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FINAL PROJECT REPORT

**IMPLICATIONS OF NATURAL GAS
INTERCHANGEABILITY FOR
CALIFORNIA CUSTOMERS**

Appendices D-F

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Implications of Natural Gas Interchangeability for California Customers is the final report for the Implications of Natural Gas Interchangeability for California Customers project (CEC-500-05-026) conducted by Gas Technology Institute and Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's Energy-Related Environmental Research Program.

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ABSTRACT

This study provided guidance on fuel interchangeability and the potential environmental impacts – with a focus on emissions and exposures to air pollutants – of increased variability in California’s natural gas supply, specifically related to the use of imported liquefied natural gas.

Industrial and commercial burners were examined with their combustion control systems, commercial foodservice equipment, and residential furnaces, water heaters, and cooking burners. Air quality and exposure impacts were evaluated for outdoor and indoor air. Interchangeability considerations included performance and safety, in addition to the environmental impacts of liquefied natural gas and other substitute gases relative to traditional natural gas formulations.

Laboratory and field tests identified classes of industrial burners most sensitive to changes in natural gas composition. Various gas compositions that provided acceptable interchangeability for specific burners were identified, and protocols were developed to adapt them to a wider range of natural gas compositions. Adjustments that allow substituting different gas compositions for industrial burners were found to vary from none to numerous adjustments in operating and control protocols.

Appliance tests in the laboratory and in homes measured performance and emissions of various gas compositions and all appliances and industrial burners operated safely over the range of natural gas compositions tested. Appliance impacts on indoor air quality were measured and modeled. Impacts to outdoor air quality were modeled based on potential changes to emissions. Commercial cooking appliances were tested in the laboratory, and divided into those requiring no, minor, or significant adjustments to address interchangeability with varying gas compositions. The performance of multiple range hoods was measured, with performance found to vary significantly.

Keywords: interchangeability, natural gas, LNG, industrial burners, appliances, air quality, emissions

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Appendix E: Commercial Foodservice Equipment

Appendix F: Simulation-Based Estimates of Indoor Exposures to Pollutants from Natural Gas
Cooking Burners

APPENDIX D: Burner Testing Reports

**Industrial Burner Evaluations:
Infrared Burner Interchangeability Test Report**

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Objective

The purpose of the infrared burner interchangeability tests is to assess the performance of an infrared burner and industrial control system when fired with different natural gas compositions. The burner's performance when firing selected Adjust Gases was compared with its performance when firing selected Substitute Gases with and without different levels of nitrogen ballasting.

Approach

The tests used a laboratory setup intended to mimic industrial operating conditions. The burner was first tuned to operate with an "adjust" gas composition. Ignition tests and operating/switching tests were then performed. During these tests several "substitute" gas compositions were fired in sequence on the burner. Ignition tests were performed from the same start conditions of approximately 85°F, and operating tests were performed with the burner maintained at 1500°F by a PID control scheme. These tests were then repeated with the other "adjust" gases as a basis.

Table 1. Performance Metrics for the Infrared Burner

BASIC PERFORMANCE METRICS
Pollutant emissions, including ultrafine particles
Average heat transfer
Temperature distribution on the burner surface
Controller response upon ignition
Controller response upon switching

Test Apparatus

The infrared burner used for this test was a Type 50 assembly of four Maxon RadMax burners. It and the rest of the experimental setup are shown in Figure 37 through Figure 41. The assembly was mounted to fire vertically into an insulated four-walled chamber with an open top. The walls extended 4 inches above the burner surface to protect the burner face from drafts and the operator from the radiant heat. The air and fuel supply were fed using a Maxon PM200 premix blower. Simulated natural gas compositions from a custom blending station was regulated to a pressure of 6" water column upstream of the blower. A thermocouple's signal, sent as input to a Fuji Electric

feedback controller attached to a motorized butterfly valve for air flow, was used to maintain a burner surface temperature of 1500°F. A spring attached to the motorized air valve was set to calibrate the fuel-to-air ratio for the whole range of firing rates. This ratio was reset for each adjust gas.

A spark-ignited pilot and flame sensor assembly was used during ignition tests only; the flame safety system included a normally-closed solenoid on the gas line. Instruments used to perform this test are listed in Table 3; they will be described below.

Table 2. Summary of Test Instruments

Instrument	Parameter	Range	Accuracy
LabView software, National Instruments Field Point Modules, and laptop	Data logging	—	—
Type K thermocouple	Burner surface temperature	Up to 1370°C	Greater of 2°C or 0.75% of value
Medtherm 68-10 SB-1 Heat flux transmitter	Convective + Radiative heat transfer	Up to 10 Btu/ft ² /sec	±3%
Medtherm H-201 Digital heat flux meter	Converts heat flux transmitter output (mV) to Btu/ft ² /sec	0-10 mV	±2% nonlinearity
Velmex BiSlide and VP9000 controller unit	Position of heat flux transmitter	80" horizontal 15" vertical	
Thermo Environmental 42C	ppm NO _x	0-0.05 ppm to 100 ppm	±0.4 ppb / 500 ppb
Beckman Industrial 755	% O ₂	Span 3.92%	
Rosemount Analytical 880A	ppm CO	Span 830 ppm	1% full scale
Rosemount Analytical 880A	%CO ₂	Span 18.0%	1% full scale
Rosemount Analytical 400A	ppm THC	Span 341 ppm	1% full scale
National Instruments GPIB	Data collection	—	—
Dekati Fine Particle Sampler	Sampling and dilution	Dilution ratio to be measured	To be measured
TSI Ultrafine condensation particle counter	Particle size and number	3 nm-20 μm	±10%
Varian CP-4900 Gas Chromatograph	ppm CO ₂ , ppm O ₂	Depends on calibration gas; can detect as low as 1 ppm	<0.5% relative standard deviation under constant conditions

The measured flow rates of the fuel gases supplied from the custom blending station to the burner were recorded using National Instruments Field Point Modules. The fuel gas compositions were commanded through a separate program and its user interface that was dedicated to the blending station. The burner face temperature was recorded using a type K thermocouple, and additional thermocouples at the inlet and outlet of a water-cooled plate calorimeter determined heat transfer to a simulated load—the water flow rate was measured using a rotameter. The Medtherm heat flux transmitter and heat flux meter together provided a digital measurement of the heat flux through 60 locations on

the burner's surface. The heat flux transmitter was fitted to a probe that was held 1" above the surface of the burner. The probe support was on a movable platform called the Velmex BiSlide. A VP9000 controller unit moved the platform to position the heat flux transmitter above each of those 60 locations. The probe was held for ten seconds to stabilize measurement before moving to the next location. It was returned to its zero position after each test so that the heat flux would be measured above the same locations for each test.

The heat flux data and the emissions data were collected simultaneously over different halves of the burner assembly to conserve fuel. To sample emissions at approximately the same velocity as the flow from the burner, a funnel with the appropriate cross-sectional area was attached to the end of the sample line. The sample flow divided so that 5.5 cubic feet per minute flowed through the rack-mounted analyzers (listed in Table 3) and the remaining exhaust entered the Dekati dilution system upstream of the ultrafine particle analyzer. The diluted flow went to the ultrafine condensation particle counter, and excess flow was directed outdoors through an exhaust line. Figure 2 shows a sketch of the sample probe.

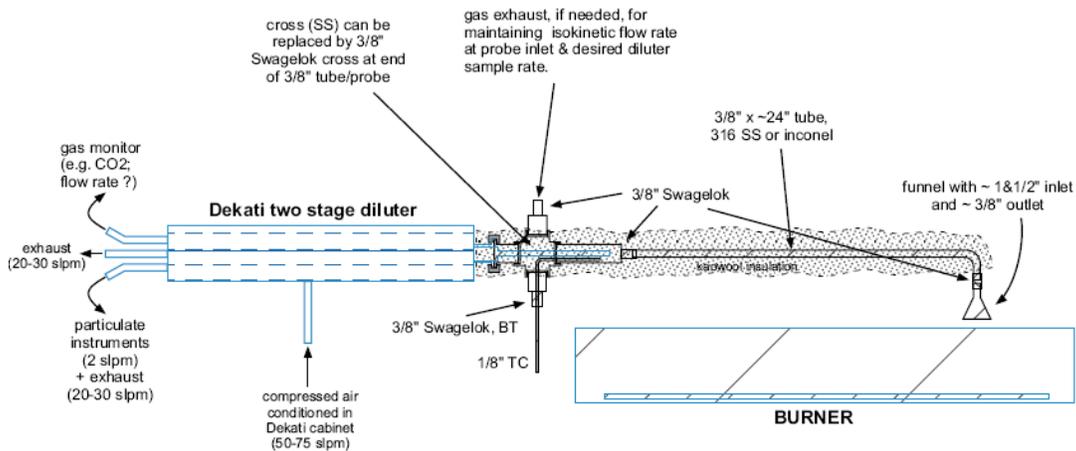


Figure 1. Sketch of the dilution sampling system setup

A Fuji Electric PID temperature controller (Model PXZ4REY2-5VC26-D) was used to control burner temperature from the thermocouple placed on the burner face. It was tuned manually to $P=8.0$, $i=42$, $d=8.0$, $AL=32$, $AH=1720$, $HYS=0$, $bal=30$, $Ar=50$. Automatic controller tuning failed after two tries, possibly because of the nonlinear response of the premixed flow to the angle the butterfly valve was opened.

Test Gases

The test gases were selected to match compositions distributed in California, and international compositions that may be imported into California. The compositions distributed in California are designated “adjust gases” and the burner was tuned for optimum performance on each of them. The remaining gases are designated “substitute gases;” they were fired on the burner to compare performance with the substitute gases to performance with the adjust gases. Table 4 summarizes the gases used. Adjust 1 is representative of natural gas in the Sacramento area, Adjust 2 is an average value for the state of California, and Adjust 3 is representative of some areas in California with higher Btu content due to local natural gas production. The two substitute gases, Sub 1 and Sub 2, were selected from a set of potential LNG compositions available to California; Sub 1 has a relatively low Wobbe Number (1408) compared with the other LNG compositions, and Sub 2 has a relatively high Wobbe Number (1425). Because it is possible that these gases will be conditioned with nitrogen prior to distribution in California, additional compositions with nitrogen added to make the Wobbe Number match those of the selected adjust gases were also test-fired.

Table 3. Summary of Test Gases

Name	Gas Composition, mol %							HHV	Wobbe
	C1	C2	C3	C4	C5+	N2	CO2		
Adjust 1	93.2	2.52	0.41	0.14	0.093	2.691	0.920	1010	1309
Adjust 2	94.5	2.55	0.42	0.14	0.094	1.361	0.931	1024	1332
Adjust 3	90.61	2.45	3.41	1.25	0.094	1.305	0.893	1094	1374
Sub 1	92.4	4.9	1.9	0.79	0.0	0.0	0.0	1099	1408
@1385	91.3	4.8	1.9	0.79	0.0	1.2	0.0	1086	1387
@1375	90.7	4.8	1.9	0.79	0.0	1.9	0.0	1080	1375
@1332	88.3	4.8	1.8	0.79	0.0	4.4	0.0	1053	1331
@1308	87.8	4.6	1.8	0.70	0.0	5.5	0.0	1036	1308
Sub 2	89.4	7.1	2.5	1.04	0.0	0.0	0.0	1131	1426
@1385	87.5	7.0	2.4	1.00	0.0	2.1	0.0	1106	1387
@1375	86.9	6.9	2.4	1.00	0.0	2.7	0.0	1098	1376
@1332	84.5	6.7	2.4	1.00	0.0	5.4	0.0	1070	1330
@1308	83.6	6.6	2.3	1.00	0.0	6.5	0.0	1057	1310

Test Schedule

The ignition tests were performed separately from the performance tests, because the pilot flame for the Maxon Radmax burners interfered with the heat flux measurements; the burner assemblies are usually larger, with more than four individual burners per assembly, and it would usually be possible to measure the heat flux through a single burner without interference from the pilot. For this reason, the burner air-to-fuel ratio was adjusted twice for each Adjust Gas: once with the pilot firing, before all of the ignition tests were performed for that Adjust Gas, and once without the pilot firing, before all of the performance tests for a given Adjust Gas. Figure 3 illustrates the schedule.

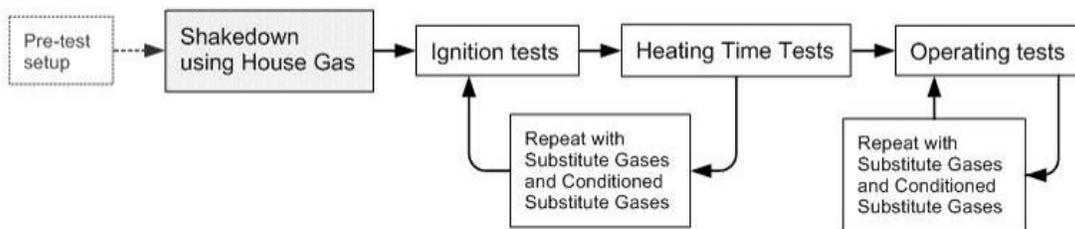


Figure 2. Test schedule for the infrared burner

Activities Performed

Ignition Tests

The ignition tests measure whether the burner lights and the controller response. For the ignition tests only, a spark-ignited pilot was used. An integral flame sensor was used for the flame safety switch; loss of flame results in a single attempt to re-light, followed by shutdown of fuel flow. Attempts to re-light, if there were any, were noted. The burner was cooled back to room temperature (approximately 85°F) between tests.

Heat Flux and Heat Transfer Measurement

With the burner firing and the controller maintaining a 1500°F (\pm about 5°F) surface temperature, a heat flux sensor stepped across one single burner tile in one-inch increments to assess the surface heat flux distribution. The rate of heat transfer to a water-cooled plate calorimeter was calculated from the flow rate of water through the plate and the water's temperature rise.

Exhaust Composition and Ultrafine Particle Emissions Measurements

With the burner firing and the controller maintaining a 1500°F (\pm about 5°F) surface temperature, a probe 0.15 inches above the center of one burner tile was fitted with a funnel to sample emissions at the exhaust flow velocity. Part of the flow was diverted to a drying train and then to the emissions analyzers listed in Table 3. The remaining flow was diluted with nitrogen, cooled, and then sent to the ultrafine particle counter. The number of particles must be multiplied to account for dilution: to determine the dilution ratio, the %O₂ and the %CO₂ in the dry emissions were compared with the %O₂ and the %CO₂ from the diluted sample; the diluted sample was passed through a drying train prior to entering a gas chromatograph.

Observation of Controller Response

Pressure changes in the mixing manifold of about $\pm 12\%$ occurred during switching from one gas composition to the next; this will be discussed further in the conclusions section, but it is important because it means the controller response is better interpreted from the ignition tests than the continuous operation tests.

Results

Data for each of the three tests, with the burner tuned for Adjust 1, Adjust 2, and Adjust 3, are presented in this section. The Calculations section follows, to explain how these data were redacted.

Continuous Test Results

During the continuous-firing tests, emissions data were collected every two minutes, ultrafine particle sampling took about four minutes per set of three samples, and burner temperature and firing rate were averaged over a 25-second window, with data automatically recorded every five seconds.

Firing Rate

In all the figures for the continuous tests, the shaded areas of the figure denote periods when the Adjust Gas is firing, and the unshaded areas denote periods when the Substitute Gases are firing. Figure 5, Figure 7, and Figure 8 show the burner temperature (top, blue) and the firing rate (bottom, red) of the infrared burner over the course of the continuous test. The first 30 seconds of each run, where pressure changes in the blending station manifold correlate with spikes in the flow rate, were discarded; Figure 6 illustrates that pressure spikes occur during fuel switching for Adjust 1—the same phenomenon occurs for the other adjust gases. Multiple regulators in the stream protect the burner from the large pressure spike, but some increase in flow is observed that does not indicate a controller response but an artifact of this instantaneous pressure increase. The average firing rate and burner temperature for each fuel over its time period are listed in Table 5. The burner temperature is nearly the same for all tests, and so is not plotted. The average firing rate is shown in Figure 4.

Table 4. Average Temperature and Firing Rate over 4 minutes During Continuous Operation; Burner Adjust Gas is Listed in Each Column Header

		Average Firing Rate (Btu/hr) and Temperature (°F)					
Sub↓ \ Adj →		Adjust 1		Adjust 2		Adjust 3	
Adjust		80,356	1492	85,401	1495	85,514	1496
Sub1-1308		83,317	1498	86,189	1498	87,783	1498
Sub2-1308		86,696	1499	85,553	1498	88,290	1498
Sub2-1332		81,992	1496	85,425	1498	87,421	1498
Sub1-1332		80,922	1498	86,720	1498	88,395	1498
Sub1-1375		76,185	1499	85,211	1498	84,772	1499
Sub2-1375		76,391	1500	85,277	1498	87,106	1499

Sub1-1385	78,338	1497	84,481	1499	84,020	1499
Sub2-1385	73,962	1501	85,461	1498	84,430	1499
Sub1	76,858	1502	83,723	1499	--	--
Sub2	69,852	1496	81,921	1499	82,415	1499

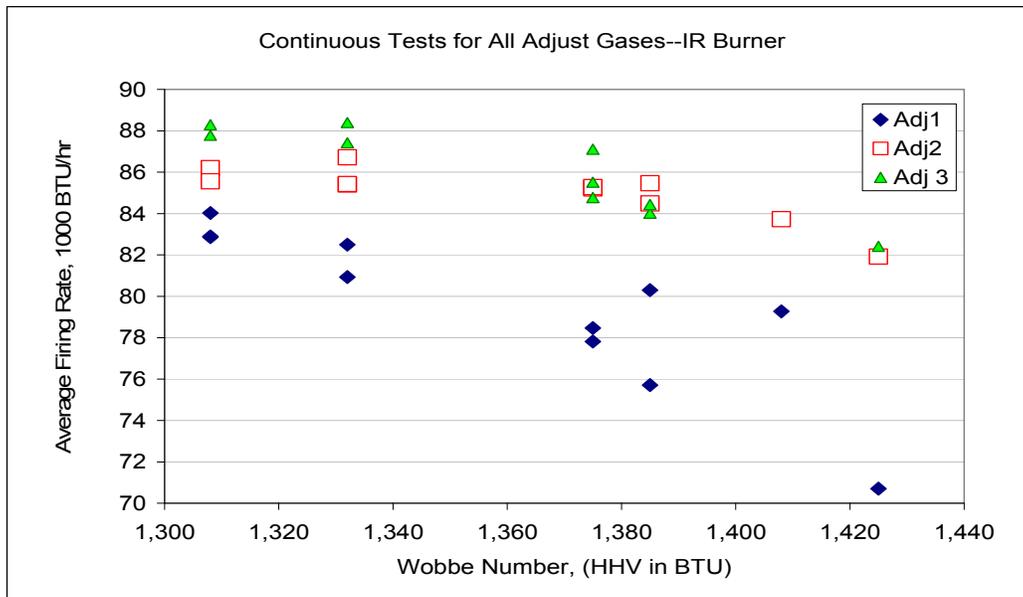


Figure 3. Average firing rate for each fuel at all burner adjustments

Emissions

Emissions data collected during the last 10 minutes of each continuous-firing test gas run determined the average values presented. Since the burner was controlled to maintain a 1500°F surface temperature, the air flow and the fuel-to-air ratio were not constant during the test. During tuning an effort was made to maintain a consistent air-to-fuel ratio with approximately 8.5% O₂ in the exhaust stream, but the ratio varied by about ±0.5% along the operating range, and also changed with direction of valve travel (opening or closing). Tuning was performed with the emissions sampling probe approximately 0.15 inches above the burner surface because less air was entrained during tuning. During continuous data collection, the probe was moved to 0.4 inches above the burner surface to keep temperatures low enough for the ultrafine particle counter sampling conditions to simulate the particle formation in air. With different fuel gas compositions, the air-to-fuel ratio changes. Also, at the higher height above the burner, the %O₂ measured increases, possibly because of entrainment of the surrounding air.

Figure 9 through Figure 20 show the volume fraction (dry) of the %O₂ and chemical pollutant emissions from the burner, as a function of both the Wobbe Number and the Weaver Air Index. Figure 21 through Figure 23 show the particulate emissions; the sample range is for a spherical diameter between 12 nm and 673 nm. Error bars for all plots show the entire range of data collected, not a standard deviation.. The pollutant emissions data are below 20% of their calibrated scale. The intent of the high calibration was to accurately capture an instantaneous emissions excursion; no excursion occurred. It is still reasonable to expect a repeatability of $\pm 1\%$ or $\pm 2\%$ of the full-scale value, meaning these data can be used to identify qualitative trends and how they relate to the fuel-gas Wobbe Number.

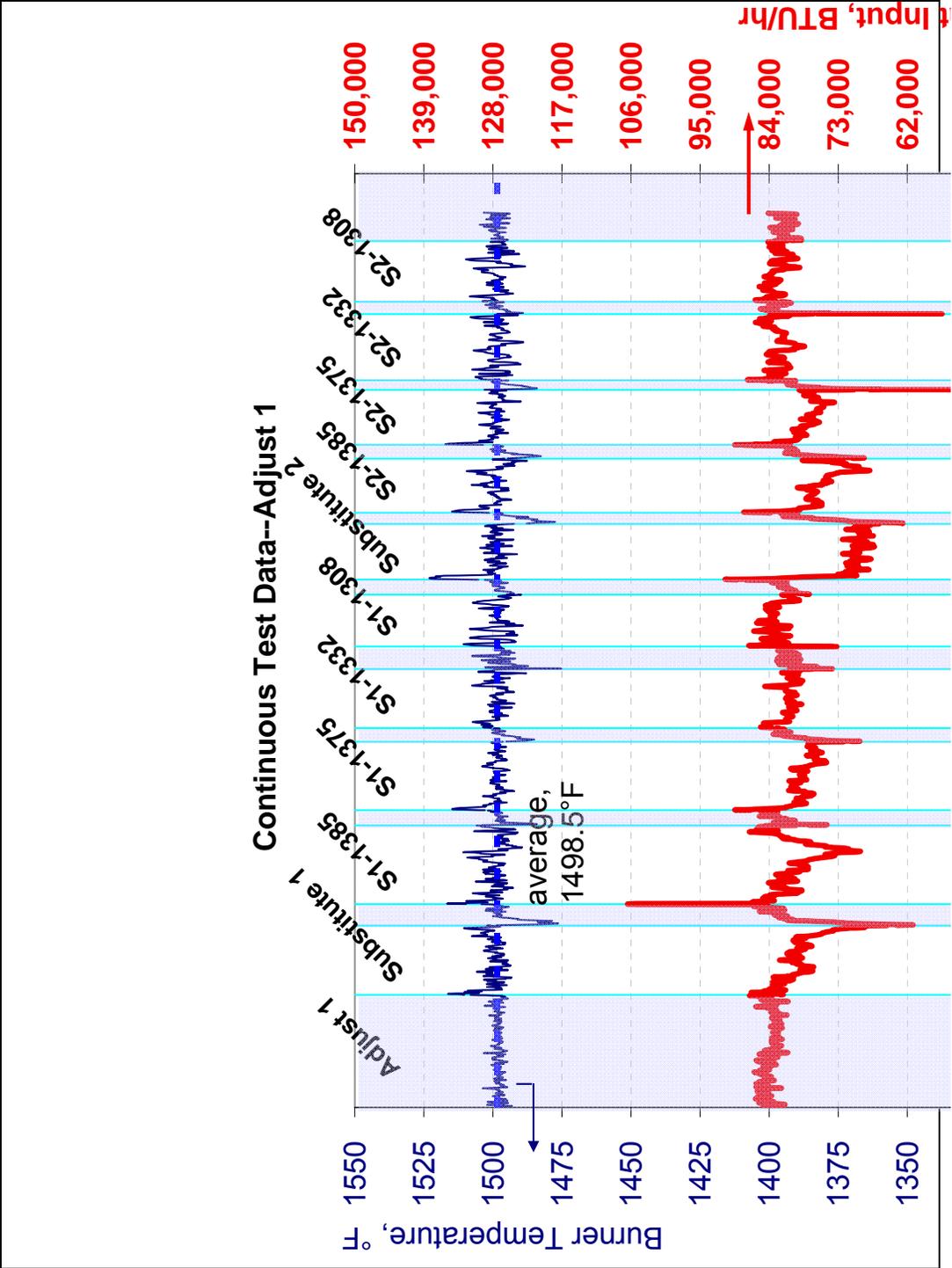


Figure 4. Continuous test, tuned to Adjust 1: Infrared burner face temperature and firing rate

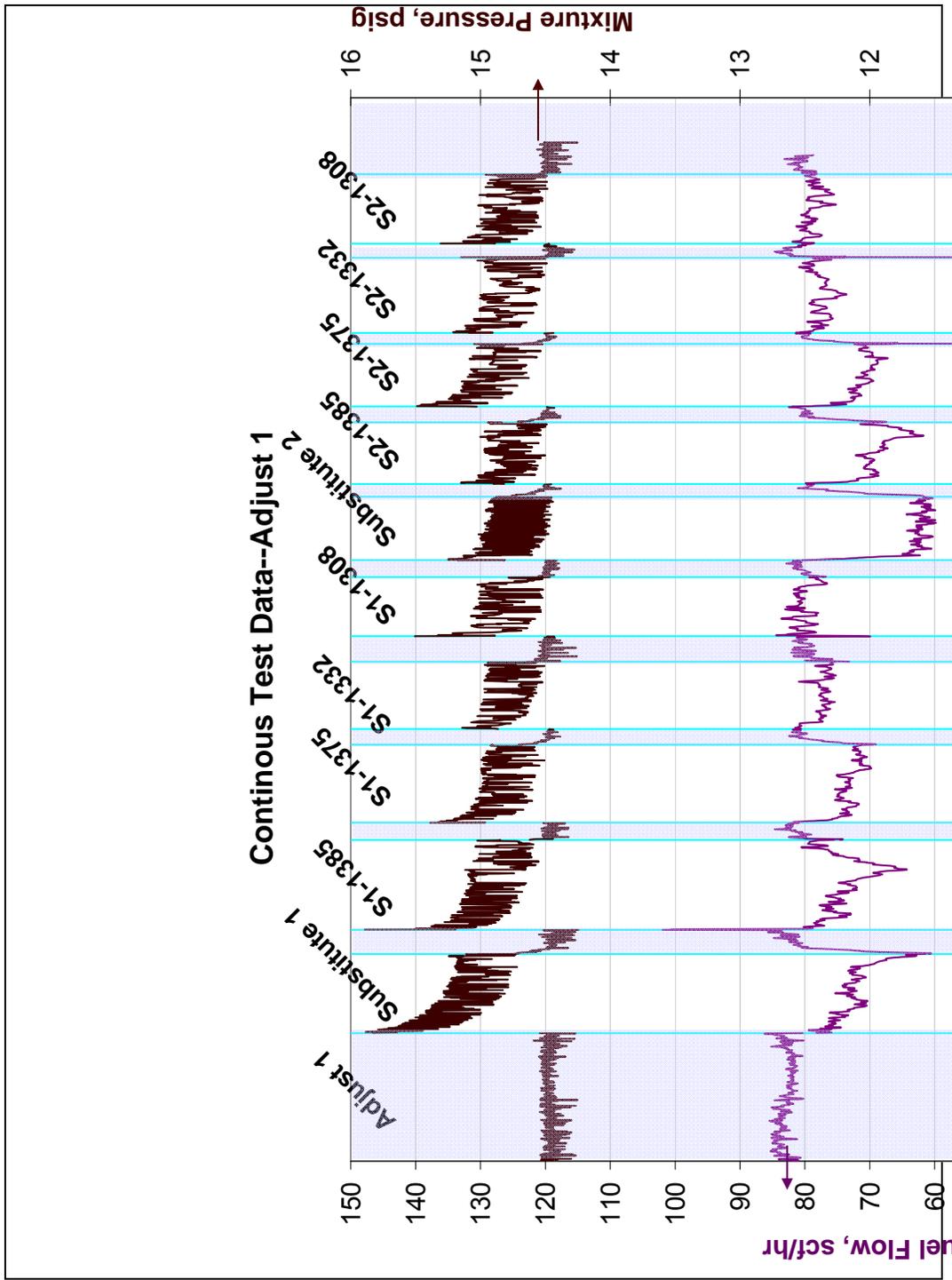


Figure 5. Continuous Test, Tuned to Adjust 1: Infrared Burner Face Temperature and Blending Station Manifold Pressure

