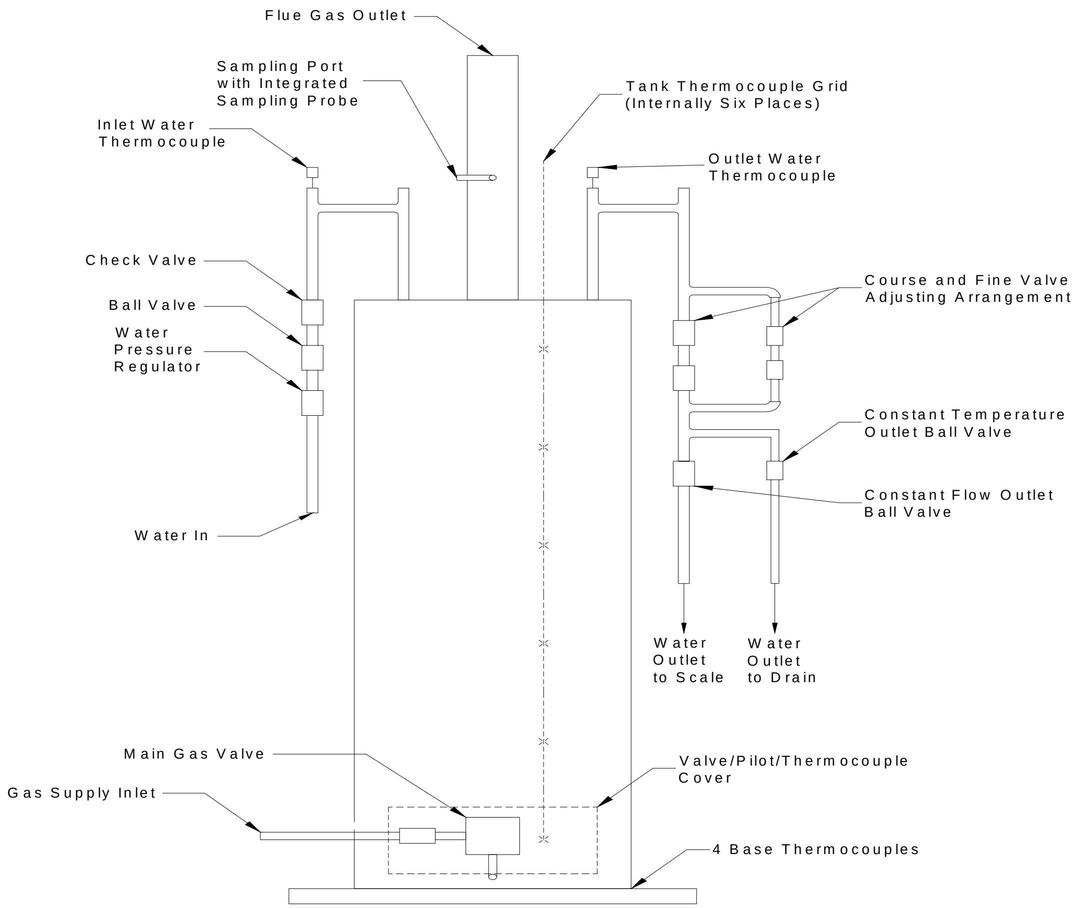


Figure B2 – FVIR-WH Schematic with Instrumentation



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

		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
Primary														
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		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								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		0.75	1376	1100
5a	or 4 component mix	90.85		7.00						1.40		0.75	1376	1099

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
gas composition	Stanford Research Institute QMS-300	quadrapole mass spectroscopy	0-100% methane 0-15% non-methane

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 = $RawCO_2 \times \left[\frac{20.9}{20.9 - RawO_2} \right]$

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 FVIR Residential Water Heater As-Found, Overfire, Underfire Test June 11, 2004			
Base Gas	**As-Found**	**Overfire**	**Underfire**
HHV (Btu/cf)	1,018	1,019	1,019
Wobbe (Btu/cf)	1,348	1,348	1,348
Input Rate (Btu/hr)	35,463	38,044	30,702
Corrected SCFH	34.8	37.3	30.1
Emissions (not from certified tests)			
Raw O_2 (%)	4.09	2.55	6.59
Raw CO_2 (%)	9.27	10.18	7.90
CO (ppm @ 3% O_2)	4.6	40.3	4.6
NO_x (ppm @ 3% O_2)	78.1	70.1	88.9
Ultimate CO_2 (%)	15.10	16.79	12.83
Equivalence Ratio (f)	0.64	0.63	0.64
Temperatures (°F)			
Ambient	80.5	81.2	82.2
Gas	77.8	78.2	78.7
Exhaust	263.7	335.7	368.2
Storage Tank	106.1	121.0	139.4
Pressures			
Supply (in. w.c.)	7.01	7.00	3.89
Manifold (in. w.c.)	4.18	4.97	3.22

Test Gas Composition June 11, 2004 As-Found, Overfire, and Underfire Test			
Component	As-Found	Overfire	Underfire
C1	98.28	98.15	98.11
C2	0.80	0.89	0.89
C3	0.21	0.22	0.23
iC4	0.00	0.00	0.00
nC4	0.15	0.15	0.15
iC5	0.00	0.00	0.00
nC5	0.00	0.00	0.00
C6	0.00	0.00	0.00
CO2	0.67	0.65	0.66
O2	0.00	0.00	0.00
N2	0.19	0.24	0.25
Total Mole %	100.31	100.31	100.29