Continuous Test Data--Adjust 2

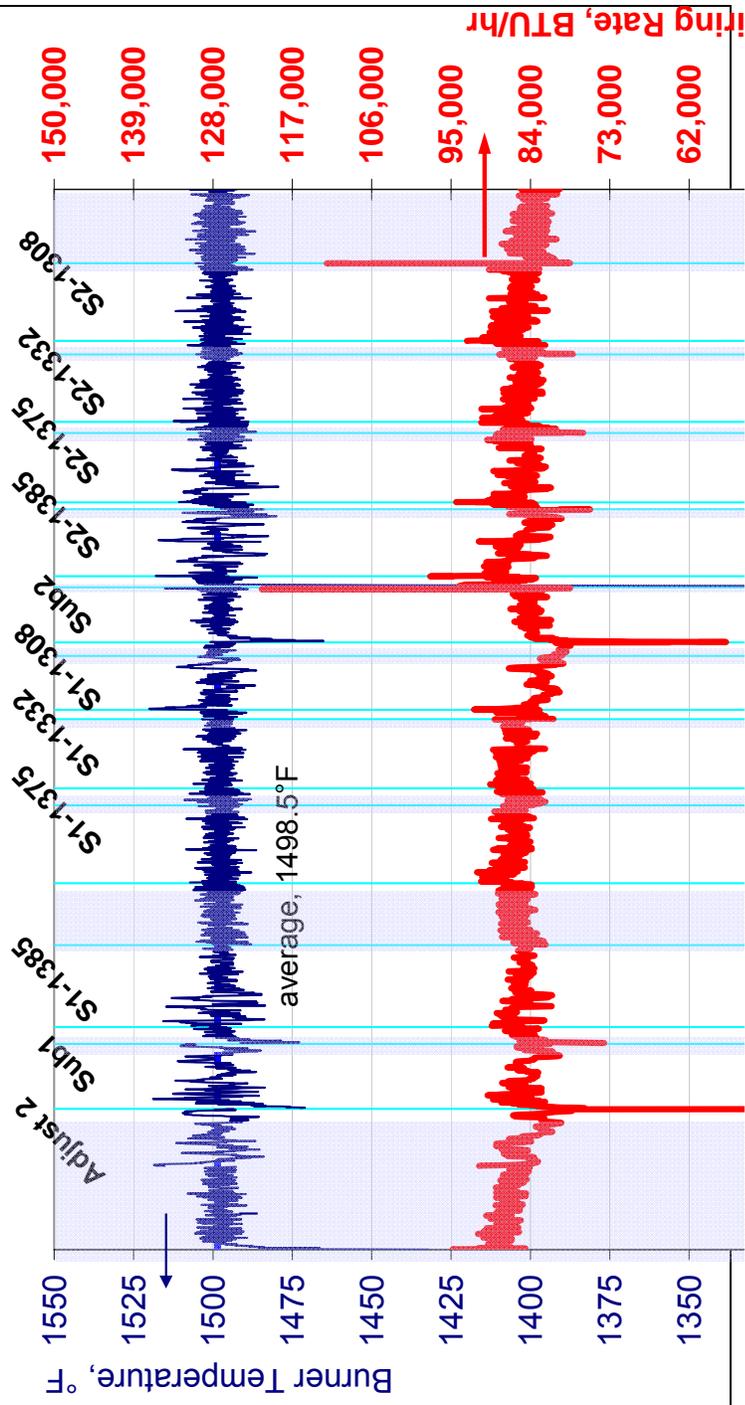


Figure 6. Continuous Test, Tuned to Adjust 2: Infrared Burner Face Temperature and Firing Rate

Continuous Test Data--Adjust 3

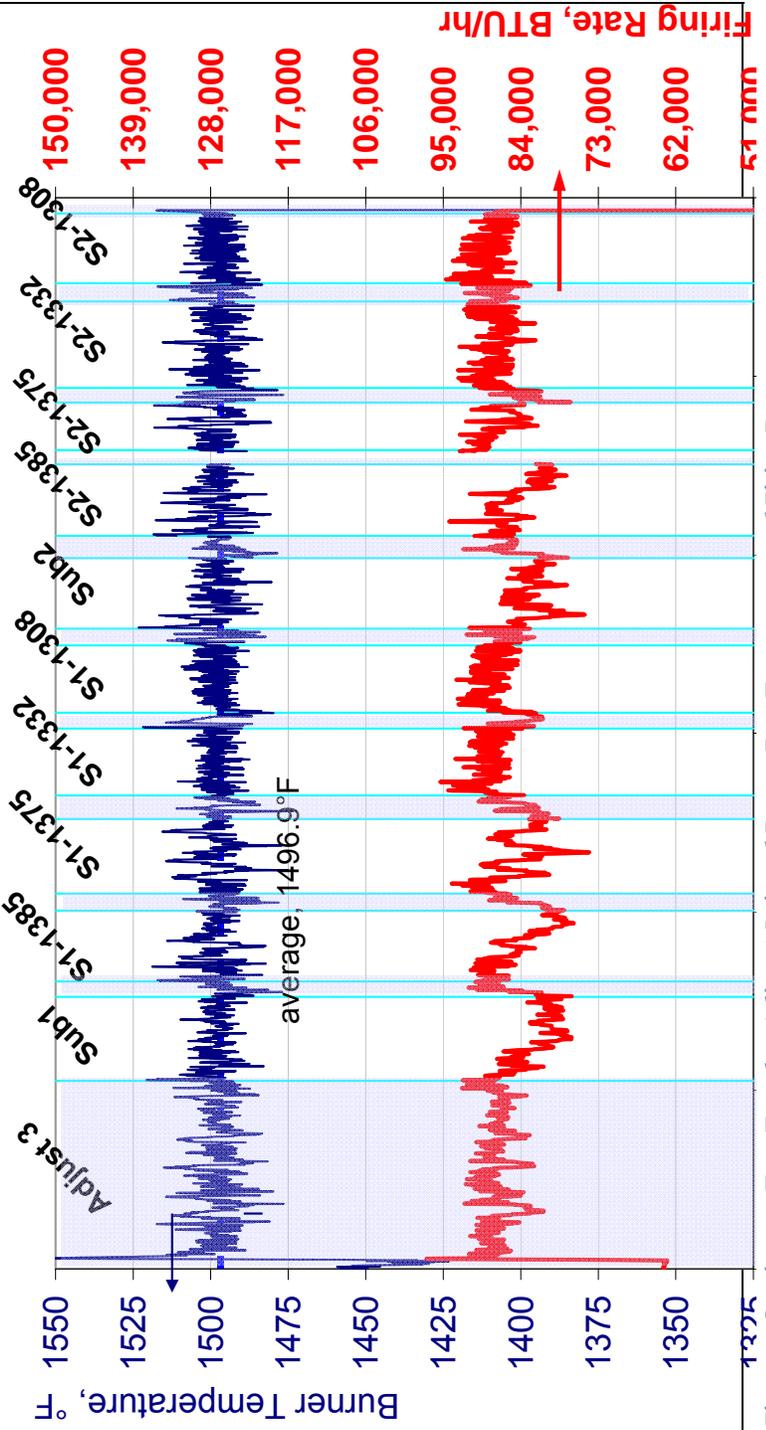


Figure 7. Continuous Test, Tuned to Adjust 3 Infrared Burner Face Temperature and Firing Rate

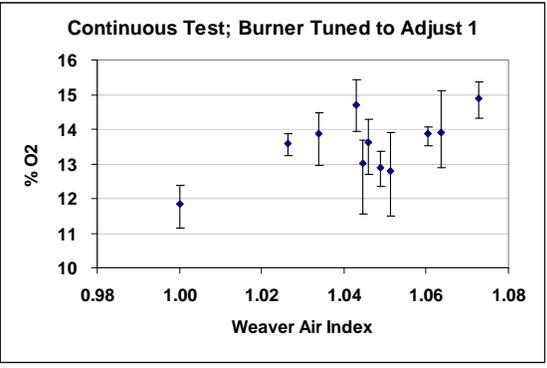
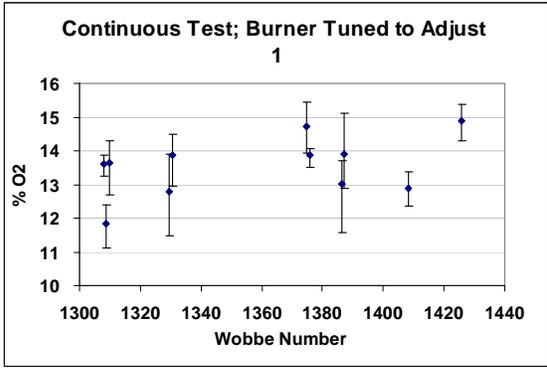


Figure 8. Volume %O₂ in dry exhaust, with the burner tuned to Adjust 1

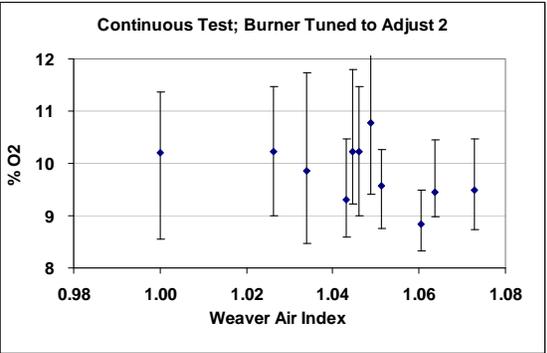
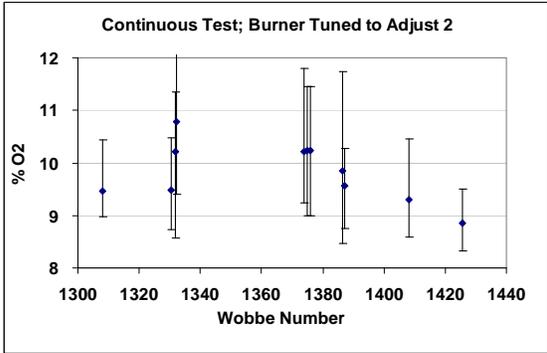


Figure 9. Volume %O₂ in dry exhaust, with the burner tuned to Adjust 2

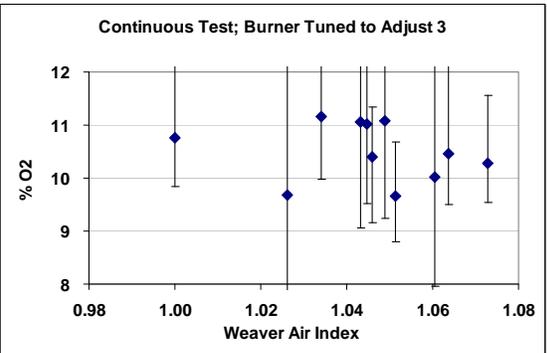
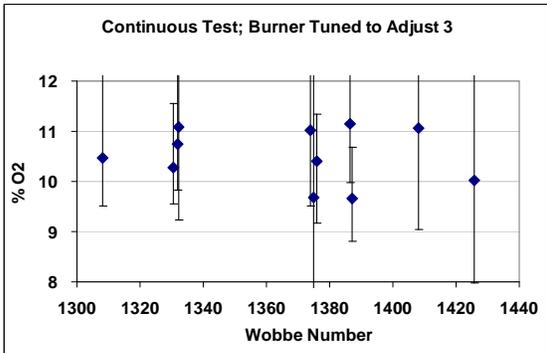


Figure 10. Volume %O₂ in dry exhaust, with the burner tuned to Adjust 3

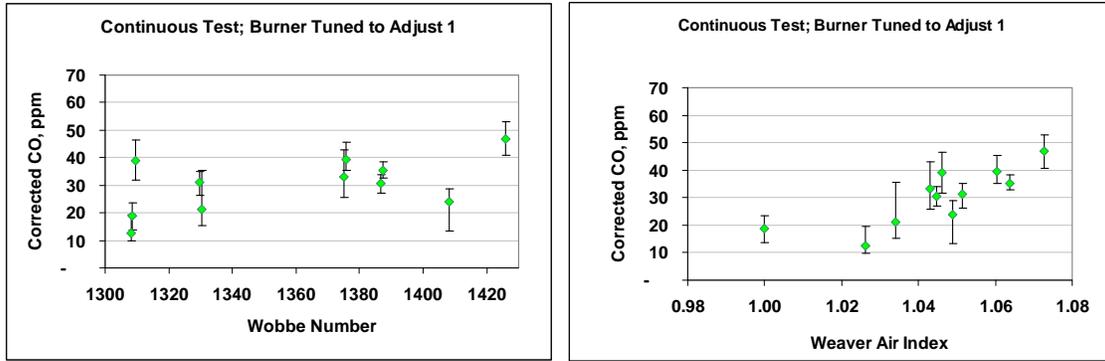


Figure 11. CO concentration in the exhaust with the burner tuned to Adjust 1

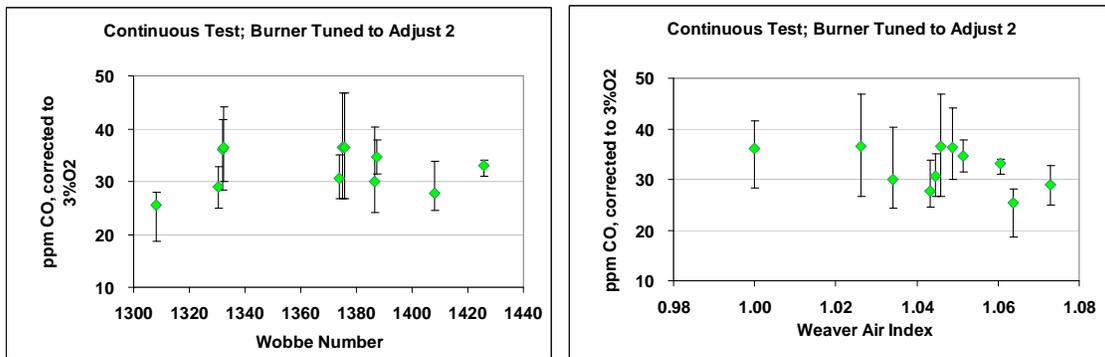


Figure 12. CO concentration in the exhaust with the burner tuned to Adjust 2

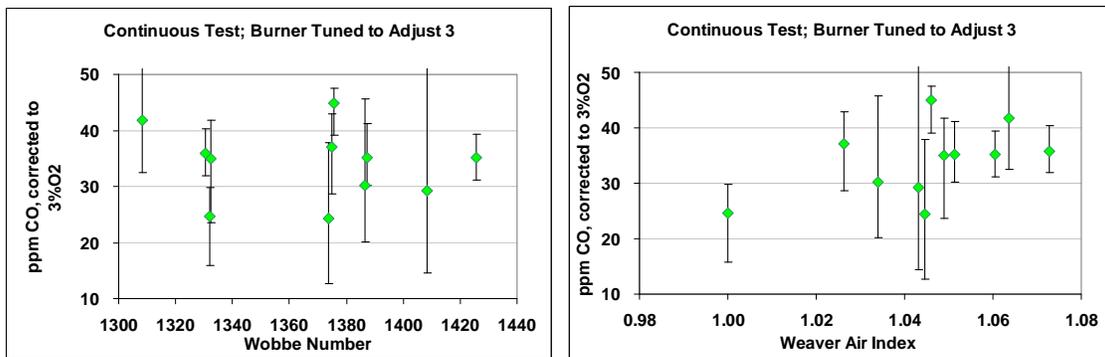


Figure 13. CO concentration in the exhaust with the burner tuned to Adjust 3

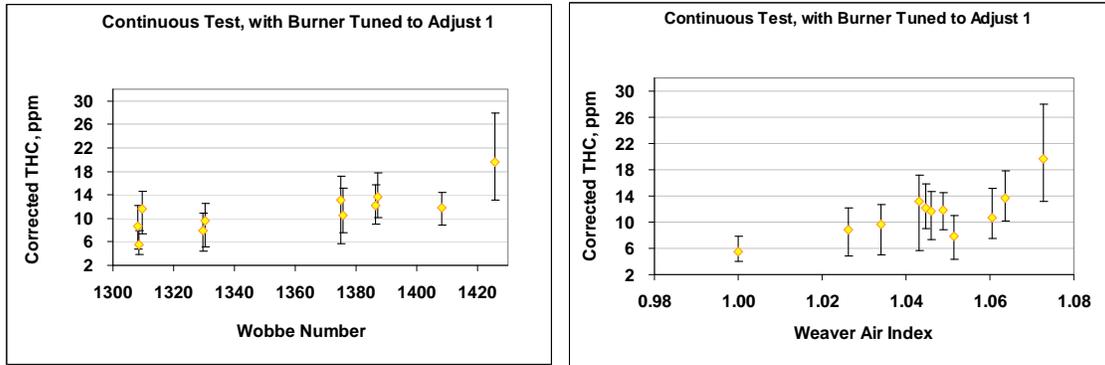


Figure 14. THC concentration in the exhaust with the burner tuned to Adjust 1

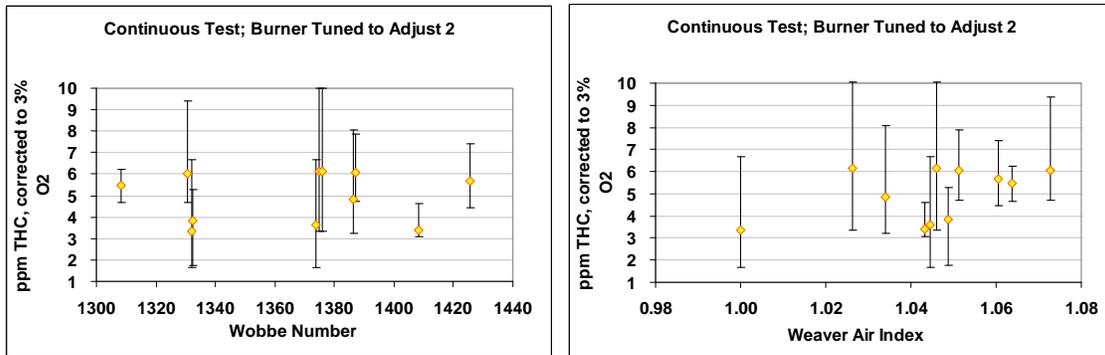


Figure 15. THC concentration in the exhaust with the burner tuned to Adjust 2

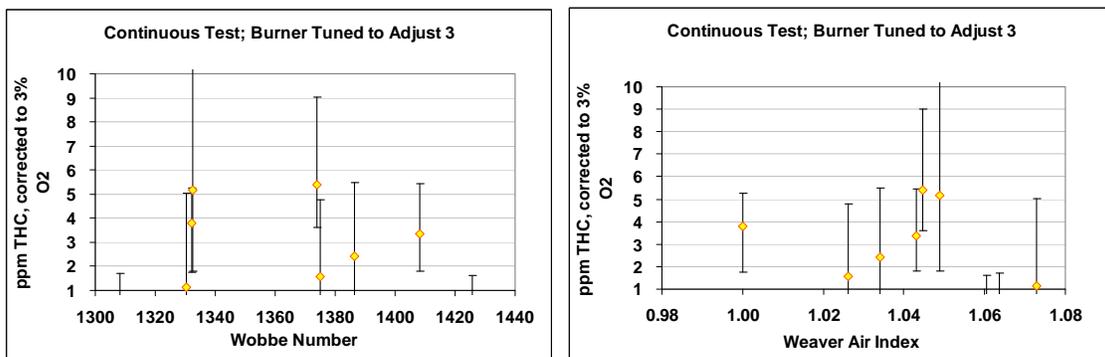


Figure 16. THC concentration in the exhaust with the burner tuned to Adjust 3

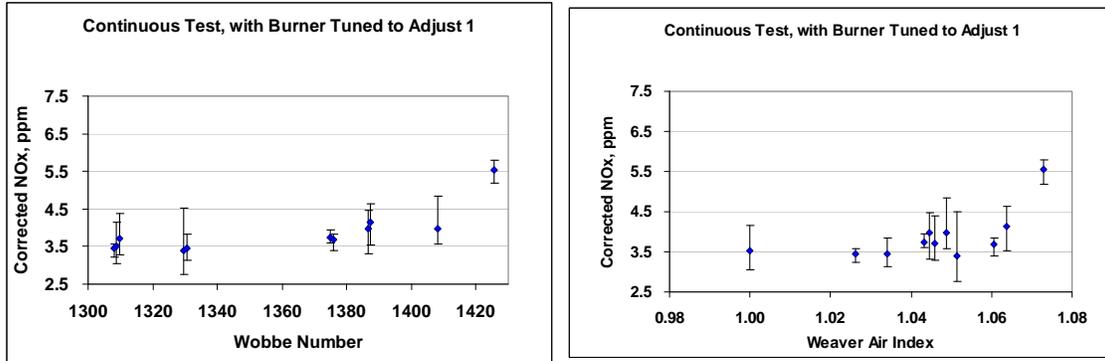


Figure 17. NOx concentration in the exhaust with the burner tuned to Adjust 1

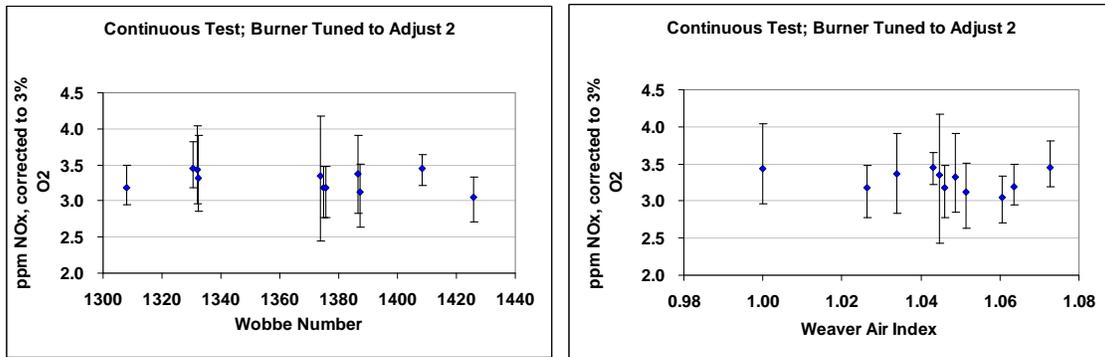


Figure 18. NOx concentration in the exhaust with the burner tuned to Adjust 2

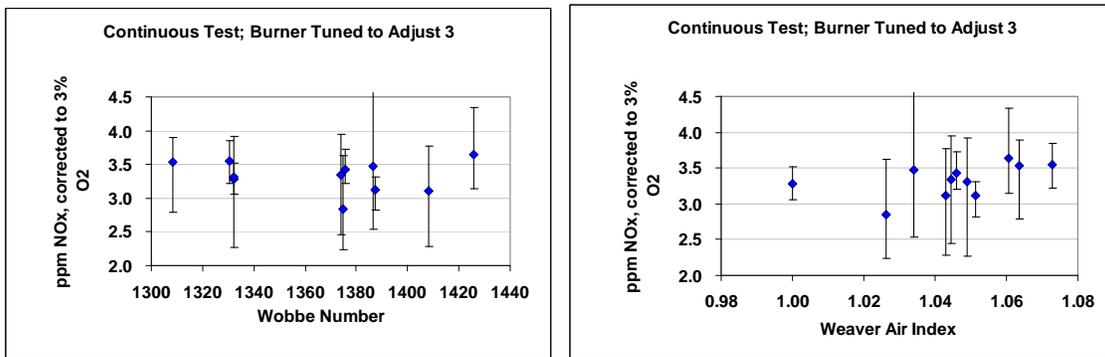


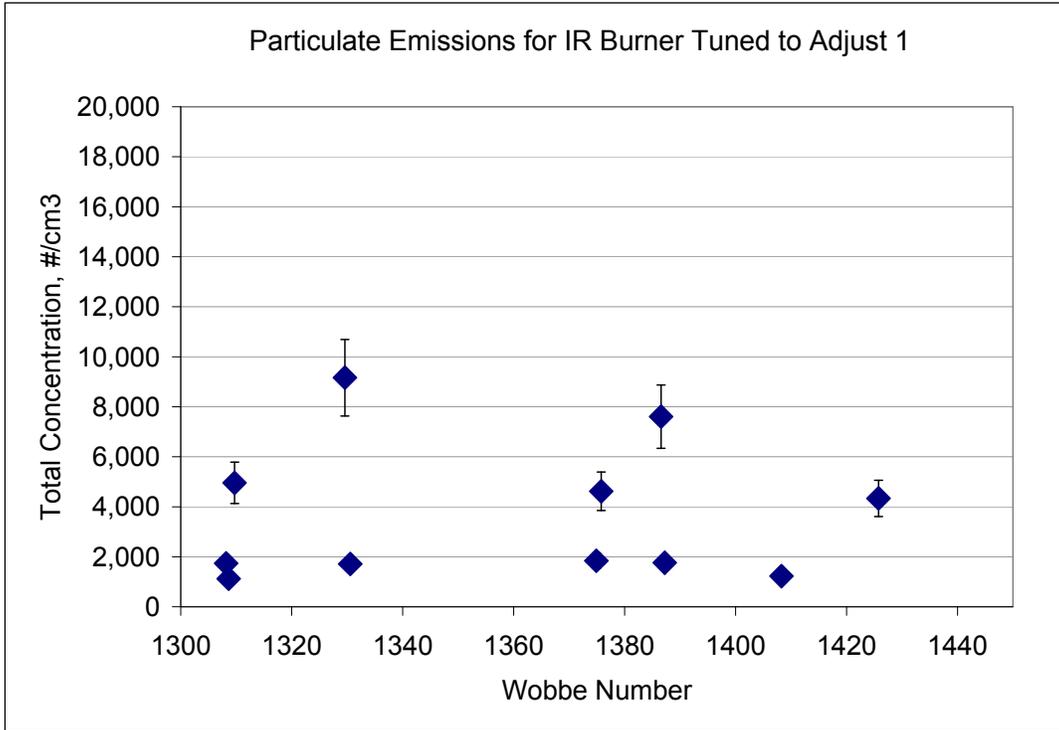
Figure 19. NOx concentration in the exhaust with the burner tuned to Adjust 3

For the ultrafine particle count, the sample temperature upstream of the first dilution ranged from about 350°F to 500°F, and the second dilution brought sample temperatures below about 100°F, with a goal of room temperature—76°F. A dilution ratio of 17 was requested—the value is calculated from a pressure difference in the Dekati sampling probe, but dilution ratios of between 25:1 and 45:1 were calculated by comparing the oxygen content in the sample stream before and after dilution; the stream was diluted with nitrogen instead of air in order to allow this calculation.

Calculations using CO₂ instead of O₂ indicate a wider range of dilution ratios—up to 70:1. These occurred rarely and otherwise the dilution ratios were close to 35, so the O₂ dilution ratios were used and the CO₂ ratios discarded. Each data point in the figures is averaged from between two and four sets of three two-minute scans. The dilution ratio for the air sample (in red) in Figure 23 was taken from a previous scan.

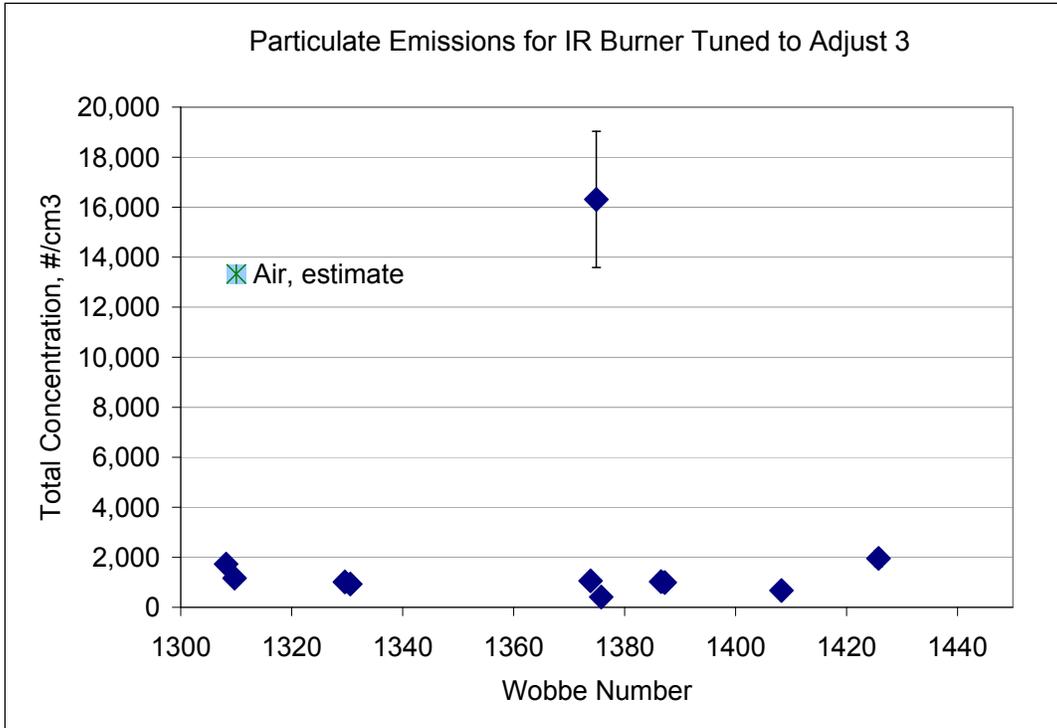
The exhaust sample was isokinetically drawn and diluted twice to simulate particle formation upon exit from the stack. The sample temperature upstream of the first dilution ranged from about 350°F to 500°F, and the second dilution brought sample temperatures below about 100°F, with a goal of room temperature—76°F. A dilution ratio of 17 was requested—the value is calculated from a pressure difference in the Dekati sampling probe, but dilution ratios of between 25:1 and 45:1 were calculated by comparing the oxygen content in the sample stream before and after dilution; the stream was diluted with nitrogen instead of air in order to allow this calculation. Calculations using CO₂ instead of O₂ indicate a wider range of dilution ratios—up to 70:1. These occurred rarely and otherwise the dilution ratios were close to 35, so the O₂ dilution ratios were used and the CO₂ ratios discarded.

Each data point in the figures below is averaged from between two and four sets of three scans. The scan is programmed to identify particles with an apparent diameter of 15 nm to 673 nm, and one scan takes two minutes. Ambient air was sampled prior to the tests with Adjust 2 and Adjust 3. The dilution ratio for the air sample (in red) in Figure 23 was not measured, so it is estimated from the average over all of the scans. It is reasonable that there are more particles present in the ambient air than in many of the combustion products of natural gas.



	Fuel	Wobbe	Dilution ratio	Avg Concentration (#/cm ³), Diluted	Estimated Undiluted Concentration (#/cm ³)
Adjust 1	Adj1	1309	29.5	38	1120
	Sub1	1408	31.5	39	1226
	Sub1-1308	1308	30.6	57	1738
	Sub1-1332	1331	30.3	56	1713
	Sub1-1375	1375	31.3	59	1840
	Sub1-1385	1387	33.4	228	7605
	Sub2	1426	28.7	151	4336
	Sub2-1308	1310	33.1	150	4958
	Sub2-1332	1330	33.1	277	9164
	Sub2-1375	1376	33.7	137	4621
	Sub2-1385	1387	29.6	60	1762

Figure 20. Particulate emissions in the burner's with it tuned for Adjust 1



	Fuel	Wobbe	Avg Ratio	Avg Concentration (#/cm ³), Diluted	Estimated Undiluted Concentration (#/cm ³)
Adjust 3	Air only	0	39.2	341	13333
	Adj3	1374	47.0	23	1058
	Sub1	1408	34.1	20	672
	Sub1-1308	1308	32.5	53	1728
	Sub1-1332	1331	41.5	22	932
	Sub1-1375	1375	32.6	500	16310
	Sub1-1385	1387	48.9	21	1025
	Sub2	1426	42.2	46	1953
	Sub2-1308	1310	41.4	28	1166
	Sub2-1332	1330	34.4	29	1011
	Sub2-1375	1376	41.2	10	410
	Sub2-1385	1387	34.6	29	990

Figure 22. Particulate emissions in the burner's with it tuned for Adjust 3

Heat flux

A heat flux sensor scanned the burner surface at 1-inch increments. The burner was controlled to maintain a 1500°F surface temperature, so the overall heat flux should not vary significantly, although the temperature distribution may change depending on the firing rate required to maintain the control value. Table 6 through Table 8 show the average, maximum, and minimum heat flux recorded over the burner surface. Figure 24 through Figure 26 show heat flux contours over the burner face.

Table 5. Heat flux with the burner tuned to fire Adjust 1

	Wobbe	Heat flux, BTU/ft ²		
		Max	Avg	Min
Adj1	1309	6.1	4.19	2.0
Sub1-1308	1308	5.7	4.17	2.1
Sub2-1308	1310	5.6	4.28	2.1
Sub2-1332	1330	5.9	4.41	2.2
Sub1-1332	1331	6.0	4.34	2.0
Sub1-1375	1375	6.0	4.44	2.8
Sub2-1375	1376	5.9	4.46	2.5
Sub1-1385	1387	6.0	4.34	2.5
Sub2-1385	1387	5.8	4.49	2.1
Sub1	1408	6.0	4.36	2.5
Sub2	1426	6.2	4.57	2.2

Table 6. Heat flux with the burner tuned to fire Adjust 2

	Wobbe	Heat flux, BTU/ft ²		
		Max	Avg	Min
Adj2	1332	5.8	3.98	2.5
Sub1-1308	1375	5.7	3.94	2.2
Sub2-1308	1376	5.8	3.96	2.1
Sub2-1332	1387	5.4	4.11	2.3
Sub1-1332	1387	5.7	4.12	2.0
Sub1-1375	1408	5.9	3.86	1.9
Sub2-1375	1426	5.4	3.99	2.3
Sub1-1385	1374	5.5	3.96	1.7
Sub2-1385	1308	5.5	4.07	2.0
Sub1	1332	5.8	3.94	1.7
Sub2	1331	5.7	3.98	1.9

Table 7. Heat flux with the burner tuned to fire Adjust 3

	Wobbe	Heat flux, BTU/ft ²		
		Max	Avg	Min
Adj3	1375	5.5	3.85	1.5
Sub1-1308	1375	5.5	4.15	2.1
Sub2-1308	1376	6.0	4.21	1.9
Sub2-1332	1387	6.0	4.11	2.1
Sub1-1332	1387	5.7	4.15	1.9
Sub1-1375	1408	6.2	4.22	1.7
Sub2-1375	1426	6.0	4.16	1.8
Sub1-1385	1374	5.7	4.29	1.9
Sub2-1385	1308	6.1	4.22	1.8
Sub1	1332	6.1	4.35	1.7
Sub2	1331	6.0	4.21	1.9

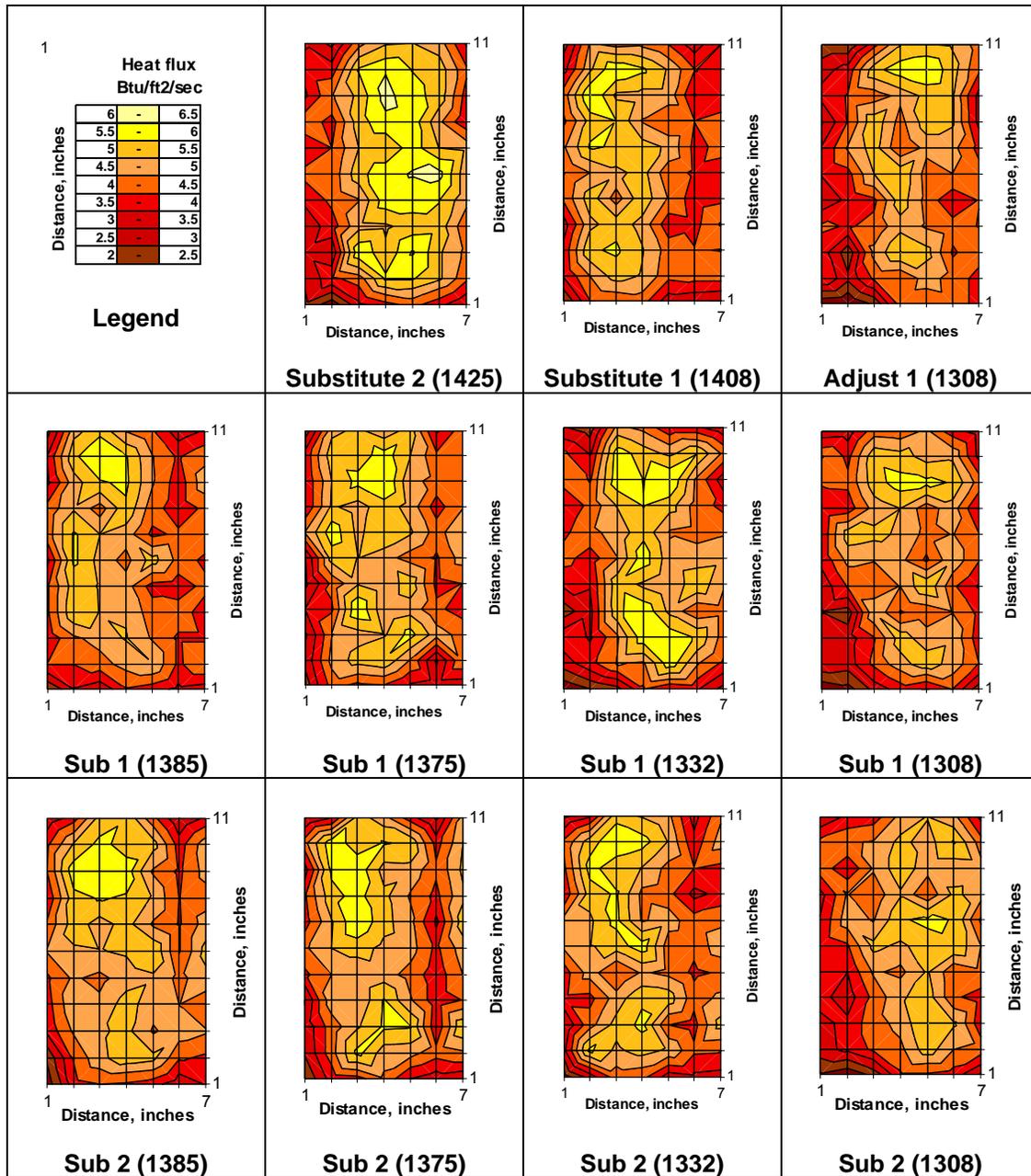


Figure 23. Continuous Test, Tuned to Adjust 1: Heat Flux through one Burner Face

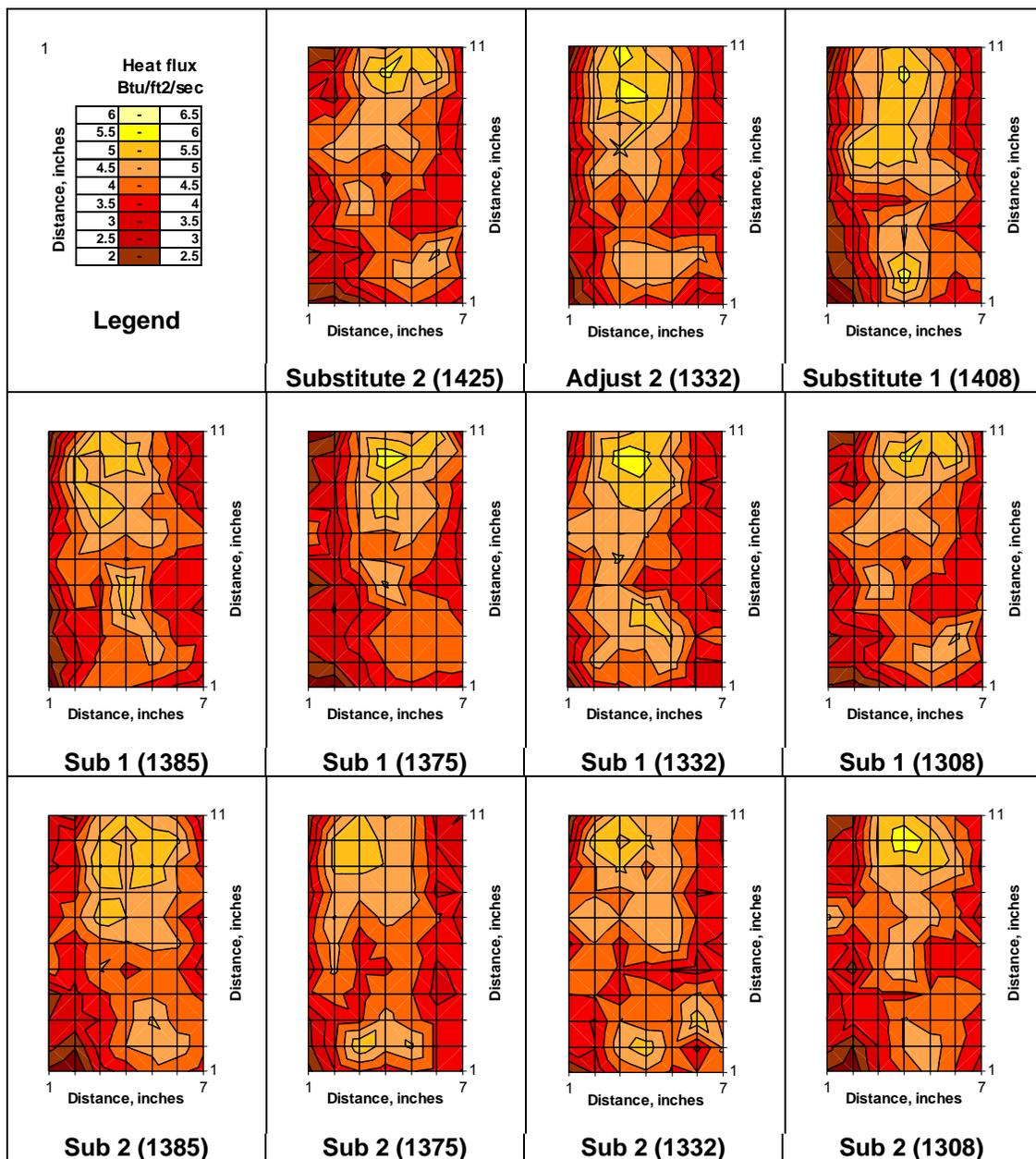


Figure 24. Continuous Test, Tuned to Adjust 2: Heat Flux through one Burner Face

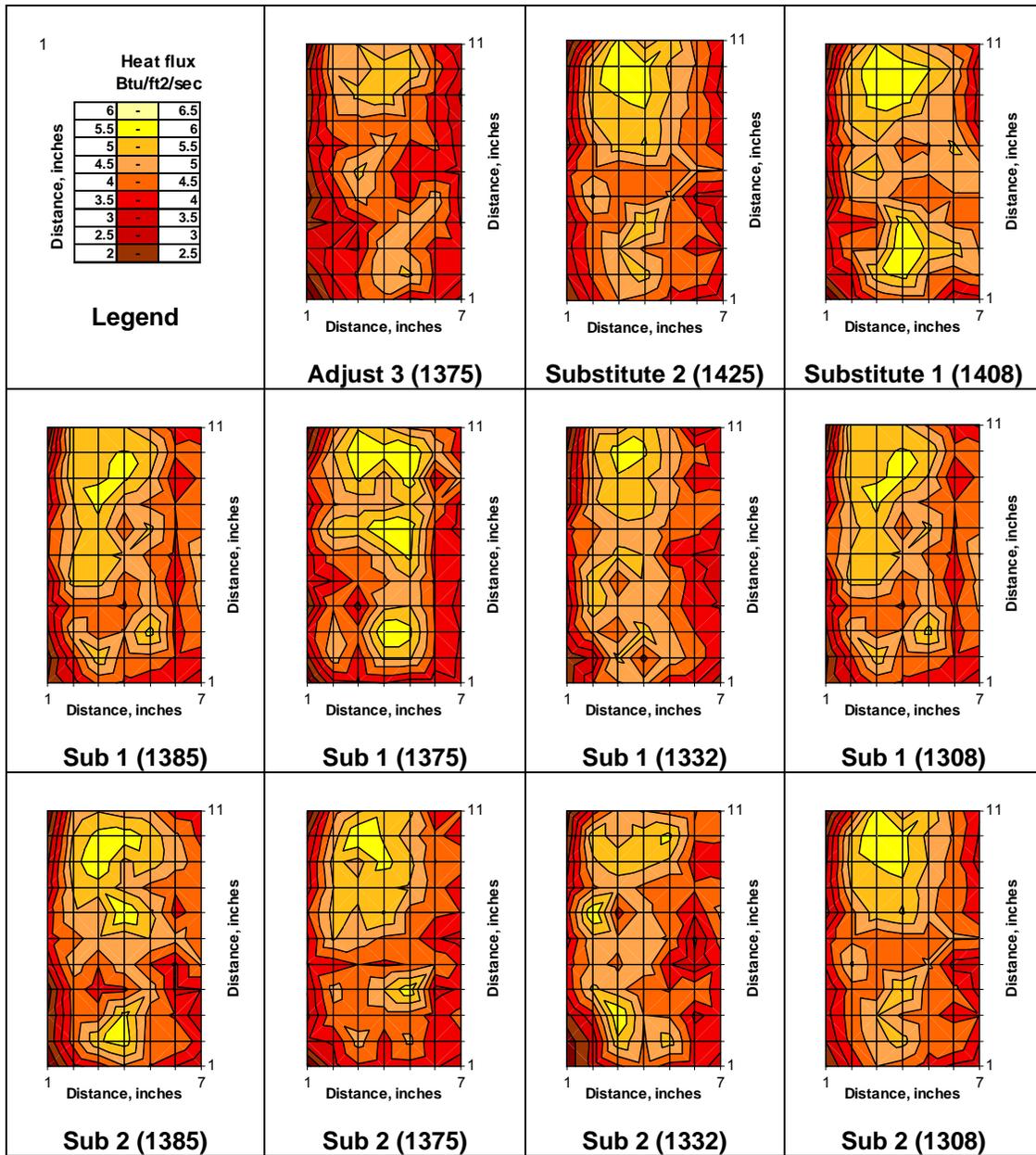


Figure 25. Continuous Test, Tuned to Adjust 3: Heat Flux through one Burner Face

Ignition Test Results

Firing rate and burner temperature

Figure 26 through Figure 36 show the firing rate and burner temperature during the ignition tests. They are separated into multiple charts, with the Adjust Gas repeated, to better show detail of the change with respect to time. The test protocol used for the Adjust 2 ignition tests in Figure 30 through Figure 33 was different from that used for

the other tests; the firing rate was held at low fire for two minutes prior to being released to the feedback controller, which immediately turned to high fire until the burner reached temperature. The forced-low firing rate was required because the pilot burner, which taps off of the burner's manifold, would otherwise blow off or extinguish causing the safety shutoff to trip. Extinguishment occurred once even with the two minutes of low-fire built in; this is shown in Figure 30. The burner was adjusted for Adjust 2, and when it was fired with Adjust 1 the flame went out. The automatic re-ignition sequence successfully relit the pilot, but this incident demonstrated that the burner should not be operated so lean with the pilot on. Adjusting the air-to-fuel ratio stopped this from happening, so the tests with Adjust 1 and Adjust 3 were performed with modified ratios (the %O₂ in the exhaust was reduced from about 8.5%±0.5% to about 7%±0.5%).