Table of Averages FVIR Residential Water Heater Performance Tests June 13, 2004								
Gases	**Base**	**2**	**Base**	**3**	**Base**	**4A**	**Base**	**2**
HHV (Btu/cf)	1,020	979	1,021	1,143	1,020	1,145	1,021	979
Wobbe (Btu/cf)	1,349	1,276	1,349	1,431	1,348	1,373	1,349	1,275
Input Rate (Btu/hr)	35,218	32,712	35,238	36,950	35,135	35,339	34,090	32,761
Corrected SCFH	34.5	33.4	34.5	32.3	34.5	30.9	33.4	33.5
Emissions (not from certified tests)								
Raw O_2 (%)	4.28	5.57	4.29	2.63	4.37	3.87	4.30	5.48
Raw CO_2 (%)	9.40	8.77	9.35	10.43	9.15	10.06	9.38	8.78
CO (ppm @ 3% O_2)	4.2	3.2	4.0	10.9	3.8	4.5	3.9	3.0
NO_X (ppm @ 3% O_2)	80.2	77.5	80.4	82.1	81.9	82.3	83.4	79.8
Ultimate CO_2 (%)	11.82	11.96	11.76	11.92	11.57	12.35	11.81	11.90
Equivalence Ratio (f)	0.81	0.75	0.81	0.89	0.81	0.83	0.81	0.76
Temperatures (°F)								
Ambient	83.3	83.2	83.4	83.4	84.2	83.4	83.4	83.4
Combustion Chamber	340.2	326.3	337.0	357.4	342.2	353.2	345.2	329.5
Gas	80.6	80.8	81.0	81.1	81.7	81.4	81.4	81.4
Exhaust	354.6	346.9	354.0	360.6	348.4	349.9	352.3	340.4
Inlet Water	77.1	77.2	76.1	75.7	75.7	79.1	75.8	75.6
Outlet Water	124.7	126.4	129.9	129.9	127.9	130.8	135.3	135.5
Pressures								
Supply (in. w.c.)	6.99	7.05	7.00	7.05	7.01	7.04	7.00	7.05
Manifold (in. w.c.)	4.13	4.12	4.12	4.14	4.13	4.12	4.12	4.13

Gas Composition
13-Jun-04
Performance Test

Component	Base	Gas 2	Base	Gas 3	Base	Gas 4a	Base	Gas 2
C1	98.4	96.5	98.2	87.7	98.3	85.4	98.3	96.4
C2	0.8	0.0	0.9	9.1	0.8	0.0	0.8	0.0
C3	0.2	0.0	0.2	2.5	0.2	11.0	0.3	0.0
iC4	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0
nC4	0.2	0.1	0.2	0.5	0.2	0.1	0.2	0.1
iC5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
nC5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CO2	0.7	2.9	0.7	0.0	0.7	2.8	0.7	3.0
O2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N2	0.1	0.9	0.2	0.0	0.2	1.0	0.2	0.9
Total Mole %	100.4	100.4	100.4	100.3	100.5	100.4	100.5	100.4

Table of Averages FVIR Residential Water Heater Emissions Tests June 14, 2004					
Gases	**Base**	**2**	**3**	**2**	**Base**
HHV (Btu/cf)	1,020	978	1,153	980	1,031
Wobbe (Btu/cf)	1,350	1,274	1,437	1,277	1,360
Input Rate (Btu/hr)	35,896	33,890	39,062	34,079	36,406
Corrected SCFH	35.2	34.7	33.9	34.8	35.3
Emissions (not from certified tests)					
Raw O_2 (%)	11.80	12.37	10.88	12.31	11.54
Raw CO_2 (%)	4.88	4.65	5.55	4.72	5.02
CO (ppm @ 3% O_2)	8.17	7.90	44.89	7.55	9.11
NO_X (ppm @ 3% O_2)	73.20	46.23	69.10	70.40	70.84
Ultimate CO_2 (%)	11.21	11.39	11.57	11.49	11.22
Equivalence Ratio (f)	0.46	0.44	0.51	0.44	0.47
Temperatures (°F)					
Ambient	79.2	78.4	81.6	79.9	82.2
Combustion Chamber	328.1	316.7	321.9	310.4	320.1
Gas	80.0	79.6	80.1	80.0	80.6
Exhaust	256.6	251.6	254.0	247.9	247.1
Tank Thermocouples	122.9	123.2	119.5	121.6	120.6
Pressures					
Supply (in. w.c.)	7.04	7.07	7.02	7.05	6.98
Manifold (in. w.c.)	4.28	4.28	4.30	4.30	4.30

Gas Quality and LNG Research Study
Appendix A - 2

Gas Composition 14-Jun-04 Emissions Test					
Component	Base	Gas 2	Gas 3	Gas 2	Base
C1	97.7	95.8	86.8	96.4	97.5
C2	1.5	0.3	10.1	0.0	1.6
C3	0.4	0.2	2.6	0.0	0.4
iC4	0.0	0.0	0.3	0.0	0.0
nC4	0.2	0.1	0.5	0.1	0.2
iC5	0.0	0.0	0.0	0.0	0.0
nC5	0.0	0.0	0.0	0.0	0.0
C6	0.0	0.0	0.0	0.0	0.0
CO2	0.4	2.6	0.0	3.0	0.4
O2	0.0	0.0	0.0	0.0	0.0
N2	0.2	1.4	0.0	0.9	0.2
Total Mole %	100.4	100.3	100.4	100.4	100.3