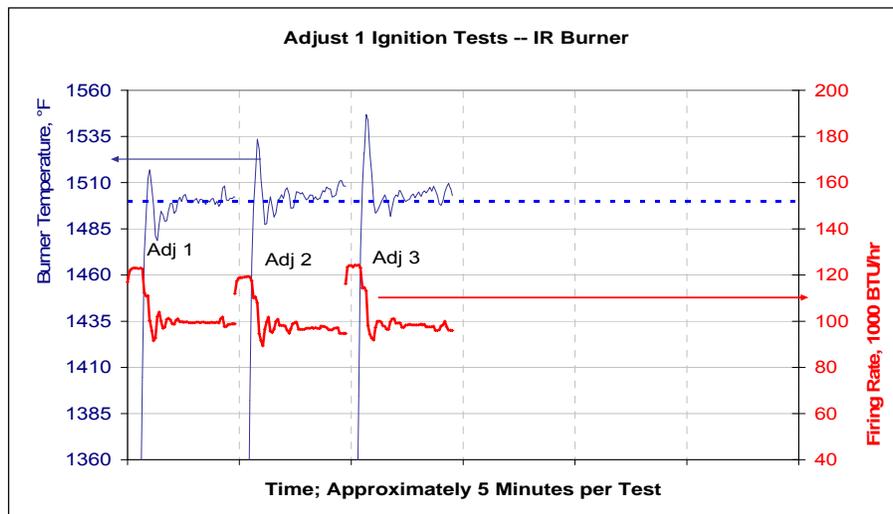


Figure 26. Burner Tuned to Adjust 1--Compare Adjusts

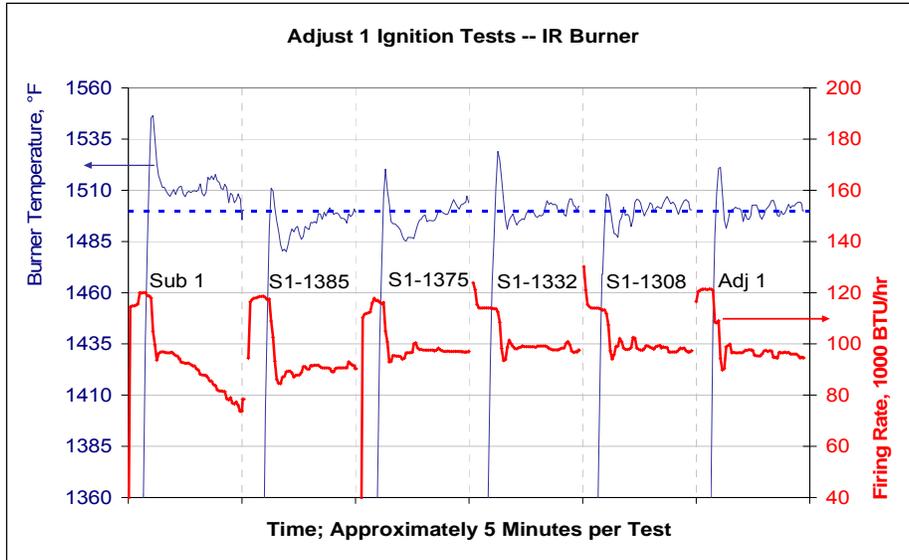


Figure 27. Burner Tuned to Adjust 1--Compare Substitute 1 Blends

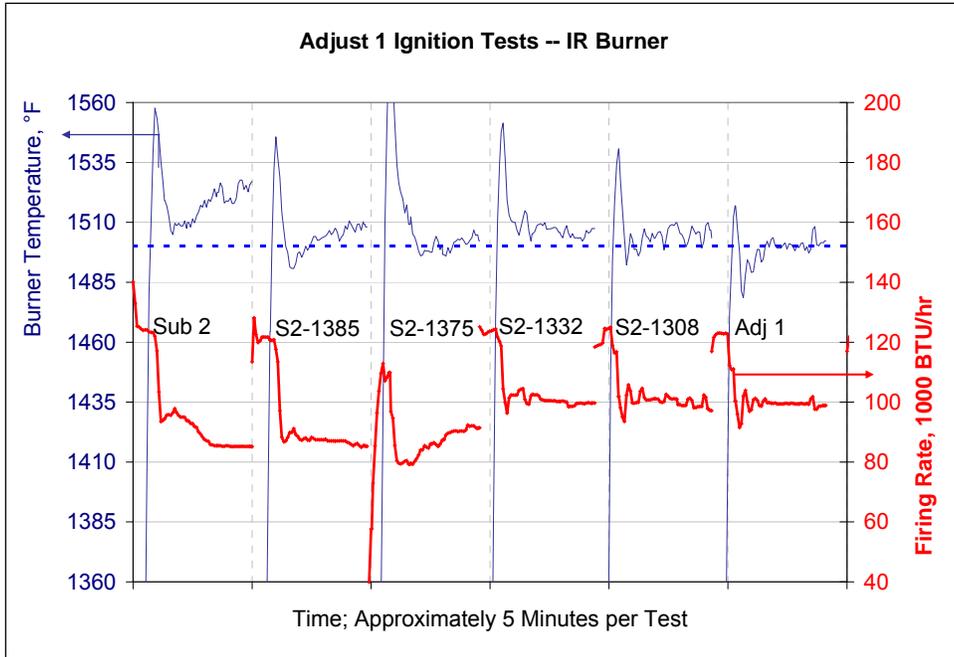


Figure 28. Burner Tuned to Adjust 1--Compare Substitute 2 Blends

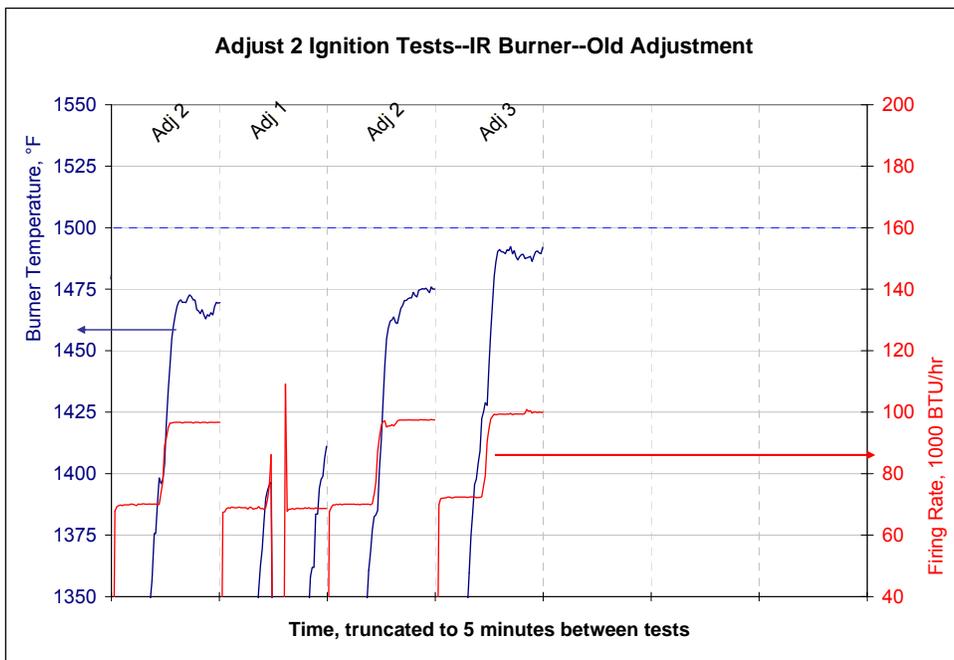


Figure 29. Burner Tuned (Lean) to Adjust 2--Compare Adjusts

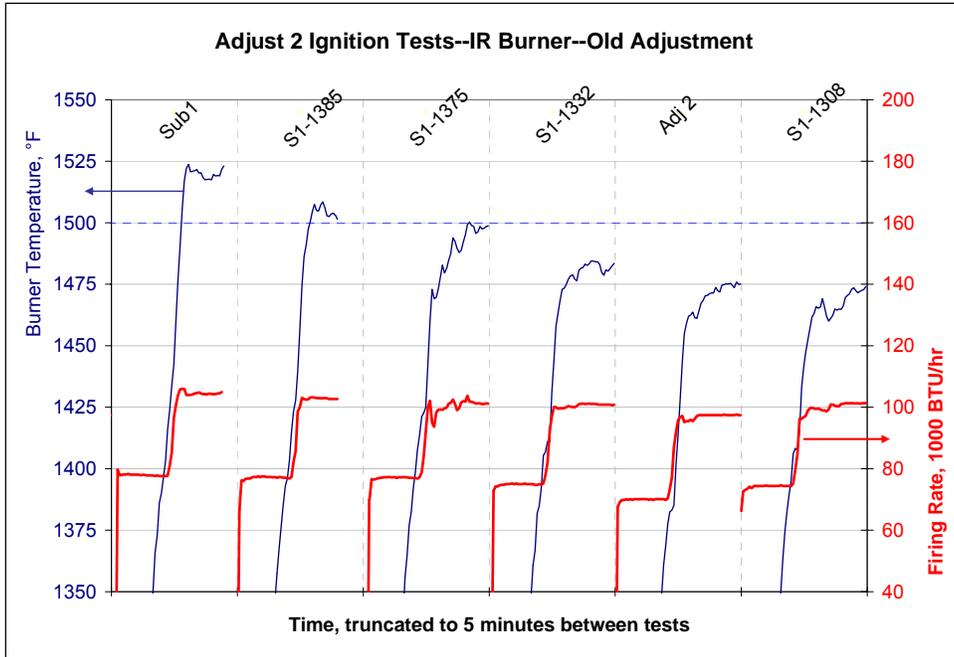


Figure 30. Burner Tuned (Lean) to Adjust 2--Compare Substitute 1 Blends

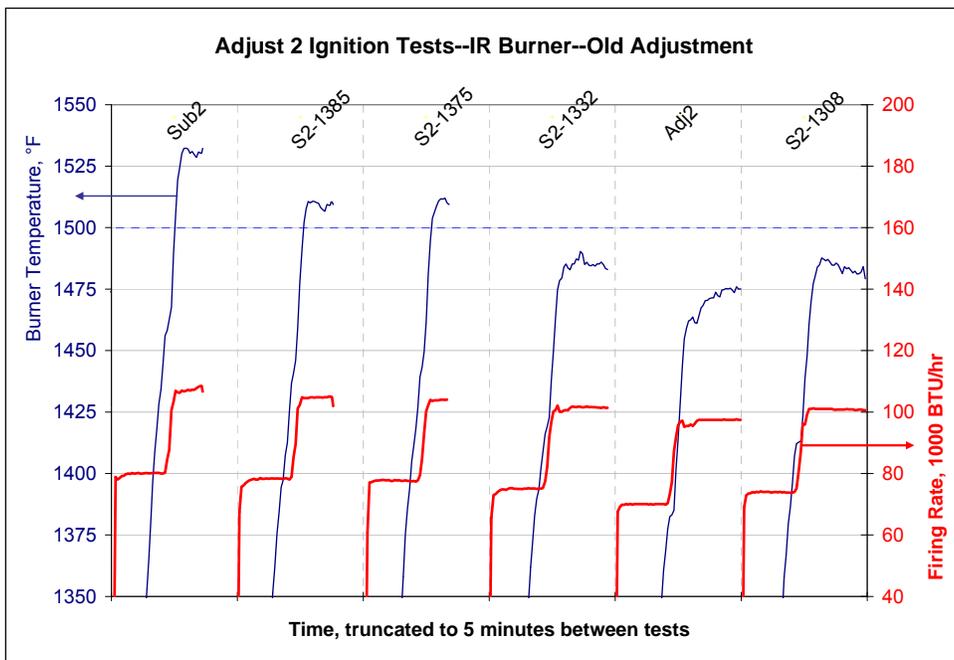


Figure 31. Burner Tuned (Lean) to Adjust 2--Compare Substitute 2 Blends

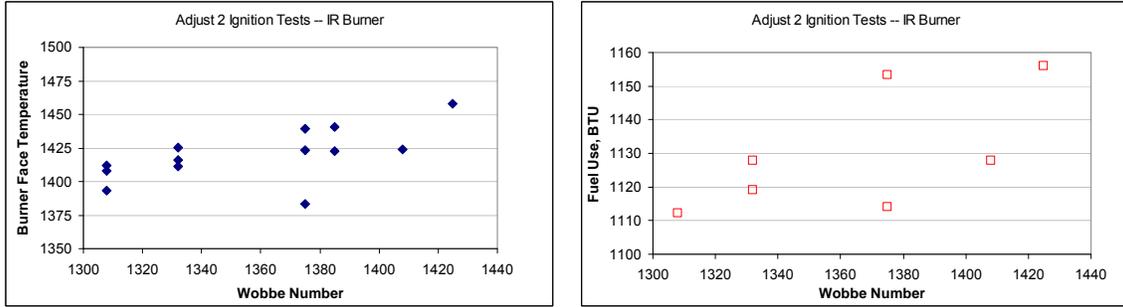


Figure 32. Burner Temperature (Left) and Total Btus Used (Right) after 2 Minutes at Low Fire, with Burner Tuned (Lean) to Adjust 2

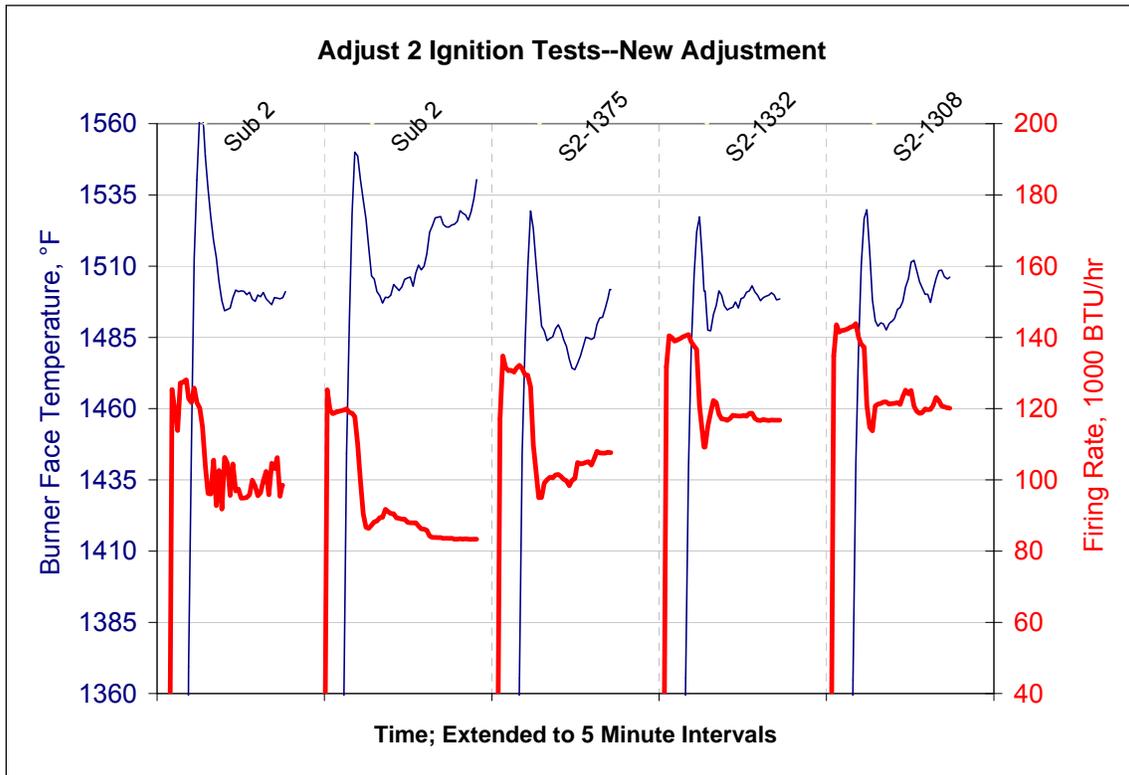


Figure 33. IR Burner Tuned (Not Lean) to Adjust 2--Compare Adjusts

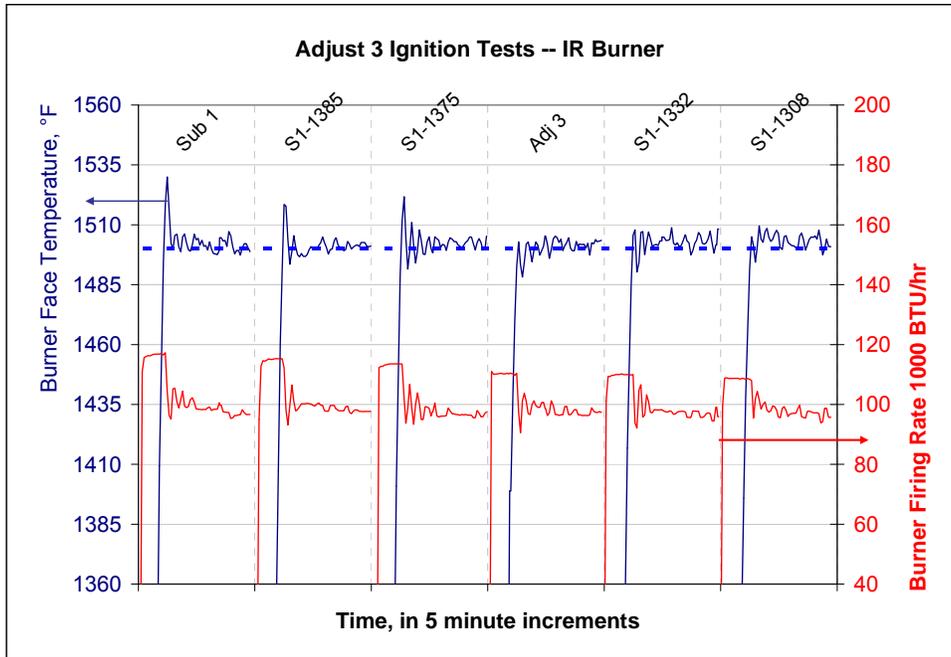


Figure 34. IR Burner Tuned to Adjust 3--Compare Substitute 1 Blends



Figure 35. IR Burner Tuned to Adjust 3--Compare Substitute 2 Blends

Calculations

The equation below is the linear correction used to approximately cancel out the analyzer drift;

$$X_{corr} = X_{meas} - \left((Zero\ drift) + (Span\ drift) \frac{X_{meas}}{Span\ value} \right) \frac{T_1}{T_2},$$

where X_{corr} is the corrected emissions value, X_{meas} is the measured value, the drift values are as labeled, T_1 denotes the time elapsed from the previous analyzer calibration, and T_2 denotes the time from the previous analyzer calibration to the next analyzer calibration.

After this correction, the emissions were normalized to 3%O₂ using the formula,

$$X_{3\%O_2} = X_{corr} \left(\frac{21 - 3\%}{21 - \%O_2} \right),$$

where $X_{3\%O_2}$ is the final value after both the correction for drift and the normalization to a common %O₂ in the exhaust.

The Wobbe Number and the Weaver Air index were calculated not from the actual flow data but from the commanded flows, however the Heating Value indicated for the firing rate was calculated from the actual flow data. The heating value calculation followed the ASTM D 3588 – 98(03) standard at 70°F, and the remaining calculations are from the AGA definitions of the Wobbe Number and the Weaver Air Index.

Analysis

The charts and data are analyzed in the same sections below as appear in the Results section.

Continuous Test Analysis

Firing Rate

The average firing rate for all of the tests over the middle four minutes of continuous operation of the burner are presented in Table 5 and in Figure 4. The firing rate is monotonically decreasing with respect to Wobbe Number, except with the burner tuned to Adjust 2. The firing rate for Adjust 2 at 1332 Wobbe was slightly higher than at 1308 Wobbe. The burner temperature and firing rate data for the tests are expanded in Figure 5, Figure 7, and Figure 8; it is possible to visually see that the firing rate is lower for the higher-Wobbe Number gases.

Emissions

The emissions data are shown plotted both against the Wobbe Number and the Weaver Air Index. The Weaver Air Index was selected because the numbers appeared to correlate better with the data than others of the commonly used AGA and Weaver indices. The error bars on the plots do not represent a standard deviation, but the entire range of data collected. %O₂ is shown in Figure 9 through Figure 11; there does not appear to be a clear correlation between the variation and the Wobbe Number (left charts) or the Weaver Air Number (right charts) because the total range of variation across the different fuel compositions is often larger than the variation between the average %O₂ for every fuel. This can, but does not necessarily imply that the variation is insignificant over the range of gases. Since the burner's firing rate was modulating, the %O₂ varied not only over the range of test gas compositions, but also over the firing rate. The 75% to 100% open part of the valve's range of motion did not change the firing rate, so instead the %O₂ was lowered to maintain a monotonically increasing temperature profile with a maximum of about 1600°F at the 100% open valve position. Still, the steady position of the valve when firing the adjust gas was about 40% open, and it would only open further briefly on ignition, or else when firing a gas with a lower Wobbe Number.

Figure 12 through Figure 14 show the measured ppmv CO, normalized to 3%O₂. With the burner tuned to Adjust 1, the concentration of CO appears to increase with Wobbe Number, however for the remaining adjust gases its concentration does not appear to show a trend. If the data point for 1425 Wobbe were removed from Figure 12, it could be argued that there is not a trend even for the Adjust 1 data. The same observations are true for the ppmv THC shown in Figure 15 through Figure 17, and the ppmv NO_x shown in Figure 18 through Figure 20. It is not usual for both CO emissions and NO_x emissions to rise simultaneously. First, the total NO_x formation is very small for all cases; at most about 8% of the calibration gas value. Next, the burner is fired in open air

the flame quenches quickly. Third, for Adjust 1 the heat flux from the burner surface is higher than for the other gases; heat flux will be discussed below; so some more NO_x could form before quenching and the CO and the THC would not completely combust. It would make sense that any such response would be less noticeable when firing Adjust 2 and Adjust 3, because their Wobbe Numbers are not as low, so the disparity between these fuels and the Substitute gas compositions is smaller.

The particulate emissions are summarized in Figure 21 through Figure 23. The data, like the other emissions data, are scattered and do not appear to show a trend with respect to Wobbe Number. The particle count in the emissions is usually less than and at least comparable to the particle count in air.

Heat Flux

The heat flux data in Table 6 through Table 8 and Figure 24 through Figure 26 show that the highest average heat flux occurs when firing Substitute 2 on a burner adjusted to fire Adjust 1. The biggest difference, a 12% change in average heat flux over the burner surface, was between Adjust 3 and Substitute 1. These data were collected while the burner was modulating, so the color pattern does not necessarily reflect a static temperature distribution. The data demonstrate a relatively consistent heat flux, sometimes with higher Wobbe Number gases corresponding to a higher heat flux, but not always.

Ignition Test Analysis

Firing Rate and Burner Temperature

Figure 27 through Figure 36 show three things: first, the higher Wobbe-Number gases overshoot the setpoint more than the lower Wobbe-Number gases on ignition. Second, the higher Wobbe Number gases can take longer to settle to the setpoint temperature than the lower Wobbe-Number gases. Third, it is possible for a poorly tuned; in this case lean; burner to extinguish when firing a lower Wobbe Number gas. Figure 21 shows ignition tests with the burner tuned to Adjust 2, and an ignition failure, with successful relight on Adjust 1. In this case, the Substitute gases with the same Wobbe Number actually did light, and only Adjust 1 did not light on the first time. These tests are labeled “Old Adjustment” because they used the same burner adjustment as for the continuous-firing tests. This appeared to be too lean, and did not provide sufficient heat; S1-1308 in Figure 31 fired for 20 minutes and still did not reach temperature. The firing rate is held constant for the first two minutes in an effort to keep the pilot lit. All of this was abandoned when it became clear the burner was too far out of tune to respond rapidly enough even when firing the gas it was adjusted to, Adjust 2. For the remaining tests, the burner was tuned again before ignition tests, to compensate for the pilot. No ignition problems were encountered after this decision.

The firing rate for ignition began the same for all of the gases. When the burner was tuned to Adjust 3, all of the Substitute Gas firing rates settled in well under five minutes;

when tuned to Adjust 2 or Adjust 1, the highest few Wobbe Number Substitute Gases had not settled after five minutes. It appears that with the burner tuned to Adjust 1 (1308) but igniting with Substitute 2 (1425 Wobbe Number - about a 9% change) the firing rate is flat at its lowest but the burner temperature is still rising above 1500°F.

Conclusions

Conclusions are listed in the same sections below as appear in the Results and Analysis sections.

Continuous Test Conclusions

Firing Rate

That the firing rate is lower for the higher-Wobbe Number gases makes sense because the higher-Wobbe gases require more air to burn but are still premixed with the same amount of air, meaning there is less excess air to absorb heat from the reaction. The data indicate that when the fuel gas Wobbe Number changes from a smaller to a larger value, a lower firing rate is needed to maintain the same process temperature for the burner.

Emissions

It appears that the variation in emissions across the fuel gases tested is comparable to the variation in emissions for a single fuel over time. When the burner tuned to Adjust 1 was fired with Substitute 2, there was a clear increase in NO_x, THC, CO. This could imply that the burners tuned to Adjust 1, with a Wobbe Number of 1308, should not be expected to fire Substitute 2, with a Wobbe Number of 1425. Further, it could imply that a burner adjusted to Adjust 2 or Adjust 3 can be expected to fire Substitute 2 without a significant measurable change in emissions. There also does not appear to be a correlation between Wobbe Number and particulate emissions for any of the Adjust Gas/Substitute Gas pairings.

Heat Flux

The heat flux through the burner does appear to increase slightly, up to 12% at most, with an increase in Wobbe Number, even though the burner face temperature is held at a set temperature.

Ignition Test Conclusions

Firing Rate and Burner Temperature

For these test gases, an excessively lean burner adjustment to Adjust 2 caused an ignition failure using Adjust 1, although the burner did light once the relight sequence engaged. When the burner was tuned so that it could reach its setpoint in about a minute when firing on its Adjust Gas, there were no ignition problems. Still, it may be that a change from Adjust 1 to Substitute 2 exceeds the turndown ability of the burner—it cannot fire low enough on Substitute 2 to meet the setpoint temperature. Ignition tests could not be conducted with the same air-to-fuel settings on the modulating valve as were set for the continuous operation tests. This was discovered during the first set of ignition tests for Adjust 2: with the continuous pilot on, the flame appeared to burn very lean. The flame monitor lost flame detection in a few cases, and when the fuel was switched from Adjust 2 to Adjust 1, the flame would not re-light. With a new air-to-fuel ratio, the flame monitor did not lose flame detection for any of the tests.

Selected Photographs



Figure 36. Infrared Burner Test Apparatus



Figure 37. Motorized Valve atop the Premix Blower

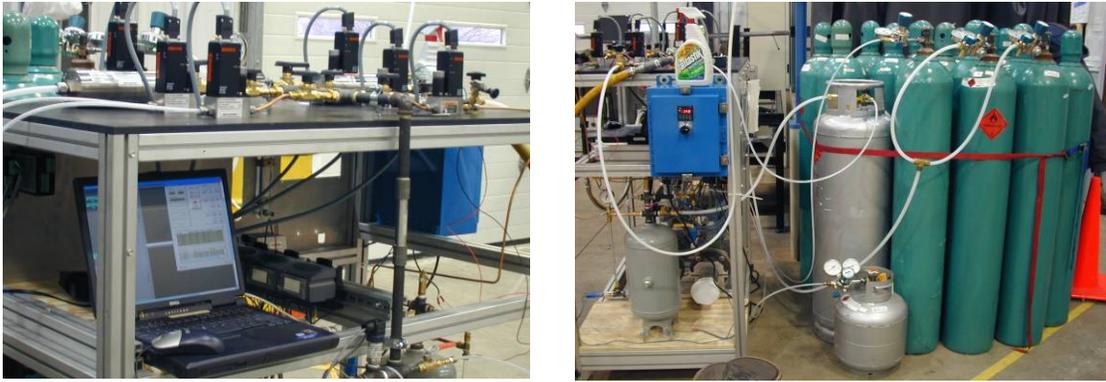


Figure 38. Two Views of the Blending Station with Constituent Gases



Figure 39. Emissions Analyzers (left) and Gas Chromatograph (right)

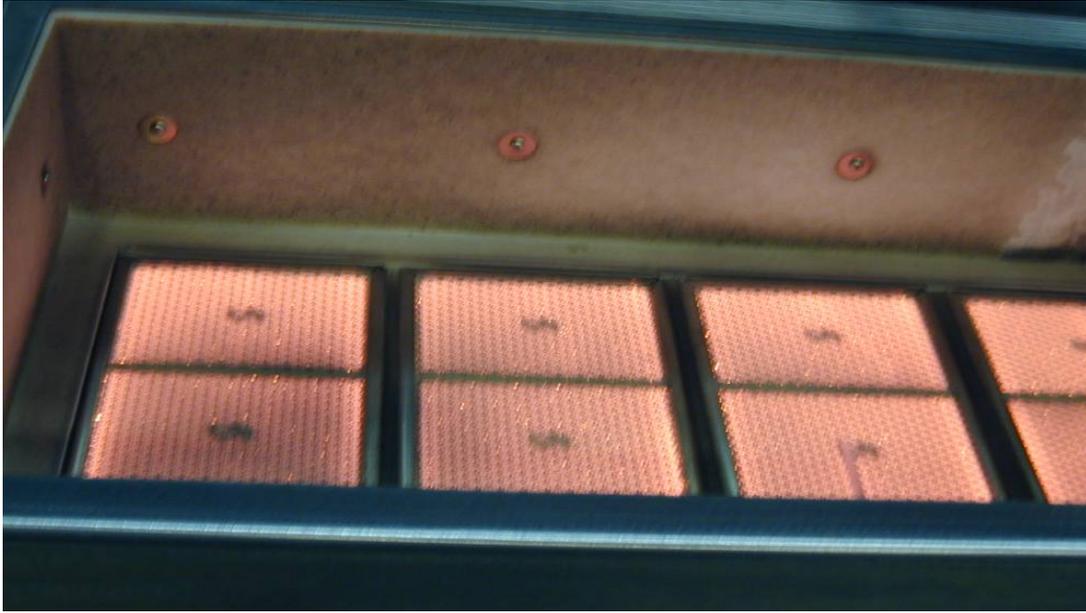


Figure 40. Infrared Burner with 4" Tall Insulating Walls and a Thermocouple (on the Bottom Right tile) for Burner Temperature Control

NATURAL GAS IN CALIFORNIA: ENVIRONMENTAL IMPACTS
AND DEVICE PERFORMANCE

**Industrial Burner Evaluations:
Line Burner Test Report**

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(GTI Project No. 20352)

For

California Energy Commission

Contract No. CEC-500-05-026

**Commission Project Manager
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May 2010

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Objective

The purpose of the line burner interchangeability tests is to assess the performance of a linear ribbon burner, used in industrial food processing operations, when fired with different natural gas compositions. The burner's performance when firing selected Adjust Gases was compared with its performance when firing selected Substitute Gases with and without different levels of nitrogen ballasting.

Approach

The tests used a laboratory setup intended to mimic industrial operating conditions. Ignition tests and Operating/switching tests were then performed. During these tests, the burner was first tuned to operate with an "adjust" gas composition, then several "substitute" gas compositions were fired in sequence on the burner. These tests were then repeated with the other two "adjust" gases as a basis.

Ignition tests were performed from the same start conditions of an approximately 180°F chamber temperature to the same end conditions of an approximately 360°F chamber temperature at 25-30% firing rate as recommended by the manufacturer.

Operating tests were performed in two modes, constant firing rate and constant chamber temperature. Both tests used a zero gas governor and venturi mixer to maintain the gas flow rate proportional to the air flow rate. Constant firing rate tests were performed with the air flow rate set manually, yielding a firing rate of about 80,000 Btu/hr. Constant temperature tests were performed with a PID-loop temperature controller manipulating a control valve on the air line to maintain the chamber temperature at 950°F.

For all test sequences, the chamber was first warmed up on house gas. The fuel was then switched to an "adjust" gas, and the burner was tuned so that the exhaust gases contained 3% O₂.

Table 9 shows the specific performance measurements.

Table 8. Performance Metrics for the Line Burner

BASIC PERFORMANCE METRICS
Gaseous Pollutant Emissions
Chamber and Exhaust Temperatures
System or Controller Response upon Switching

Test Apparatus

The linear burner used for this test was an EXTRUded Band Burner BB102A by Flynn Burner Corporation rated for 4,000 Btu/inch of flame space with a stable turndown to 200 Btu/inch. Two linear ribbon burners were selected to simulate baking oven operation and eliminate any wall effects. Flame space of 36 inches was selected for each burner. The burners were ignited and their flames were sensed using a combination spark ignition rod/flame rod for each burner. Two flame safeguards were used, one for each burner. They were wired such that if either burner lost flame during operation, the gas to both burners would be shut off. The burner assembly is shown in Figure 37.

The test burners fired into a cylindrical furnace chamber equipped with four water-cooled load simulators located above the burners and three thermocouples to measure temperatures inside the furnace. One of these was used for temperature control. A fourth thermocouple measured the exhaust temperature. The overall view of the test rig is shown in Figure 67. Water was flowed in series through the load simulators. The water flow rate was measured by a magnetic flow meter. The water temperature was measured with thermocouples before the first load simulator, between the second and third load simulators, and after the fourth load simulator.

Added to the exhaust of the test chamber was a stainless steel sampling probe, which was connected through a filtering and drying train to a set of continuous emissions analyzers for THC, NO_x, CO₂, CO, and O₂. These are shown in Figure 68.

A custom-built blending station was used to provide simulated natural gas compositions to the test chamber at 0.5 psig. The blending station allowed for one of two main streams, house gas and methane, to be selected, to which metered amounts of ethane, propane, butane, and nitrogen could be added. The house gas was the normal natural gas delivered to GTI. The methane was the basis for all the "adjust" and "substitute" gases. House gas was used only for warming up the burners.

Mass flow controllers were used in "wide open" mode to measure house gas and methane flows. Which mass flow controller was "wide open" and which was "shut" was used to select one of these two main streams. The "wide open" mass flow controller was ordered to flow the maximum amount of gas. The system only allowed so much gas to flow, so this method allowed the mass flow controllers to act as mass flow meters. The "shut" mass flow controller was simply commanded to flow a zero amount of gas.

Mass flow controllers were used to add ethane, propane, butane, and nitrogen to the main stream. Methane was supplied from one of two gas cylinders, which could be switched on the fly, allowing an empty one to be swapped out while keeping the experiments running. Ethane was supplied from a single gas cylinder, propane was supplied from the gaseous outlet of a liquid cylinder, and nitrogen was supplied from GTI's header, which is fed by a liquid tank. Butane was supplied from a heated evaporation tank and delivered as a gas at a pressure well above its saturation vapor pressure of about 14 psig. The evaporation tank was replenished from a liquid cylinder.

Table 9. Summary of Test Instruments

Instrument	Parameter	Range	Accuracy
National Instruments Field Point Modules	Data logging and control	4-20 mA, 0-5 V, 0-10 V, ±100 mV, on/off (relay)	16 bit input current; 12 bit input voltage; 12 bit output current; 16 bit temperature
LabView software	Data logging	—	—
Custom software	Control	—	—
Laptop computer	Data logging and control	—	—
Type K thermocouple	Chamber and Exhaust temperatures	2502°F	—
ABB Mini-Mag 10D1475W	Water flow rate	26.42 gpm	0.5% of rate @ ≥ 7% full scale
Type T thermocouple	Water temperatures	752°F	—
Rosemount Analytical 400A	THC concentration	0-1000 ppm, Span 889 ppm	1% full scale
Rosemount Analytical 755R	O ₂ concentration	0-25%, Span 8.0%	0.01% O ₂ or 1% full scale
Thermo Environmental 42C High Level	NO conc, NOx conc.	0-100 ppm, Span 76.7 ppm	0.5 ppm
Rosemount Analytical 880A	CO concentration	0-1000 ppm, Span 790 ppm	1% full scale
Rosemount Analytical 880A	CO ₂ concentration	0-20%, Span 18.0%	1% full scale
Brooks Instruments 5853S	House gas flow rate	355 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5853S	Methane gas flow rate	321 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5850S	Ethane gas flow rate	24.4 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5850S	Propane gas flow rate	10.3 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5850S	Butane gas flow rate	4.26 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5850S	Nitrogen gas flow rate	22.0 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5864S	Air gas flow rate	11869 SCFH	0.7% of rate plus 0.2% of full scale
Wika S-10	Mixed gas pressure	0-200 psig	0.25% of span
Type T thermocouple	Mixed gas temperature	752°F	—

All gases except butane were regulated down to about 50-100 psig before or upon entering the blending station. The selected main stream was further regulated down to about 15 psig before the other gases were blended in. A pressure transmitter and thermocouple were used to monitor the mixed gas pressure and temperature. A mass flow meter was added to the blending station to measure air flow rate. Air was supplied

by GTI's compressed air header and regulated down to 0-3 psig. The blending station with constituent gases is shown in Figure 69. The steam pressure transmitter, turnaround and exhaust thermocouples, continuous emissions analyzers, mass flow meters and controllers, and motorized ball valves were connected to a data acquisition and control system. Instruments used to perform this test series are listed in Table 3.

The measured flow rates of the fuel gases and air supplied from the custom blending station to the burner were recorded using National Instruments Field Point Modules and a LabView program running on a laptop computer. The fuel gas compositions were commanded through a separate, custom program on the same laptop computer. The custom program used the measured flow rate of the main stream to determine the flow rates of the added gases. A table of ratios of each added gas to the main stream for each "adjust" and "substitute" gas was created for the custom program.

The temperature of the test chamber was controlled with a Fuji Electric PXZ4 1/16 DIN PID-loop temperature controller driving a Honeywell Modmotor actuator mounted on a butterfly valve installed in the air line supplying the burners. Gas from the blending station was regulated with a Maxitrol zero gas governor before entering a Flynn FUM venturi mixer installed in the air line via a needle valve. The needle valve was used to tune the burners by adjusting the air/fuel ratio.

Test Gases

Test gases were selected to match compositions distributed in California, and international compositions that may be imported into California. The compositions distributed in California are designated "adjust gases" for tuning the burners for optimum performance on each of them. The remaining gases are designated "substitute gases" to compare performance with substitute gases to performance with the adjust gases. Table 4 summarizes the gas compositions. Adjust 1 represents natural gas in the Sacramento area, Adjust 2 is an average California state value, and Adjust 3 is representative of some areas in California with higher Btu content due to local natural gas production. The two substitute gases, Sub 1 and Sub 2, were selected from a set of potential LNG compositions available to California; Sub 1 has a relatively low Wobbe Number (1408) compared with other LNG compositions, and Sub 2 has a relatively high Wobbe Number (1425). Because it is possible that these "substitute" gases will be conditioned with nitrogen prior to distribution in California, additional compositions with nitrogen are added to make the Wobbe Number match those of the selected "adjust" gases.

Table 10. Summary of Adjust and Substitute Gases

Name	Gas Composition, mol %							HHV	Wobbe
	C1	C2	C3	C4	C5+	N2	CO2		
Adjust 1	93.2	2.52	0.41	0.14	0.093	2.691	0.920	1010	1309
Adjust 2	94.5	2.55	0.42	0.14	0.094	1.361	0.931	1024	1332
Adjust 3	90.61	2.45	3.41	1.25	0.094	1.305	0.893	1094	1374
Sub 1	92.4	4.9	1.9	0.79	0.0	0.0	0.0	1099	1408
@1385	91.3	4.8	1.9	0.79	0.0	1.2	0.0	1086	1387
@1375	90.7	4.8	1.9	0.79	0.0	1.9	0.0	1080	1375
@1332	88.3	4.8	1.8	0.79	0.0	4.4	0.0	1053	1331
@1308	87.8	4.6	1.8	0.70	0.0	5.5	0.0	1036	1308
Sub 2	89.4	7.1	2.5	1.04	0.0	0.0	0.0	1131	1426
@1385	87.5	7.0	2.4	1.00	0.0	2.1	0.0	1106	1387
@1375	86.9	6.9	2.4	1.00	0.0	2.7	0.0	1098	1376
@1332	84.5	6.7	2.4	1.00	0.0	5.4	0.0	1070	1330
@1308	83.6	6.6	2.3	1.00	0.0	6.5	0.0	1057	1310

For small-scale testing (up to about 40,000 Btu/h), it is practical to purchase cylinders with these exact compositions, with only nitrogen being blended in as needed. For medium-scale testing (up to about 350,000 Btu/h), multiple cylinders with the same exact composition would be needed, so it becomes practical to create these compositions from cylinders of pure gases using a blending station. The "adjust" gases could be simulated (same heating value and Wobbe index) by blending in ethane, propane and butane from cylinders, and nitrogen from a liquid tank into GTI's house gas or into methane. Methane was chosen as the basis for consistency. The final compositions are shown in Table 12.

Table 11. Summary of Test Gases

Name	Gas Composition, mol %					HHV	Wobbe
	Methane	Ethane	Propane	Butane	Nitrogen		
Adj1B	93.00%	2.50%	0.50%	0.30%	3.70%	1010.4	1313.7
Adj2B	94.30%	2.50%	0.50%	0.30%	2.40%	1023.6	1337.0
Adj3B	90.10%	2.30%	4.00%	1.50%	2.10%	1105.7	1386.9
Sub1	92.41%	4.90%	1.90%	0.79%	0.00%	1098.9	1408.4
Sub1-1385	91.25%	4.84%	1.88%	0.78%	1.26%	1085.0	1385.5
Sub1-A3	90.67%	4.81%	1.86%	0.77%	1.89%	1078.0	1374.1
Sub1-A2	88.35%	4.68%	1.82%	0.75%	4.40%	1050.4	1329.2
Sub1-A1	87.33%	4.63%	1.80%	0.75%	5.50%	1038.3	1309.7
Sub2	89.36%	7.10%	2.50%	1.04%	0.00%	1130.6	1425.6
Sub2-1385	87.49%	6.95%	2.45%	1.02%	2.10%	1106.8	1387.7
Sub2-A3	86.95%	6.91%	2.43%	1.01%	2.70%	1100.0	1377.0
Sub2-A2	84.54%	6.72%	2.37%	0.98%	5.40%	1069.3	1329.2
Sub2-A1	83.55%	6.64%	2.34%	0.97%	6.50%	1056.9	1309.9

Figure 42 through Figure 44 illustrate actual fuel heating values produced by the blending station for the linear ribbon burner testing.

Tests with Adjustment 1 Gas and Substitute Gases

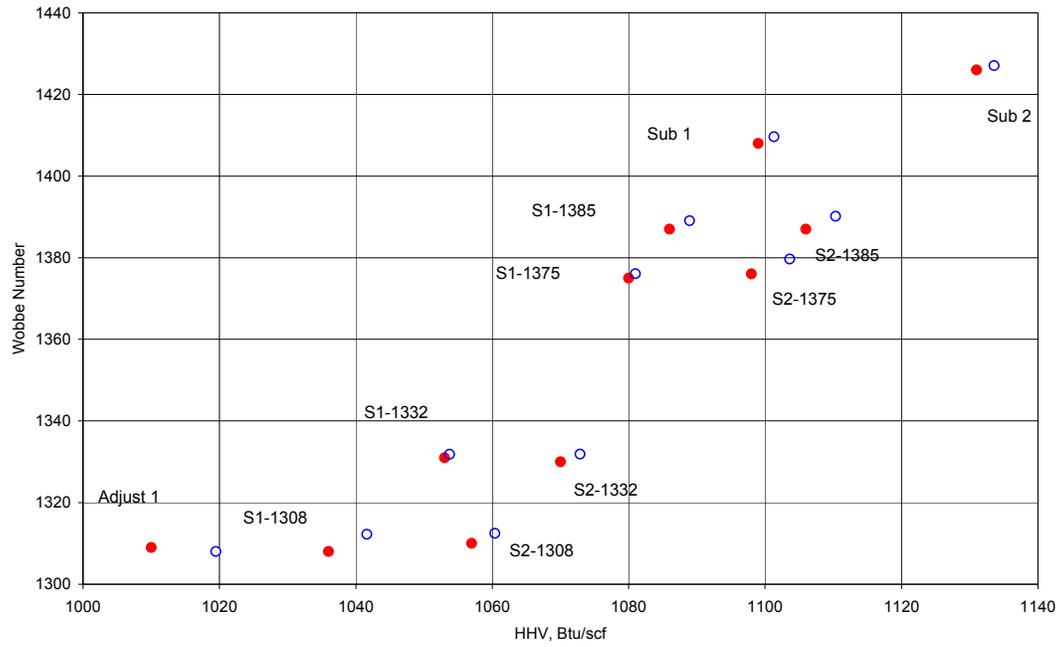


Figure 41. Actual Wobbe Indexes and Heating Values for Line Burner Tests with Adjust1 Basis

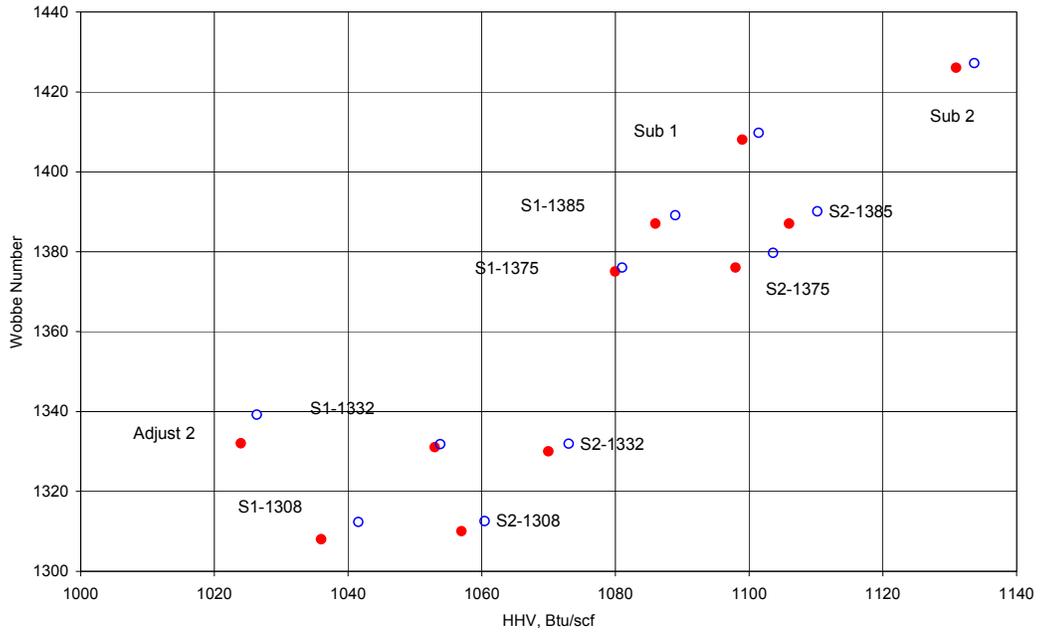


Figure 42. Actual Wobbe Indexes and Heating Values for Line Burner Tests with Adjust2 Basis

Tests with Adjustment 3 Gas and Substitute Gases

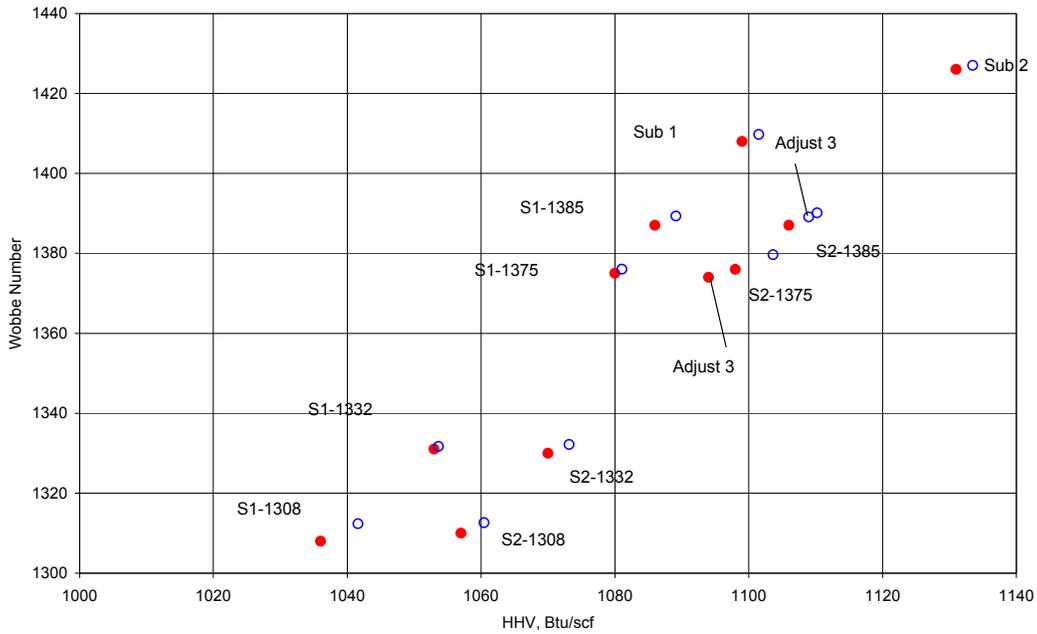


Figure 43. Actual Wobbe Indexes and Heating Values for Line Burner Tests with Adjust3 Basis

Test Schedule

The ignition tests were performed first for all three "adjust" gases. The performance tests with constant firing rate were performed next for all three "adjust" gases. These were followed by performance tests with a constant chamber temperature for all three "adjust" gases.

The ignition tests were performed separately from the performance tests, because otherwise heat-up and cool-down time would be prohibitive. Figure 45 illustrates the overall setup, testing, and analysis schedule. Table 13 shows the schedule of test sequences. Each sequence of tests (each column in Table 13) was performed during a single day.

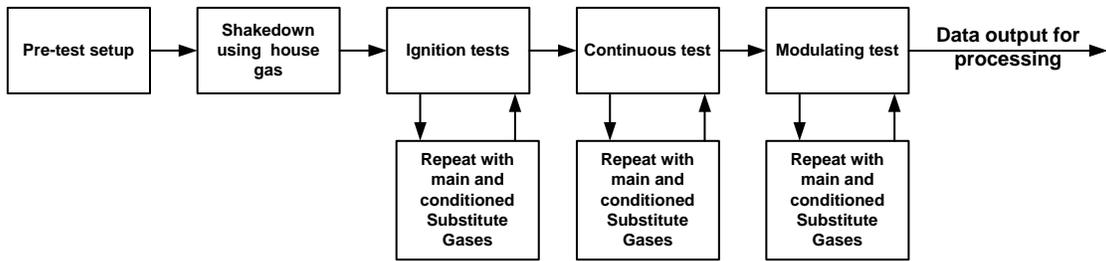


Figure 44. Test Schedule for the Linear Ribbon Burner

Table 12. Test Schedule

Type	Ignition			Constant Firing Rate			Constant Chamber Temperature		
Basis	Adj2B	Adj1B	Adj3B	Adj1B	Adj2B	Adj3B	Adj1B	Adj2B	Adj3B
Subs	Sub1	Sub1	Sub1	Sub1	Sub1	Sub1	Sub1	Sub1	Sub1
	Sub1-1385	Sub1-1385	Sub1-1385	Sub1-1385	Sub1-1385	Sub1-1385	Sub1-1385	Sub1-1385	Sub1-1385
	Sub1-A3	Sub1-A3	Sub1-A3	Sub1-A3	Sub1-A3	Sub1-A3	Sub1-A3	Sub1-A3	Sub1-A3
	Sub1-A2	Sub1-A2	Sub1-A2	Sub1-A2	Sub1-A2	Sub1-A2	Sub1-A2	Sub1-A2	Sub1-A2
	Sub1-A1	Sub1-A1	Sub1-A1	Sub1-A1	Sub1-A1	Sub1-A1	Sub1-A1	Sub1-A1	Sub1-A1
	Sub2	Sub2	Sub2	Sub2	Sub2	Sub2	Sub2	Sub2	Sub2
	Sub2-1385	Sub2-1385	Sub2-1385	Sub2-1385	Sub2-1385	Sub2-1385	Sub2-1385	Sub2-1385	Sub2-1385
	Sub2-A3	Sub2-A3	Sub2-A3	Sub2-A3	Sub2-A3	Sub2-A3	Sub2-A3	Sub2-A3	Sub2-A3
	Sub2-A2	Sub2-A2	Sub2-A2	Sub2-A2	Sub2-A2	Sub2-A2	Sub2-A2	Sub2-A2	Sub2-A2
	Sub2-A1	Sub2-A1	Sub2-A1	Sub2-A1	Sub2-A1	Sub2-A1	Sub2-A1	Sub2-A1	Sub2-A1

Activities Performed

Setup

Preliminary tests with the typical manufacturer-recommended burner setup were conducted to verify ignition of the burners on house gas and to determine typical chamber temperatures, water flow rate for the simulated load, fuel and air delivery pressures, the functionality of the blending station (by switching between the different gases), the functionality of the continuous emissions analyzers, and the functionality of the data acquisition system.

Ignition Tests

The ignition tests measured whether the burner lights and the rate of heating on various "substitute" gases with the burner tuned for a particular "adjust" gas.

The test plan was to calibrate the continuous emissions analyzers, fire the burners on house gas, bring the test chamber up to an operating temperature of about 600°F, switch to an "adjust" gas, tune the burner on the "adjust" gas by adjusting the air/fuel ratio, set the firing rate to around 25-30% of the burner nominal rated capacity (20,000-25,000 Btu/hr per burner), shut off the fuel, and allow the chamber to cool to 180°F. Next was to have a discounted ignition (#0) on the "adjust" gas, allow the chamber to warm to 360°F, shut off the fuel, and allow the chamber to cool to 180°F. This was followed by three consecutive ignition-warm up-shut off-cool down cycles with recorded ignitions (#'s 1-3) on the "adjust" gas before switching the blending station to one of the "substitute" gases. With this "substitute" gas, there was a discounted ignition-warm up-shut off-cool down cycle (#0), followed by three recorded ignition-warm up-shut off-cool down cycles (#'s 1-3). This series of four cycles was repeated with the nine other "substitute" gases. The calibration of the continuous emissions analyzers was then checked.

The above process was repeated for the second "adjust" gas and all 10 "substitute" gases, and then repeated again with the third "adjust" gas and all 10 "substitute" gases.

Continuous Tests – Constant Firing Rate

The continuous tests with constant firing rate measured how the system responds, i.e., how the chamber temperature varies and how heat transfer to the load varies, when various "substitute" gases are fired at a fixed rate with the burner tuned for a particular "adjust" gas. These tests are useful for predicting how a system will respond when there is no feedback control.

The test plan was to calibrate the continuous emissions analyzers, fire the burners on house gas, bring the test chamber up to an operating temperature of about 950°F, switch to an "adjust" gas, tune the burner on the "adjust" gas by adjusting the air/fuel ratio, and set the firing rate to around 50% of the burner nominal rated capacity (50,000 Btu/hr per

burner) by manually adjusting the air valve. Next was to allow the chamber temperature to settle and then collect chamber temperature, simulated load data, and emissions for twenty minutes. The blending station was then switched to one of the "substitute" gases. The emissions were allowed to settle and then chamber temperature, simulated load data, and emissions were collected for twenty minutes. This series of switching gases and collecting data was repeated with the four other "substitute" gases. The calibration of the continuous emissions analyzers was then checked and reset as needed. The series of switching gases and collecting data was then repeated with the other five "substitute" gases. The calibration of the continuous emissions analyzers was then checked.

The above process was repeated for the second "adjust" gas and all 10 "substitute" gases, and then repeated again with the third "adjust" gas and all 10 "substitute" gases.

For all of the above sequences with constant firing rate, the response of the system's performance in terms of chamber temperature and simulated load data was recorded with the emissions data at 5 second intervals.

Continuous Tests – Constant Chamber Temperature

The continuous tests with constant chamber temperature measured how the controller responds, i.e., how the firing rate varies, when various "substitute" gases are fired with a system with a fixed operating condition with the burner tuned for a particular "adjust" gas. These tests are useful for predicting how a system will respond when there is feedback control.

The test plan was to calibrate the continuous emissions analyzers, fire the burners on house gas, bring the test chamber up to an operating temperature of about 950°F, switch to an "adjust" gas, tune the burner on the "adjust" gas by adjusting the air/fuel ratio, and connect the temperature controller to the air flow valve actuator. Next was to allow the firing rate to settle and then collect firing rate, simulated load data, and emissions for twenty minutes. The blending station was then switched to one of the "substitute" gases. The emissions were allowed to settle and then firing rate, simulated load data, and emissions were collected for twenty minutes. This series of switching gases and collecting data was repeated with the four other "substitute" gases. The calibration of the continuous emissions analyzers was then checked and reset as needed. The series of switching gases and collecting data was then repeated with the other five "substitute" gases. The calibration of the continuous emissions analyzers was then checked.

The above process was repeated for the second "adjust" gas and all 10 "substitute" gases, and then repeated again with the third "adjust" gas and all 10 "substitute" gases.

For all of the above sequences with constant chamber temperature, the response of the controller's performance in terms of firing rate was recorded with the simulated load data and emissions at 5 second intervals.

Results

Ignition Tests

The ignition tests measured whether the burner lights and the rate of heating. All the ignition efforts were successful. No ignition failure was observed during the tests. Figure 46 shows the warm up, tuning, and typical on-off cycling during the ignition tests for one of the "adjust" gas tunings.

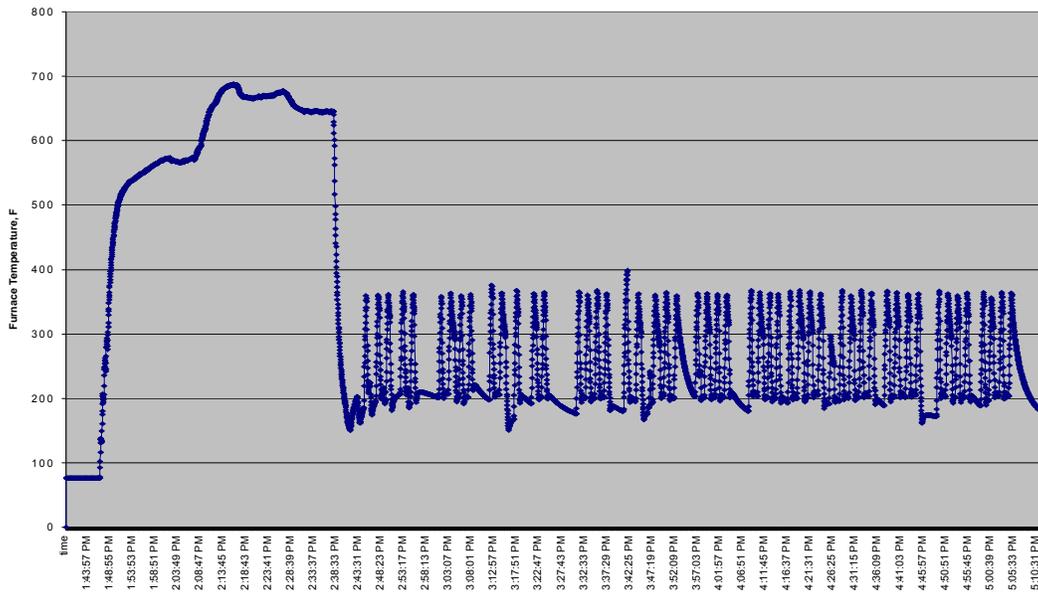


Figure 45. Typical Cycle Pattern during Ignition Testing

Continuous Tests – Constant Firing Rate

The major results from the continuous tests with constant firing rate are the emissions and the chamber temperature (the system's response) when the burner is tuned for a particular "adjust" gas, and the fuel is switched to various "substitute" gases. Figure 47 through Figure 49 show the emissions over the 20 minute data collection intervals.

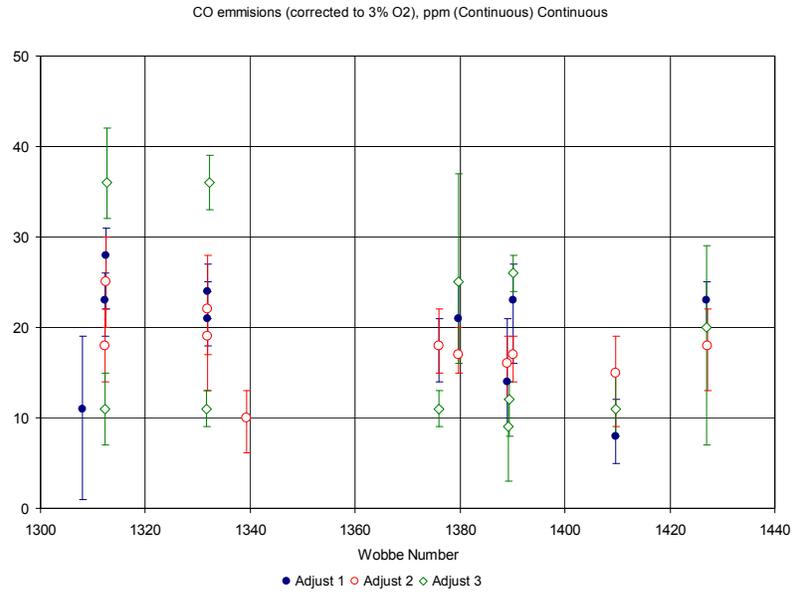


Figure 46. CO Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

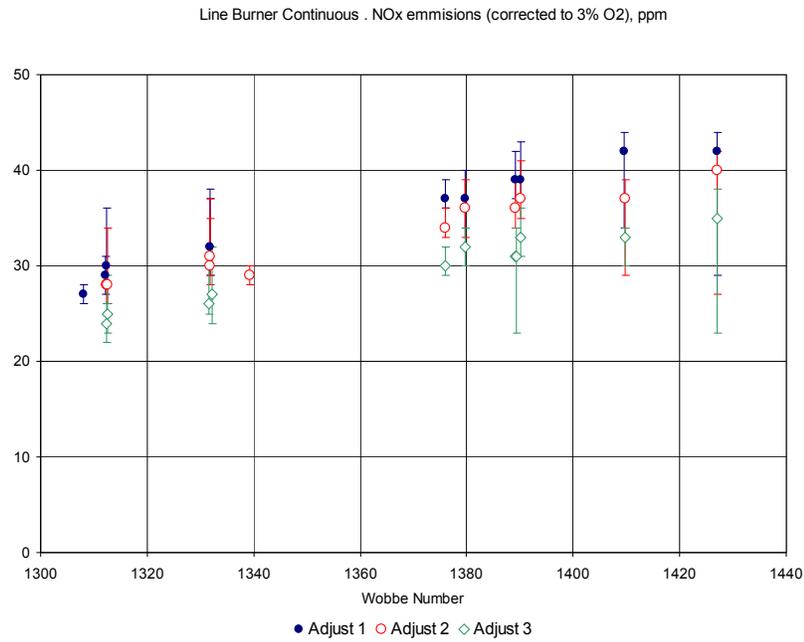


Figure 47. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

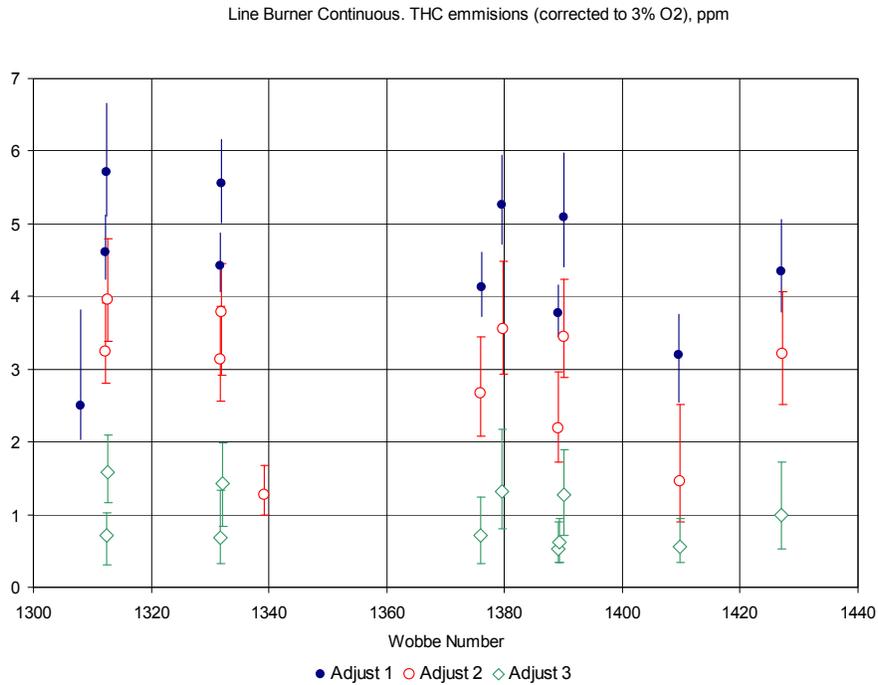


Figure 48. THC Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate (Corrected to 3% O₂)

Continuous Tests – Constant Chamber Temperature

The major results from the continuous tests with constant chamber temperature are the emissions and the fuel flow rate or heat input (the controller's response) when the burner is tuned for a particular "adjust" gas, and the fuel is switched to various "substitute" gases. Figure 50 through Figure 55 show the firing rate and emissions over the 20 minute data collection intervals.

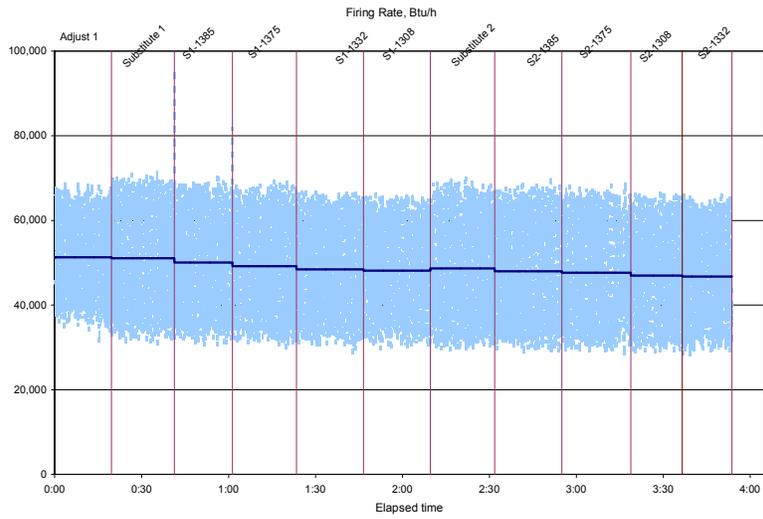
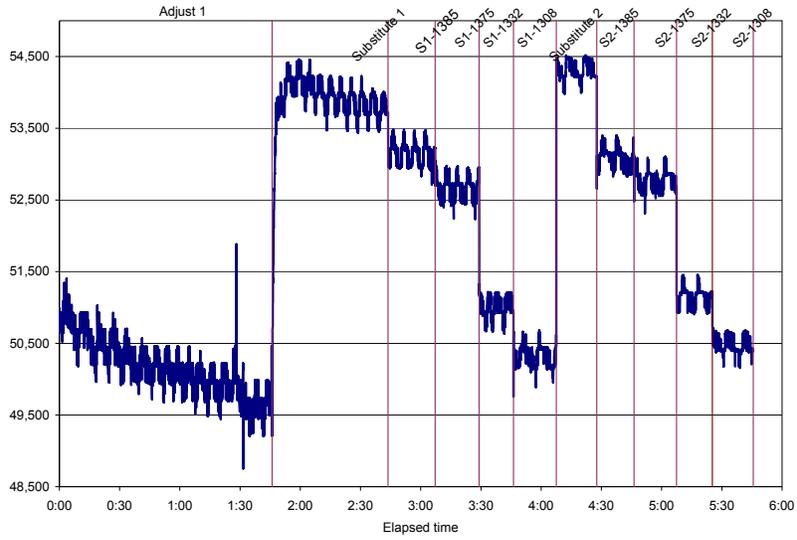


Figure 49. Firing Rate for Adjust1 tuning and All Substitute Gases for Continuous Testing with Constant Chamber Temperature

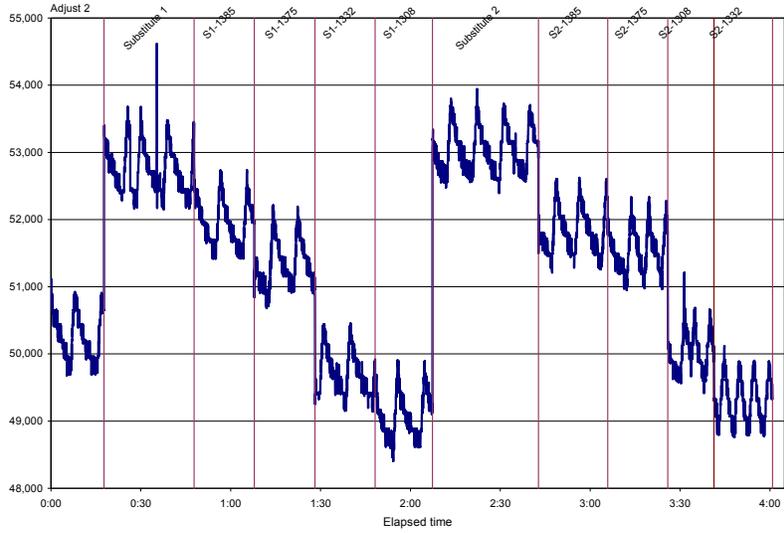


Figure 50. Firing Rate for Adjust2 tuning and All Substitute Gases for Continuous Testing with Constant Chamber Temperature

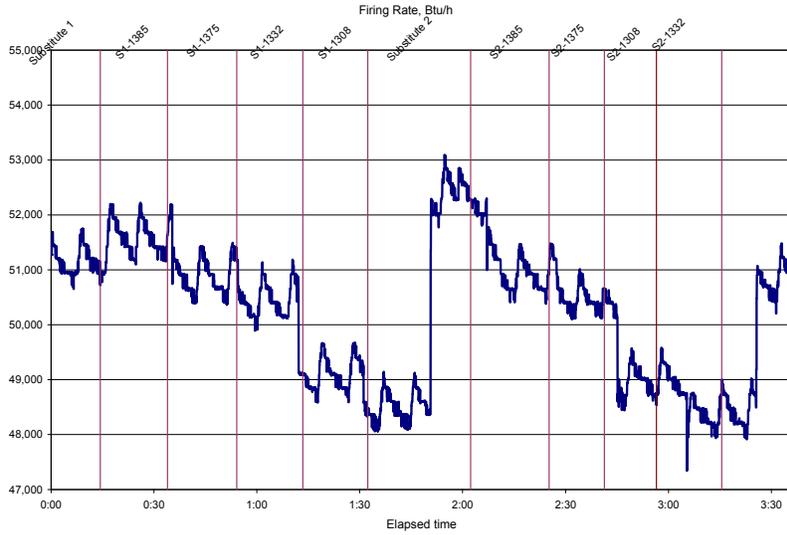
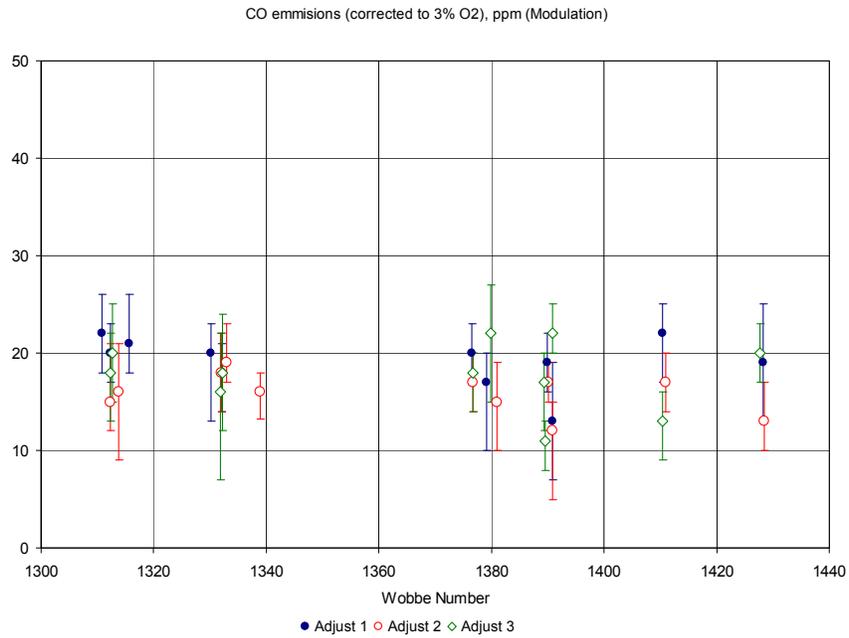


Figure 51. Firing Rate for Adjust3 tuning and All Substitute Gases for Continuous Testing with Constant Chamber Temperature



**Figure 52. CO Emissions for All Substitute Gases
for Continuous Testing with Constant Chamber Temperature**

(Corrected to 3% O₂)

Line Burner Modulation . NOx emissions (corrected to 3% O2), ppm

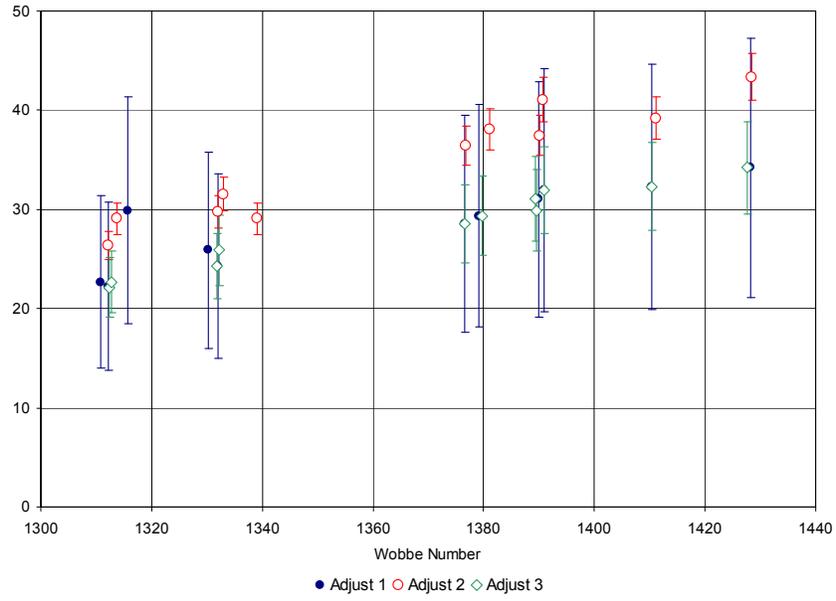


Figure 53. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Chamber Temperature

(Corrected to 3% O₂)

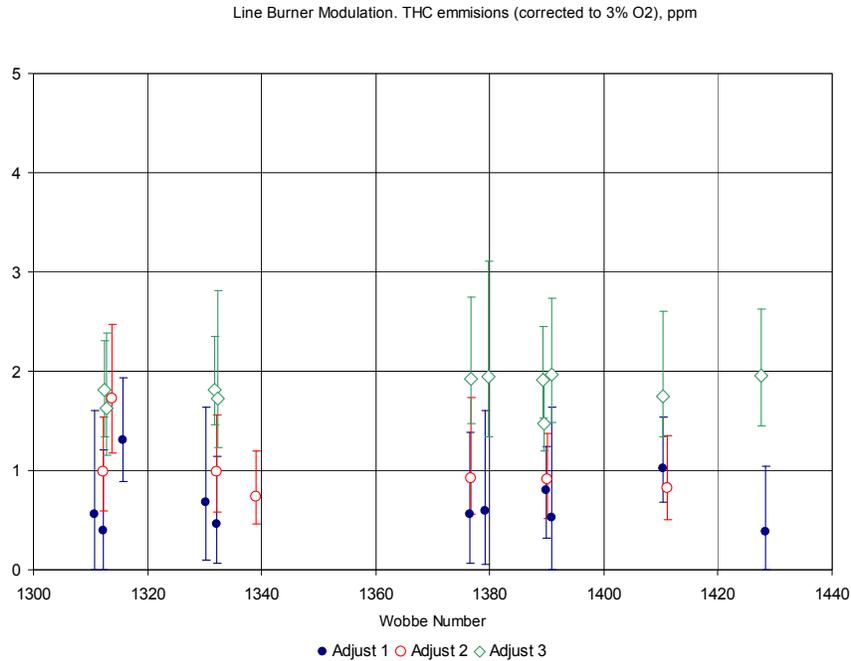


Figure 54. THC Emissions for All Substitute Gases for Continuous Testing with Constant Chamber Temperature

(Corrected to 3% O₂)

Continuous Tests – Constant Firing Rate vs. Modulating

Figure 56 through Figure 64 illustrate the differences between emissions when firing at a constant firing rate versus modulating the firing rate to maintain a set chamber temperature.

For the entire range of the test gases the carbon dioxide emissions were measured in the limits of 9.8-10.6% while total unburned hydrocarbons did not exceed 65 ppm (corrected to 3% O₂) and shown in Figure 65.

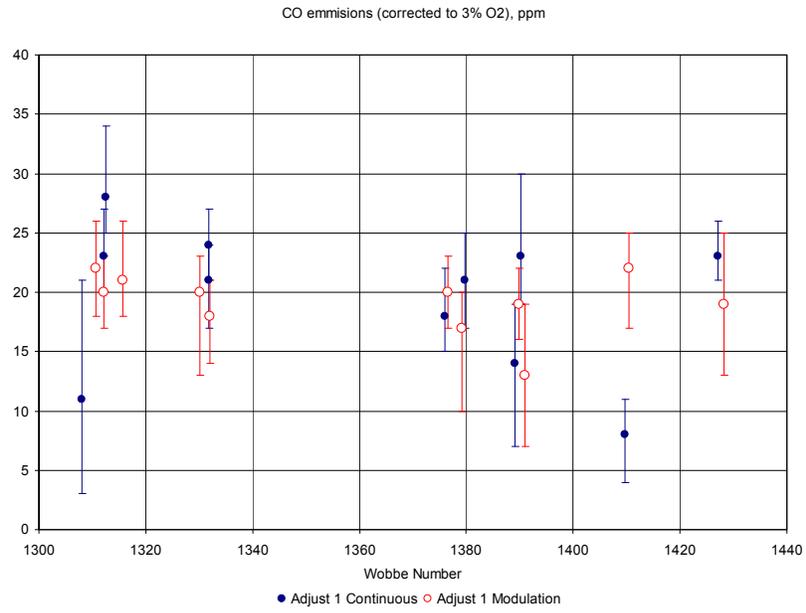


Figure 55. CO Emissions for Adjust1 tuning and All Substitute Gases for Constant Firing Rate vs. Modulating Firing Rate

(Corrected to 3% O₂)

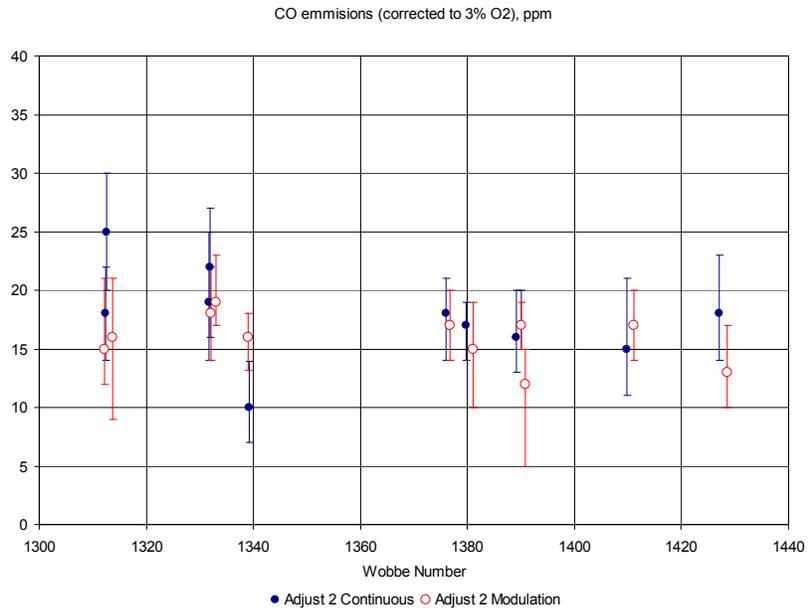


Figure 56. CO Emissions for Adjust2 tuning and All Substitute Gases for Constant Firing Rate vs. Modulating Firing Rate

(Corrected to 3% O₂)

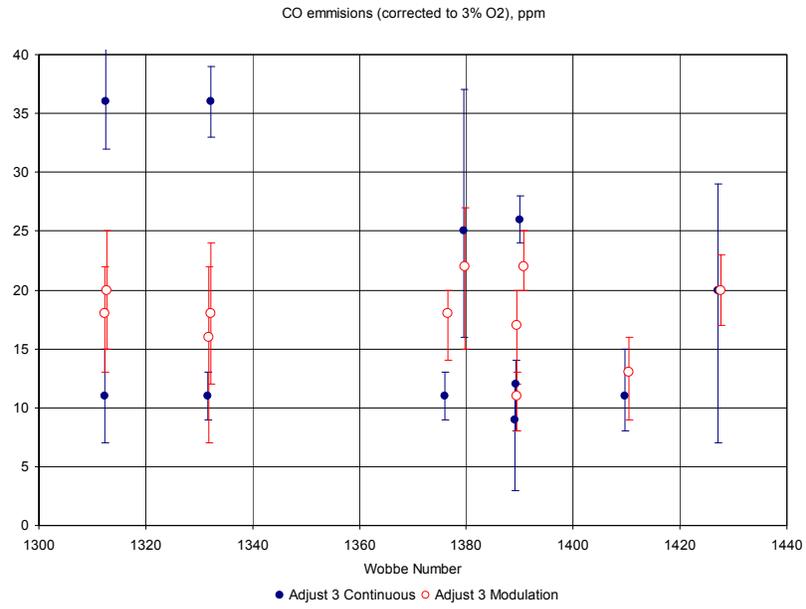


Figure 57. CO Emissions for Adjust3 tuning and All Substitute Gases for Constant Firing Rate vs. Modulating Firing Rate (Corrected to 3% O₂)

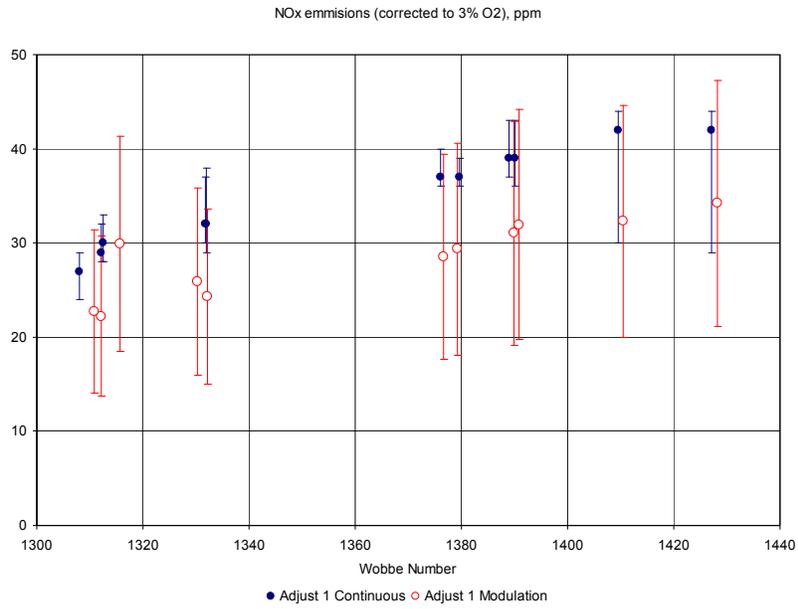


Figure 58. NOx Emissions for Adjust1 tuning and All Substitute Gases for Constant Firing Rate vs. Modulating Firing Rate

(Corrected to 3% O₂)

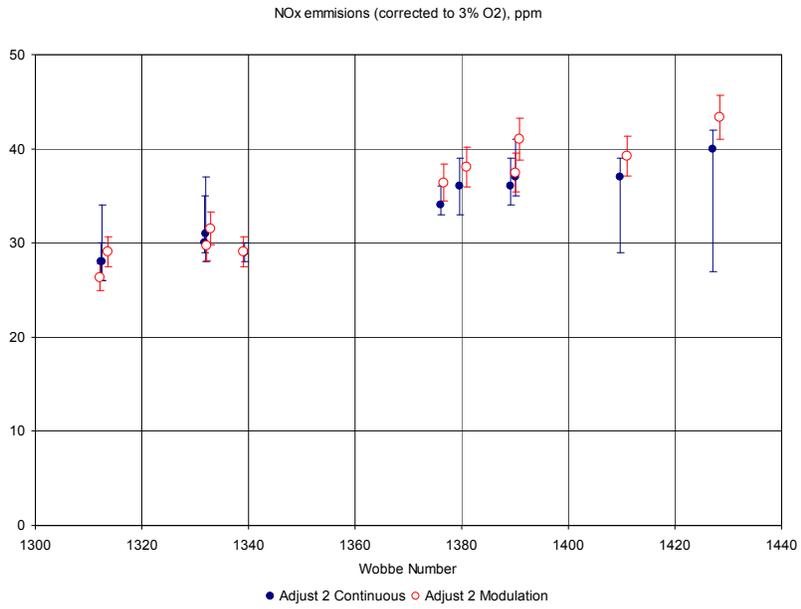


Figure 59. NO_x Emissions for Adjust2 tuning and All Substitute Gases for Constant Firing Rate vs. Modulating Firing Rate

(Corrected to 3% O₂)

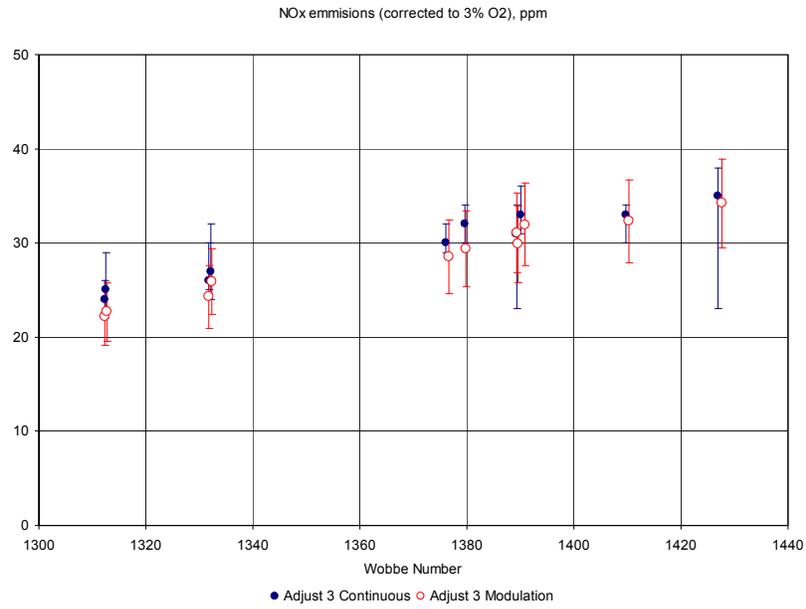


Figure 60. NOx Emissions for Adjust3 tuning and All Substitute Gases for Constant Firing Rate vs. Modulating Firing Rate

(Corrected to 3% O₂)

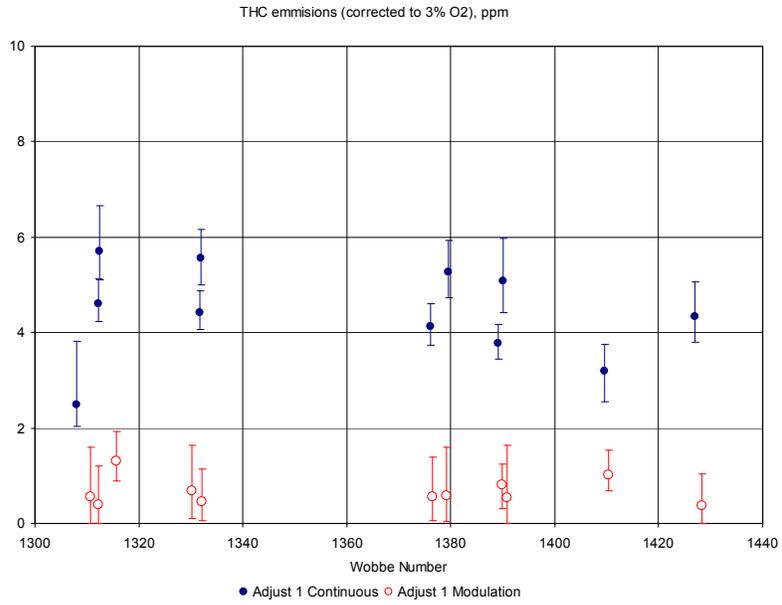


Figure 61. THC Emissions for Adjust1 tuning and All Substitute Gases for Constant Firing Rate vs. Modulating Firing Rate

(Corrected to 3% O₂)

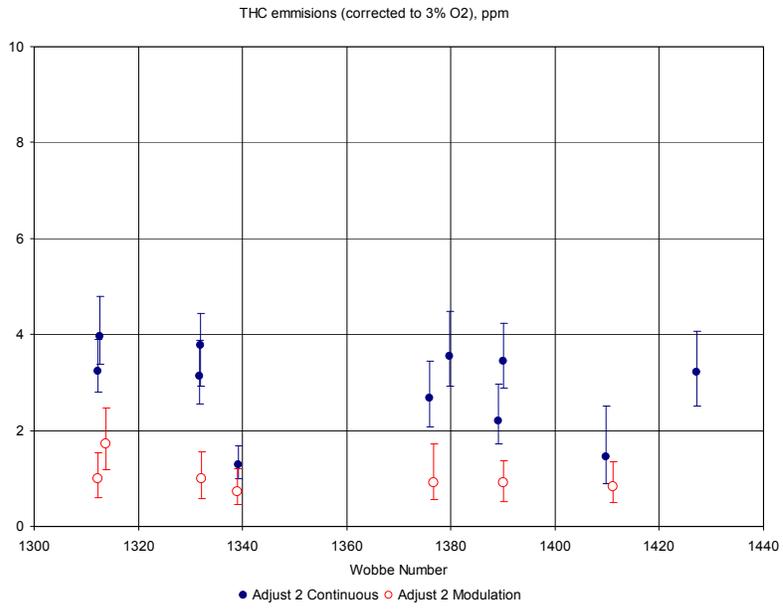


Figure 62. THC Emissions for Adjust2 tuning and All Substitute Gases for Constant Firing Rate vs. Modulating Firing Rate

(Corrected to 3% O₂)

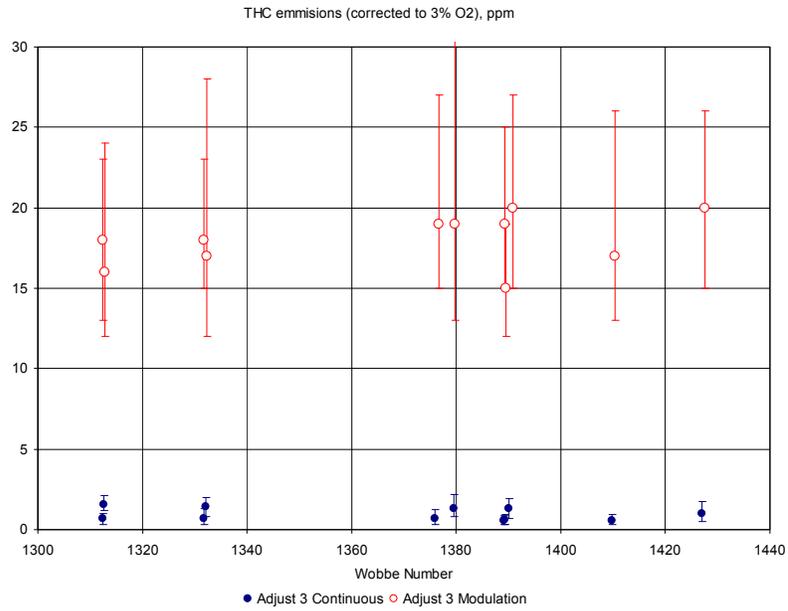


Figure 63. THC Emissions for Adjust3 tuning and All Substitute Gases for Constant Firing Rate vs. Modulating Firing Rate

(Corrected to 3% O₂)

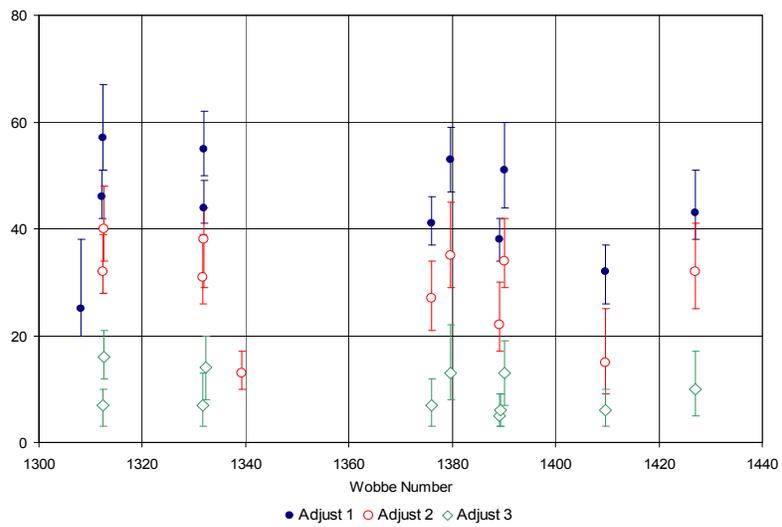


Figure 64. THC Emissions for All Substitute Gases

(Corrected to 3% O₂)

Calculations

The equation below is the linear correction used to approximately cancel out the analyzer drift;

$$X_{corr} = X_{meas} - \left((Zero\ drift) + (Span\ drift) \frac{X_{meas}}{Span\ value} \right) \frac{T_1}{T_2},$$

where X_{corr} is the corrected emissions value, X_{meas} is the measured value, the drift values are as labeled, T_1 denotes the time elapsed from the previous analyzer calibration, and T_2 denotes the time from the previous analyzer calibration to the next analyzer calibration.

After this correction, the emissions were normalized to 3%O₂ using the formula,

$$X_{3\%O_2} = X_{corr} \left(\frac{21 - 3\%}{21 - \%O_2} \right),$$

where $X_{3\%O_2}$ is the final value after both the correction for drift and the normalization to a common %O₂ in the exhaust.

The Firing Rate was calculated from the actual flow data. The heating value calculation followed the ASTM D 3588 – 98(03) standard at 70°F.

Analysis and Conclusions

The charts and data are analyzed in the same sections below as appear in the Results section.

Ignition Tests

Since all 132 startups (11 gases times 4 ignitions times 3 tuning bases) were successful, comparisons are not possible. With proper setup, the spark ignition does not appear to be affected by the fuel used.

Continuous Tests – Constant Firing Rate

For the most part, "substitute" gases with lower Wobbe indexes yielded lower NO_x emissions, while "substitute" gases with higher Wobbe indexes yielded higher NO_x emissions. There were no excursions but also no discernable trends for CO and THC emissions.

Continuous Tests – Constant Chamber Temperature

NO_x emissions followed the same trend with Wobbe index as with the constant firing rate tests (higher NO_x for higher firing Wobbe gases). As with the constant firing rate tests, there were no excursions but also no discernable trends for CO and THC emissions.

The firing rate tended to inversely follow the Wobbe index. This was not unexpected since the heat input to the burner is directly tied to Wobbe index.

In comparing constant firing rate with modulation, NO_x emissions may have been slightly lower for only "Adjust" 1 tuning with modulation versus constant firing rate and about the same for "Adjust" 2 and "Adjust" 3 tuning. There were no discernable trends for CO emissions for constant firing rate versus modulation. THC emissions were lower for "Adjust" 1 tuning and "Adjust" 2 tuning with modulation and higher for "Adjust" 3 tuning with modulation.

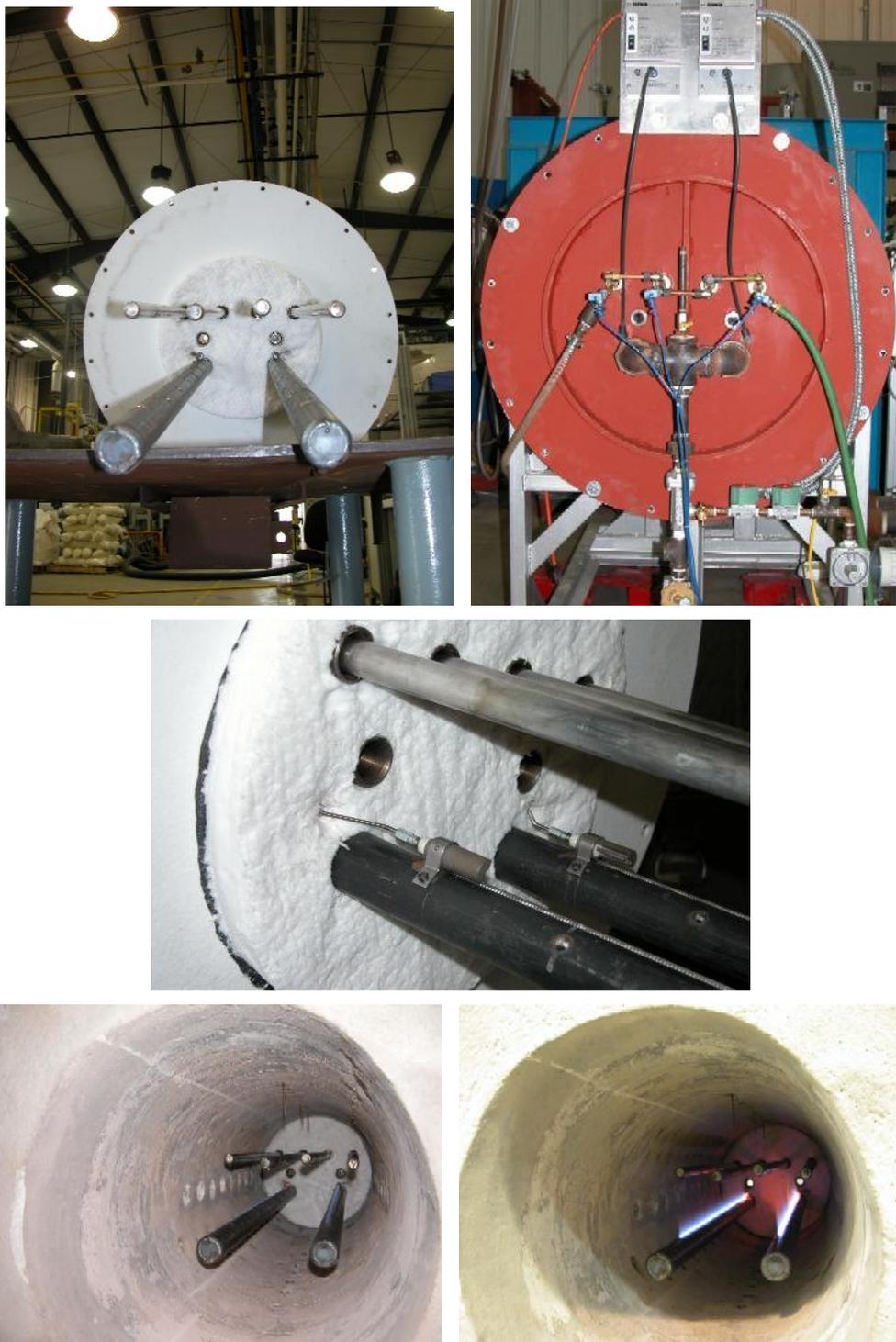


Figure 65. Linear Burners and Simulated Load



Figure 66. Test Chamber



Figure 67. Continuous Emissions Analyzers



Figure 68. Blending Station with Constituent Gases

**NATURAL GAS IN CALIFORNIA: ENVIRONMENTAL IMPACTS
AND DEVICE PERFORMANCE**

**Industrial Burner Evaluations:
High Velocity Burner Test Report**

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Objective

The purpose of the interchangeability tests is to assess the performance of a high velocity burner, used in ceramics and metals industries, when fired with different natural gas compositions. The burner’s performance when firing selected Adjust Gases was compared with its performance when firing selected Substitute Gases with and without different levels of nitrogen ballasting.

Approach

The tests used a laboratory setup intended to mimic industrial operating conditions. Ignition tests and Operating/Switching tests were then performed. During these tests, the burner was first tuned to operate with an “adjust” gas composition, then several “substitute” gas compositions were fired in sequence on the burner. These tests were then repeated with the other two “adjust” gases as a basis.

Ignition tests were performed from the same start conditions of an approximately 180°F exhaust temperature to the same end conditions of an approximately 600°F exhaust temperature at firing rate of 20% or 200,000 Btu/hr, a low firing rate as recommended by the burner manufacturer.

Operating tests were performed in two modes, constant exhaust temperature and constant firing rate. Both tests used a ratio regulator to maintain the gas flow rate proportional to the air flow rate. Constant temperature tests were performed with a PID-loop temperature controller manipulating the speed of the combustion air blower to maintain the exhaust temperature at about 1140°F. Constant firing rate tests were performed with the air flow rate set manually, yielding a firing rate of about 75% or 750,000 Btu/hr.

For all test sequences, the chamber was first warmed up on house gas. The fuel was then switched to an "adjust" gas, and the burner was tuned so that the exhaust gases contained 3% O₂.

Table 9 shows the specific performance measurements.

Table 13. Performance Metrics for the High Velocity Burner

BASIC PERFORMANCE METRICS
Gaseous Pollutant Emissions
Exhaust Temperature
System or Controller Response upon Switching

Test Apparatus

The high velocity burner used for this test was a Thermjet TJ0100 (TJ100) by Eclipse, Inc. rated for 1,000,000 Btu/hr with a stable turndown to 100,000 Btu/hr on ratio. The burner was ignited and its flame was sensed using a spark ignition rod and UV sensor. The burner assembly is shown in Figure 37.

The test burner fired into an octagonal furnace chamber equipped with water-cooled panels located behind insulated walls and a thermocouple to measure the temperatures of the exhaust gases. This thermocouple was used for temperature control. The overall view of the test rig is shown in Figure 67. Water was flowed in four parallel streams of cooling panels. The water flow rates were measured by magnetic flow meters. The inlet water temperature was measured with a thermocouple before the cooling panels, and thermocouples after each of the four sets of cooling panels.

The exhaust stack of the chamber included a damper, which was manually adjusted to maintain a neutral pressure inside the chamber. Added to the exhaust stack was a stainless steel sampling probe, which was connected through a filtering and drying train to a set of continuous emissions analyzers for THC, NO_x, CO₂, CO, and O₂. These are shown in Figure 68.

A custom-built blending station was used to provide simulated natural gas compositions to the ratio regulator at 0.9 psig. The blending station allowed for one of two main streams, house gas and cleaned gas, to be selected, to which metered amounts of ethane, propane, butane, and nitrogen could be added. The house gas was the normal natural gas delivered to GTI, and was the basis for all the "adjust" gases. The cleaned gas was the basis for the "substitute" gases. House gas without additions was used for warming up the burner.

Mass flow meters were used to measure the house gas and cleaned gas flows. Motorized ball valves were used to select one of the two main streams. Mass flow controllers were used to add ethane, propane, butane, and nitrogen to the main stream. Ethane was supplied from a bank of 5 gas cylinders, propane and butane were each supplied from the gaseous outlet of liquid cylinders, and nitrogen was supplied from GTI's header, which is fed by a liquid tank. All gases were regulated down to about 15 psig before or upon entering the blending station except butane, which is delivered at its saturation vapor pressure of about 14 psig. The selected main stream is further regulated down to about 5 psig before the other gases are blended in. A pressure transmitter and thermocouple were used to monitor the mixed gas pressure and temperature. The blending station with constituent gases is shown in Figure 69.

The exhaust and water thermocouples, continuous emissions analyzers, mass flow meters and controllers, and motorized ball valves were connected to a data acquisition and control system. Instruments used to perform this test series are listed in Table 3.

Table 14. Summary of Test Instruments

Instrument	Parameter	Range	Accuracy
National Instruments Field Point Modules	Data logging and control	4-20 mA, 0-5 V, 0-10 V, ± 100 mV, on/off (relay)	16 bit input current; 12 bit input voltage; 12 bit output current; 16 bit temperature
LabView software	Data logging	—	—
Custom software	Control	—	—
Laptop computer	Data logging and control	—	—
Type K thermocouple	Exhaust temperature	2502°F	—
ABB Mini-Mag 10D1475W	Water flow rates	26.42 gpm	0.5% of rate @ $\geq 7\%$ full scale
Type T thermocouple	Water temperatures	752°F	—
Rosemount Analytical 400A	THC concentration	0-100 ppm, Span 79 ppm	1% full scale
Rosemount Analytical 755R	O ₂ concentration	0-25%, Span 8.0%	0.01% O ₂ or 1% full scale
Thermo Environmental 42C High Level	NO concentration, NO _x concentration	0-100 ppm, Span 76.7 ppm	0.5 ppm
Rosemount Analytical 880A	CO concentration	0-1000 ppm, Span 790 ppm	1% full scale
Rosemount Analytical 880A	CO ₂ concentration	0-20%, Span 18.0%	1% full scale
Brooks Instruments 5863S	House gas flow rate	2066 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5863S	Cleaned gas flow rate	1826 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5853S	Ethane gas flow rate	224 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5851S	Propane gas flow rate	68.5 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5851S	Butane gas flow rate	31.4 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5851S	Nitrogen gas flow rate	141 SCFH	0.7% of rate plus 0.2% of full scale
Sierra Instruments 780S	Air flow rate	20000 SCFH	1% of rate plus 0.5% of full scale
Wika S-10	Mixed gas pressure	0-200 psig	0.25% of span
Type T thermocouple	Mixed gas temperature	752°F	—

The measured flow rates of the fuel gases supplied from the custom blending station and measured flow rate of air to the burner were recorded using National Instruments Field Point Modules and a LabView program running on a laptop computer. The fuel gas compositions were commanded through a separate, custom program on the same laptop computer. The custom program used the measured flow rate of the main stream to determine the flow rates of the added gases. A table of ratios of each added gas to the main stream for each "adjust" and "substitute" gas was created for the custom program.

The temperature of the exhaust gas was controlled with a Fuji Electric PXZ4 1/16 DIN PID-loop temperature controller driving a process controller and variable frequency drive installed on the positive displacement air blower supplying the burner. Gas from the blending station was controlled with a Model ES366 ratio regulator before entering the burner. The impulse line for the ratio regulator was connected to the air line upstream of a globe valve located before the burner. The globe valve was used to tune the burner by adjusting air pressure before the burner independent of the air flow rate thus setting the gas pressure and therefore the air/fuel ratio.

Test Gases

Test gases were selected to match compositions distributed in California, and international compositions that may be imported into California. The compositions distributed in California are designated "adjust gases" for the purpose of tuning the burner for optimum performance on each of them. The remaining gases are designated "substitute gases" for the purpose of comparing the performance with substitute gases to the performance with the adjust gases. Table 4 summarizes the gas compositions. Adjust 1 represents natural gas in the Sacramento area, Adjust 2 is an average value for the state of California, and Adjust 3 is representative of some areas in California with higher Btu content due to local natural gas production. The two substitute gases, Sub 1 and Sub 2, were selected from a set of potential LNG compositions available to California; Sub 1 has a relatively low Wobbe Number (1408) compared with other LNG compositions, and Sub 2 has a relatively high Wobbe Number (1425). Because it is possible that these "substitute" gases will be conditioned with nitrogen prior to distribution in California, additional compositions with nitrogen are added to make the Wobbe Number match those of the selected "adjust" gases.

Table 15. Summary of Adjust and Substitute Gases

Name	Gas Composition, mol %							HHV	Wobbe
	C1	C2	C3	C4	C5+	N2	CO2		
Adjust 1	93.2	2.52	0.41	0.14	0.093	2.691	0.920	1010	1309
Adjust 2	94.5	2.55	0.42	0.14	0.094	1.361	0.931	1024	1332
Adjust 3	90.61	2.45	3.41	1.25	0.094	1.305	0.893	1094	1374
Sub 1	92.4	4.9	1.9	0.79	0.0	0.0	0.0	1099	1408
@1385	91.3	4.8	1.9	0.79	0.0	1.2	0.0	1086	1387
@1375	90.7	4.8	1.9	0.79	0.0	1.9	0.0	1080	1375
@1332	88.3	4.8	1.8	0.79	0.0	4.4	0.0	1053	1331
@1308	87.8	4.6	1.8	0.70	0.0	5.5	0.0	1036	1308
Sub 2	89.4	7.1	2.5	1.04	0.0	0.0	0.0	1131	1426
@1385	87.5	7.0	2.4	1.00	0.0	2.1	0.0	1106	1387
@1375	86.9	6.9	2.4	1.00	0.0	2.7	0.0	1098	1376
@1332	84.5	6.7	2.4	1.00	0.0	5.4	0.0	1070	1330
@1308	83.6	6.6	2.3	1.00	0.0	6.5	0.0	1057	1310

For small-scale testing (up to about 40,000 Btu/h), it is practical to purchase cylinders with these exact compositions, with only nitrogen being blended in as needed. For medium-scale testing (up to about 200,000 Btu/h), it is practical to create these compositions from cylinders of pure gases using a blending station. For large-scale testing (over 1,000,000 Btu/h), the amount of pure methane needed requires a tube trailer, but none were available from GTI's gas supplier during the time of the test campaign. The "adjust" gases could be simulated (same heating value and Wobbe index) by blending in ethane, propane and butane from cylinders, and nitrogen from a liquid tank into GTI's house gas. However, the pure "substitute" gases and conditioned (nitrogen-diluted) "substitute" gases with higher Wobbe indexes could not be simulated this way because of the amount of inerts (CO₂ and N₂) in the house gas.

For another project, GTI assembled a CO₂ stripper which utilized three columns (towers) to remove the CO₂ from the house gas. The first tower performed the function of absorbing the CO₂ from the desired amount of house gas and an additional amount of house gas. The desired amount of cleaned gas went onto the burner being tested, while the additional amount went through the second tower, a heater, and the third tower before being vented or flared. The third tower performed the function of desorbing the CO₂ from the absorbent using the heated gas, while the second tower was being cooled

by the cleaned gas. The towers rotated their function every 3 hours, so the process was regenerative.

The cleaned gas with the heavy molecular weight CO₂ removed was then used as the basis for simulating the "adjust" gases and the conditioned "substitute" gases. The pure "substitute" gases were still not quite reached, so the points of maximum heating value and Wobbe index, along the same lines as the conditioned "substitute" gases, were used in their place. The final compositions are shown in Table 12.

Table 16. Summary of Test Gases

Name	Gas Composition, mol %						HHV	Wobbe
	House Gas	Cleaned Gas	Ethane	Propane	Butane	Nitrogen		
Adj1Q	97.28%	0.00%	0.00%	0.84%	0.00%	1.89%	1010.0	1309.0
Adj2Q	98.49%	0.00%	0.00%	0.90%	0.00%	0.61%	1024.0	1332.0
Adj3Q	92.02%	0.00%	4.62%	1.95%	0.81%	0.59%	1094.0	1374.0
Sub1QM	0.00%	93.62%	3.99%	1.69%	0.70%	0.00%	1090.3	1394.3
Sub1Q-Hi	0.00%	93.17%	3.97%	1.68%	0.69%	0.49%	1085.0	1385.5
Sub1Q-A3	0.00%	92.57%	3.95%	1.67%	0.69%	1.12%	1078.0	1374.1
Sub1Q-A2	0.00%	90.20%	3.85%	1.63%	0.67%	3.65%	1050.4	1329.2
Sub1Q-A1	0.00%	89.16%	3.80%	1.61%	0.66%	4.76%	1038.3	1309.7
Sub2QM	0.00%	90.82%	5.75%	2.43%	1.00%	0.00%	1122.0	1411.9
Sub2Q-Hi	0.00%	89.58%	5.67%	2.40%	0.99%	1.36%	1106.8	1387.7
Sub2Q-A3	0.00%	89.03%	5.64%	2.38%	0.98%	1.96%	1100.0	1377.0
Sub2Q-A2	0.00%	86.56%	5.48%	2.32%	0.96%	4.68%	1069.3	1329.2
Sub2Q-A1	0.00%	85.56%	5.42%	2.29%	0.95%	5.79%	1056.9	1309.9

Figure 42 illustrates the fuel heating values and Wobbe indexes used for the high velocity burner testing.

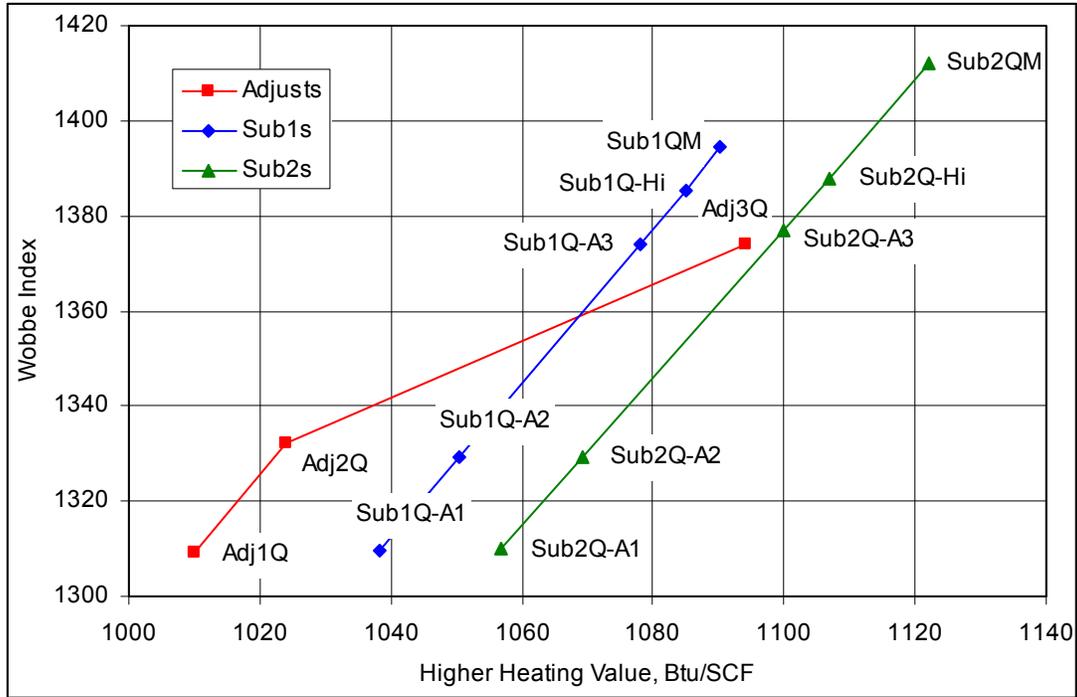


Figure 69. Wobbe Indexes and Heating Values for High Velocity Burner Tests

Test Schedule

The ignition tests were performed first for all three "adjust" gases. The performance tests with constant firing rate were performed next for all three "adjust" gases. These were followed by performance tests with a constant chamber temperature for all three "adjust" gases.

The ignition tests were performed separately from the performance tests, because otherwise heat-up and cool-down time would be prohibitive. Figure 45 illustrates the overall setup, testing, and analysis schedule. Table 13 shows the schedule of test sequences. Each sequence of tests (each column in Table 13) was performed during a single day.

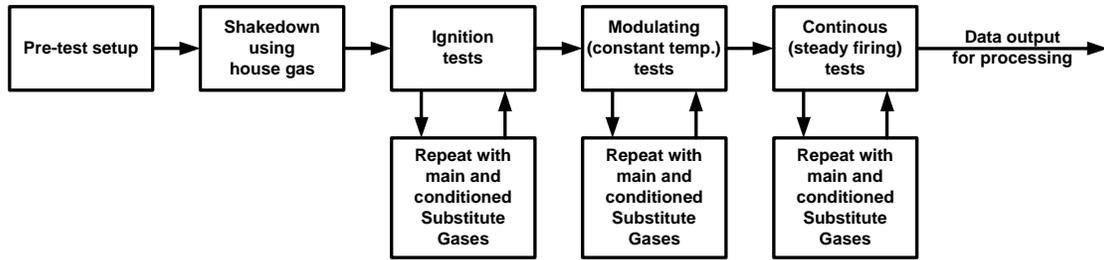


Figure 70. Test Schedule for the High Velocity Burner

Table 17. Test Schedule

Type	Ignition			Constant Exhaust Temperature			Constant Firing Rate		
Basis	Adj2Q	Adj1Q	Adj3Q	Adj2Q	Adj1Q	Adj3Q	Adj2Q	Adj1Q	Adj3Q
Subs	Sub1Q	Sub1Q	Sub1Q	Sub1Q	Sub1Q	Sub1Q	Sub1Q	Sub1Q	Sub1Q
	Sub1Q-Hi	Sub1Q-Hi	Sub1Q-Hi	Sub1Q-Hi	Sub1Q-Hi	Sub1Q-Hi	Sub1Q-Hi	Sub1Q-Hi	Sub1Q-Hi
	Sub1Q-A3	Sub1Q-A3	Sub1Q-A3	Sub1Q-A3	Sub1Q-A3	Sub1Q-A3	Sub1Q-A3	Sub1Q-A3	Sub1Q-A3
	Sub1Q-A2	Sub1Q-A2	Sub1Q-A2	Sub1Q-A2	Sub1Q-A2	Sub1Q-A2	Sub1Q-A2	Sub1Q-A2	Sub1Q-A2
	Sub1Q-A1	Sub1Q-A1	Sub1Q-A1	Sub1Q-A1	Sub1Q-A1	Sub1Q-A1	Sub1Q-A1	Sub1Q-A1	Sub1Q-A1
	Sub2Q	Sub2Q	Sub2Q	Sub2Q	Sub2Q	Sub2Q	Sub2Q	Sub2Q	Sub2Q
	Sub2Q-Hi	Sub2Q-Hi	Sub2Q-Hi	Sub2Q-Hi	Sub2Q-Hi	Sub2Q-Hi	Sub2Q-Hi	Sub2Q-Hi	Sub2Q-Hi
	Sub2Q-A3	Sub2Q-A3	Sub2Q-A3	Sub2Q-A3	Sub2Q-A3	Sub2Q-A3	Sub2Q-A3	Sub2Q-A3	Sub2Q-A3
	Sub2Q-A2	Sub2Q-A2	Sub2Q-A2	Sub2Q-A2	Sub2Q-A2	Sub2Q-A2	Sub2Q-A2	Sub2Q-A2	Sub2Q-A2
	Sub2Q-A1	Sub2Q-A1	Sub2Q-A1	Sub2Q-A1	Sub2Q-A1	Sub2Q-A1	Sub2Q-A1	Sub2Q-A1	Sub2Q-A1

Activities Performed

Setup

Preliminary tests with the typical manufacturer-recommended burner setup were conducted to verify ignition of the burner on house gas and to determine typical chamber temperatures at various firing rates on house gas and cleaned gas, fuel and air delivery pressures, the functionality of the blending station (by switching between the different gases), the functionality of the continuous emissions analyzers, and the functionality of the data acquisition system.

Ignition Tests

The ignition tests measured whether the burner lights and the rate of heating on various "substitute" gases with the burner tuned for a particular "adjust" gas.

The test plan was to calibrate the continuous emissions analyzers, fire the burner on house gas, bring the test chamber up to an operating temperature of about 750°F, switch to an "adjust" gas, tune the burner on the "adjust" gas by adjusting the air/fuel ratio, set the firing rate to around 20% of the burner nominal rated capacity (200,000 Btu/hr), shut off the fuel, and allow the chamber to cool to 180°F. Next was to have one (or two) discounted ignition (#0) on the "adjust" gas, allow the exhaust temperature to reach 600°F, shut off the fuel, and allow the chamber to cool to 180°F. This was followed by three consecutive ignition-warm up-shut off-cool down cycles with recorded ignitions (#'s 1-3) on the "adjust" gas before switching the blending station to one of the "substitute" gases. With this "substitute" gas, there were one (or two) discounted ignition-warm up-shut off-cool down cycles (#0), followed by three recorded ignition-warm up-shut off-cool down cycles (#'s 1-3). This series of four cycles was repeated with the nine other "substitute" gases. The calibration of the continuous emissions analyzers was then checked.

The above process was repeated for the second "adjust" gas and all 10 "substitute" gases, and then repeated again with the third "adjust" gas and all 10 "substitute" gases.

Continuous Tests – Constant Exhaust Temperature

The continuous tests with constant exhaust temperature measured how the controller responds, i.e., how the firing rate varies, when various "substitute" gases are fired with a system with a fixed operating condition with the burner tuned for a particular "adjust" gas. These tests are useful for predicting how a system will respond when there is feedback control.

The test plan was to calibrate the continuous emissions analyzers, fire the burner on house gas, bring the test chamber up to an operating condition with an exhaust temperature of about 1140°F, switch to an "adjust" gas, tune the burner on the "adjust" gas by adjusting the air/fuel ratio, and connect the temperature controller to the process

controller and variable frequency drive installed on the air blower, Next was to allow the firing rate to settle and then collect firing rate and emissions data for twenty minutes. The blending station was then switched to one of the "substitute" gases. The emissions were allowed to settle and then firing rate and emissions data were collected for twenty minutes. This series of switching gases and collecting data was repeated with the nine other "substitute" gases. The sampling trains for the continuous emission analyzers were purged as needed between "substitute" gases. The calibration of the continuous emissions analyzers was then checked.

The above process was repeated for the second "adjust" gas and all 10 "substitute" gases, and then repeated again with the third "adjust" gas and all 10 "substitute" gases.

For all of the above sequences with constant exhaust temperature, the response of the controller's performance in terms of firing rate was recorded with the emissions data at 5 second intervals.

Continuous Tests – Constant Firing Rate

The continuous tests with constant firing rate measured how the system responds, i.e., how the exhaust temperature varies, when various "substitute" gases are fired at a fixed rate with the burner tuned for a particular "adjust" gas. These tests are useful for predicting how a system will respond when there is no feedback control.

The test plan was to calibrate the continuous emissions analyzers, fire the burner on house gas, bring the test chamber up to an operating temperature of about 1140°F, switch to an "adjust" gas, tune the burner on the "adjust" gas by adjusting the air/fuel ratio, and set the firing rate to around 75% of the burner nominal rated capacity (750,000 Btu/hr) by manually setting the process controller and variable frequency drive installed on the air blower. Next was to allow the chamber temperature to settle and then collect exhaust temperature and emissions data for twenty minutes. The blending station was then switched to one of the "substitute" gases. The emissions were allowed to settle and then exhaust temperature and emissions data were collected for twenty minutes. This series of switching gases and collecting data was repeated with the nine other "substitute" gases. The sampling trains for the continuous emission analyzers were purged as needed between "substitute" gases. The calibration of the continuous emissions analyzers was then checked.

The above process was repeated for the second "adjust" gas and all 10 "substitute" gases, and then repeated again with the third "adjust" gas and all 10 "substitute" gases.

For all of the above sequences with constant firing rate, the response of the system's performance in terms of exhaust temperature was recorded with the emissions data at 5 second intervals.

Results

Ignition Tests

The ignition tests measured whether the burner lights and the rate of heating. All the ignition efforts were successful. No ignition failure was observed during the tests. Figure 46 through Figure 74 show the on-off cycling during the ignition tests.

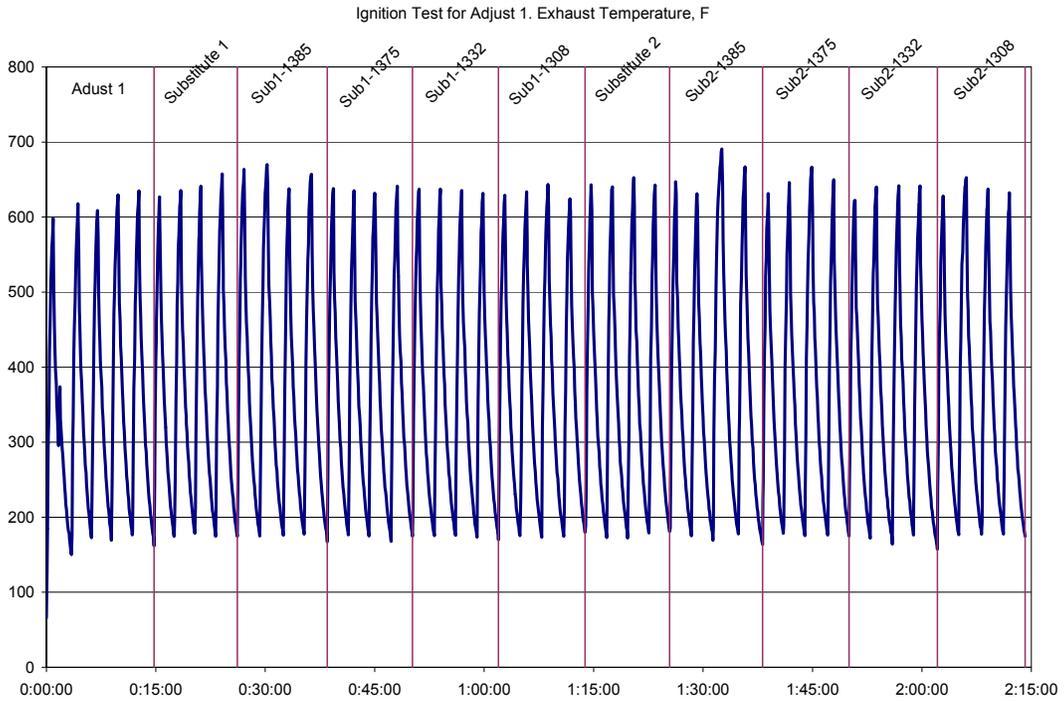


Figure 71. Cycle Pattern during Ignition Testing for Adjust 1 Basis

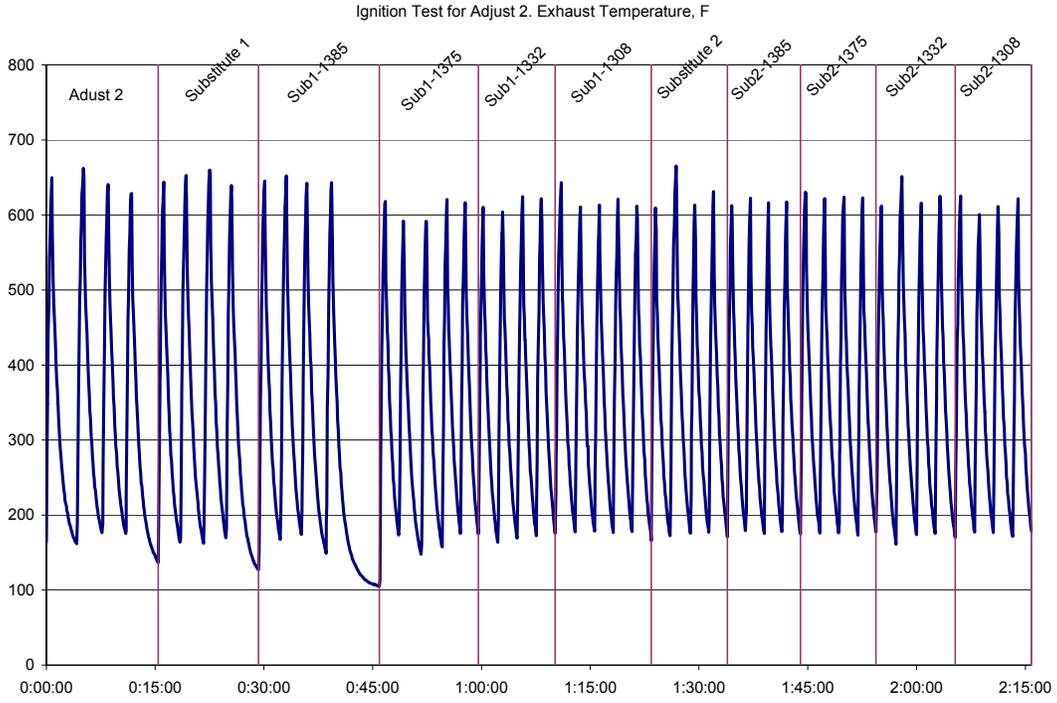


Figure 72. Cycle Pattern during Ignition Testing for Adjust 2 Basis

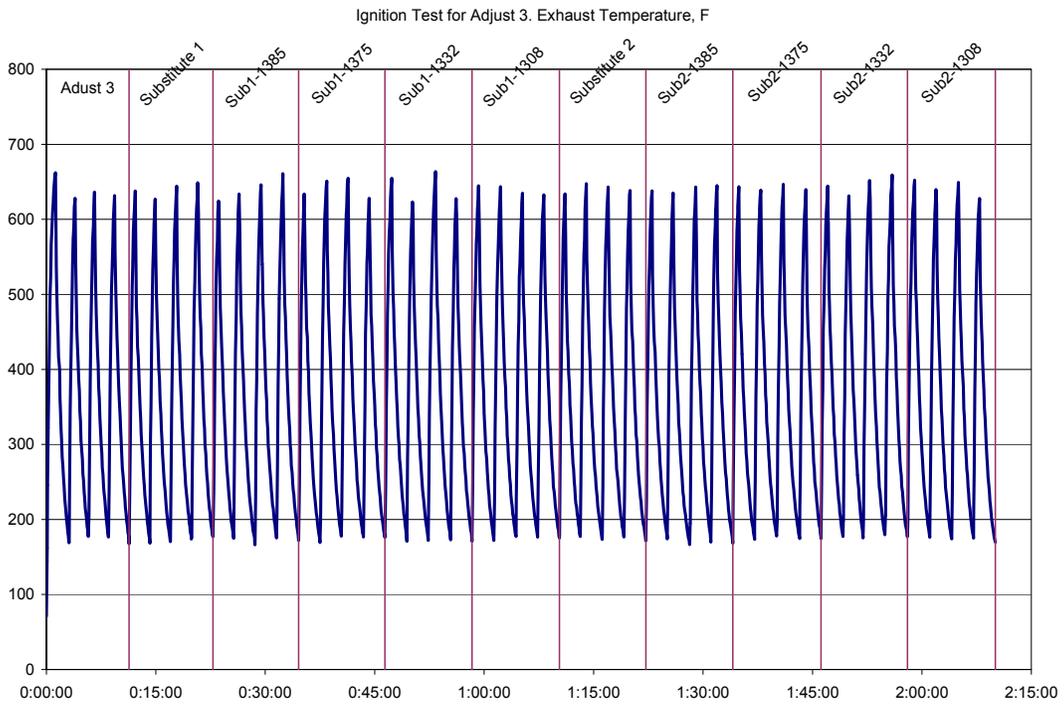


Figure 73. Cycle Pattern during Ignition Testing for Adjust 3 Basis

Continuous Tests – Constant Exhaust Temperature

The major results from the continuous tests with constant exhaust temperature are the emissions and the fuel flow rate (the controller's response) when the burner is tuned for a particular "adjust" gas, and the fuel is switched to various "substitute" gases. Figure 75 through Figure 86 show the emissions and firing rate data over the 20 minute data collection intervals for each of the three "adjust" gas tunings separately. Figure 47 through Figure 90 show the affect of Wobbe Number on emissions and firing rate data for the three different tunings combined.

Continuous Tests – Constant Firing Rate

The major results from the continuous tests with constant firing rate are the emissions and the exhaust temperature (the system's response) when the burner is tuned for a particular "adjust" gas, and the fuel is switched to various "substitute" gases. Figure 91 through Figure 102 show the emissions and exhaust temperature data over the 20 minute data collection intervals for each of the three "adjust" gas tunings separately. Figure 103 through Figure 106 show the affect of Wobbe Number on emissions and exhaust temperature data for the three different tunings combined.

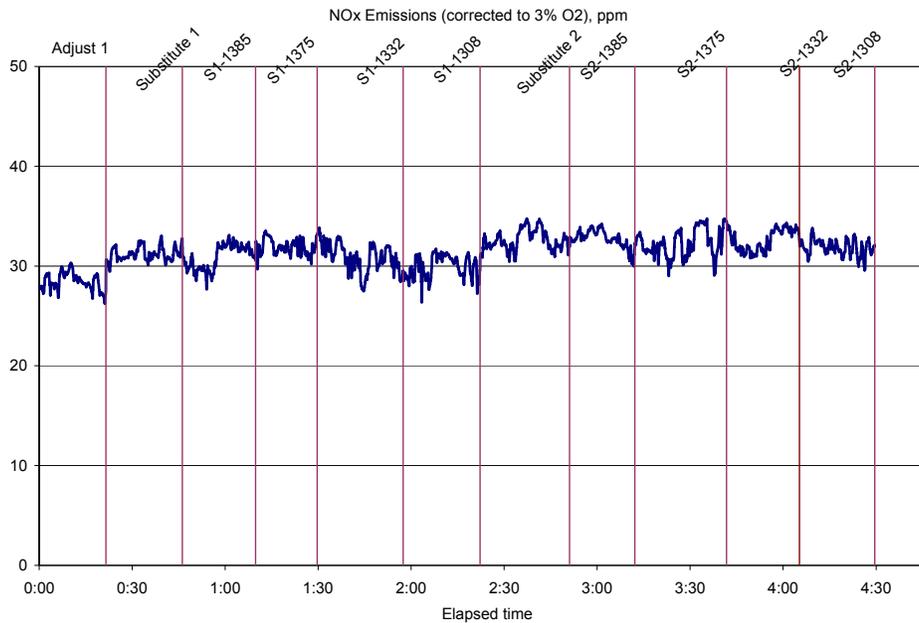


Figure 74. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 1

(Corrected to 3% O₂)

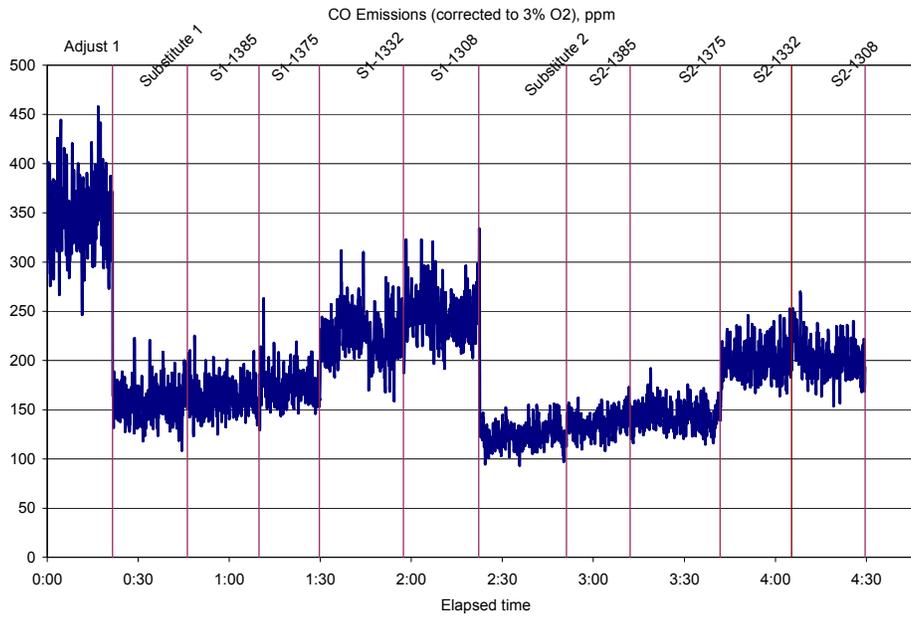


Figure 75. CO Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 1

(Corrected to 3% O₂)

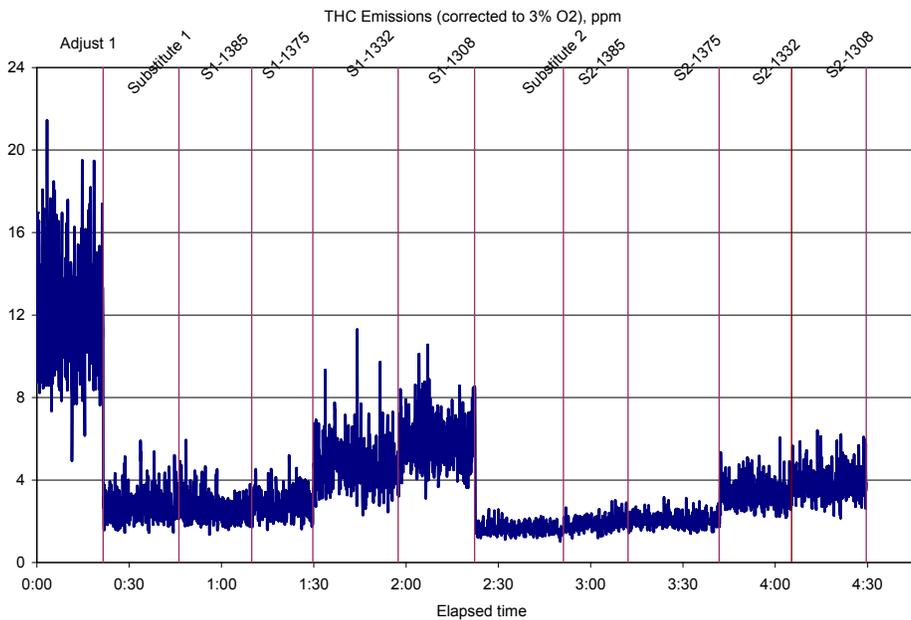


Figure 76. THC Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 2

(Corrected to 3% O₂)

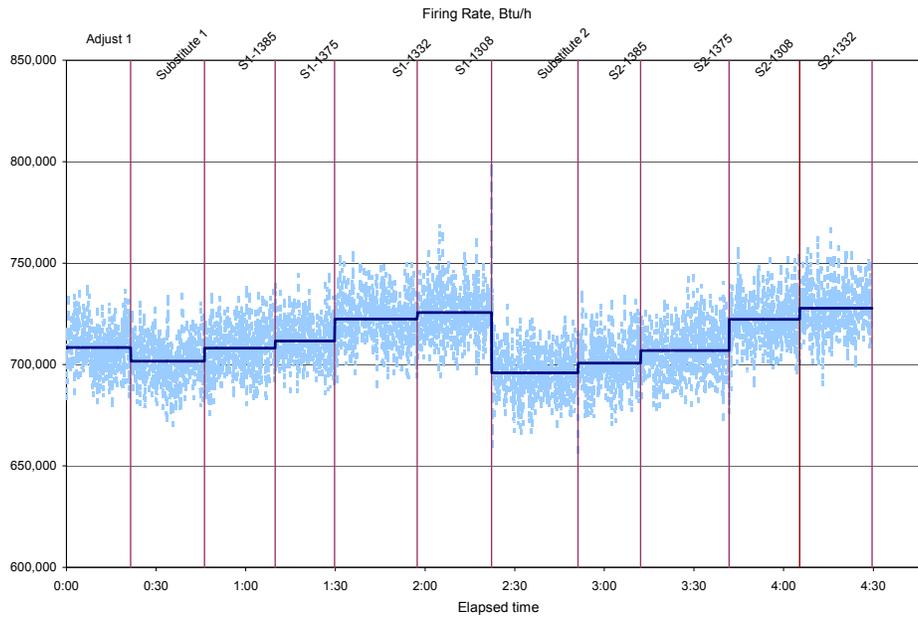


Figure 77. Firing Rate for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 1

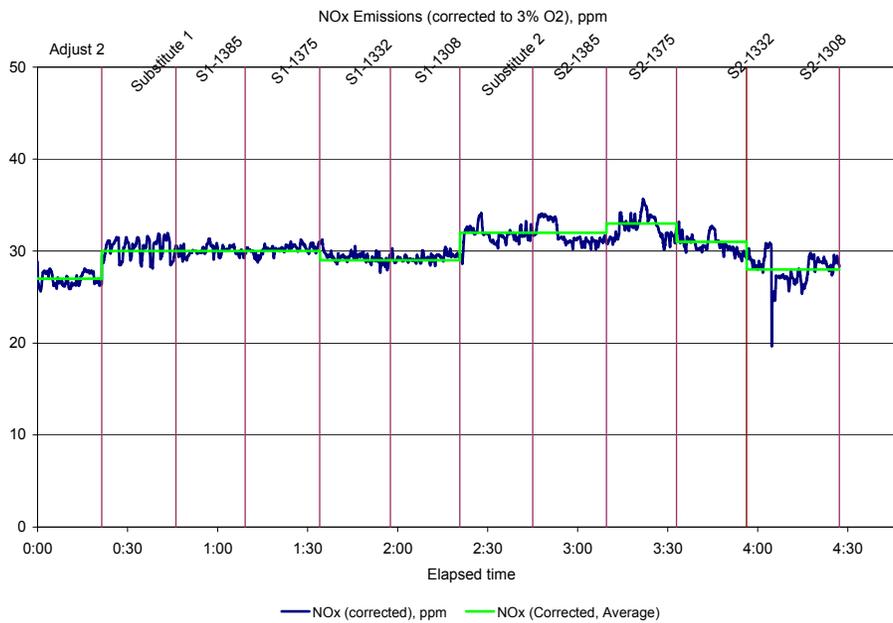


Figure 78. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 2

(Corrected to 3% O₂)

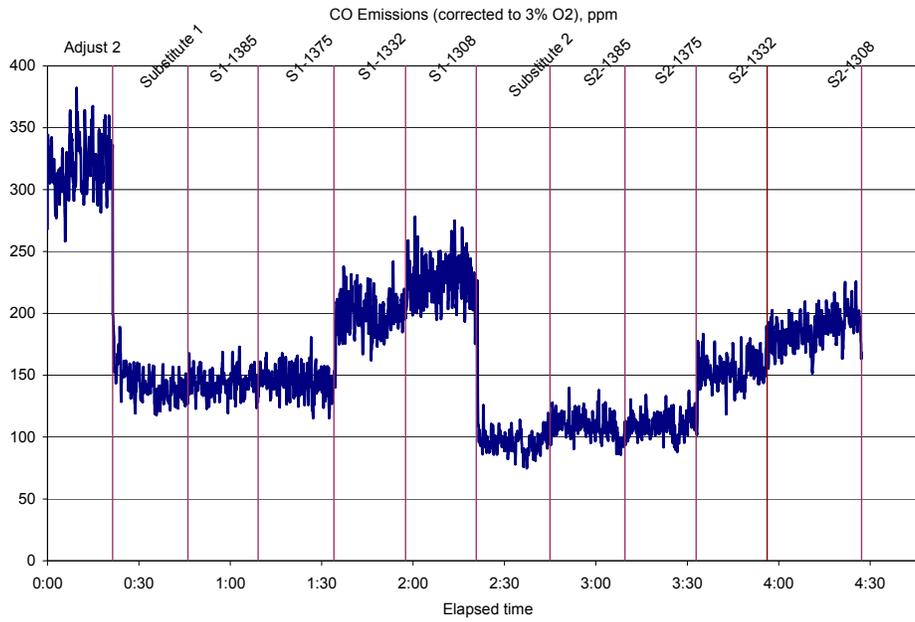


Figure 79. CO Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 2

(Corrected to 3% O₂)

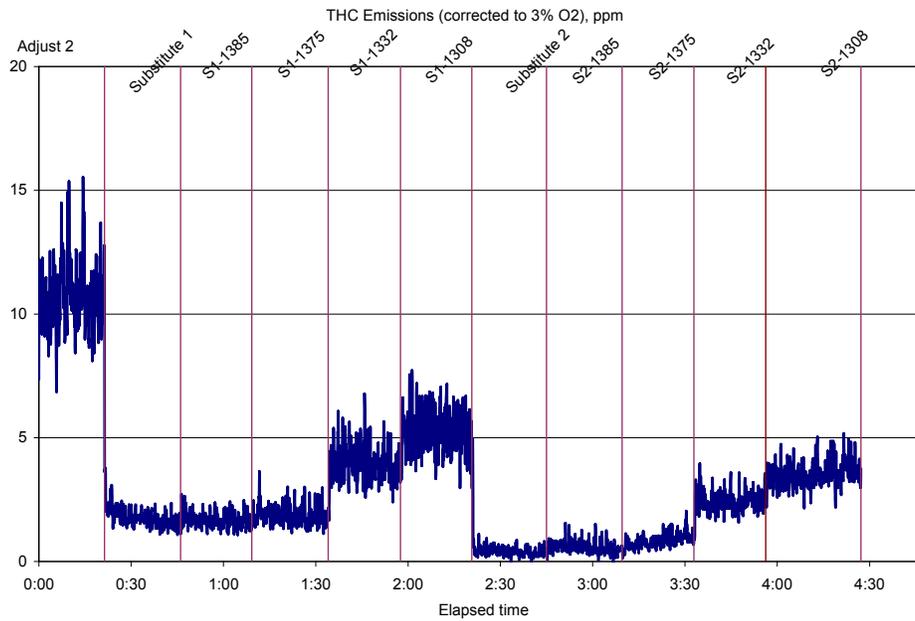


Figure 80. THC Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 3

(Corrected to 3% O₂)

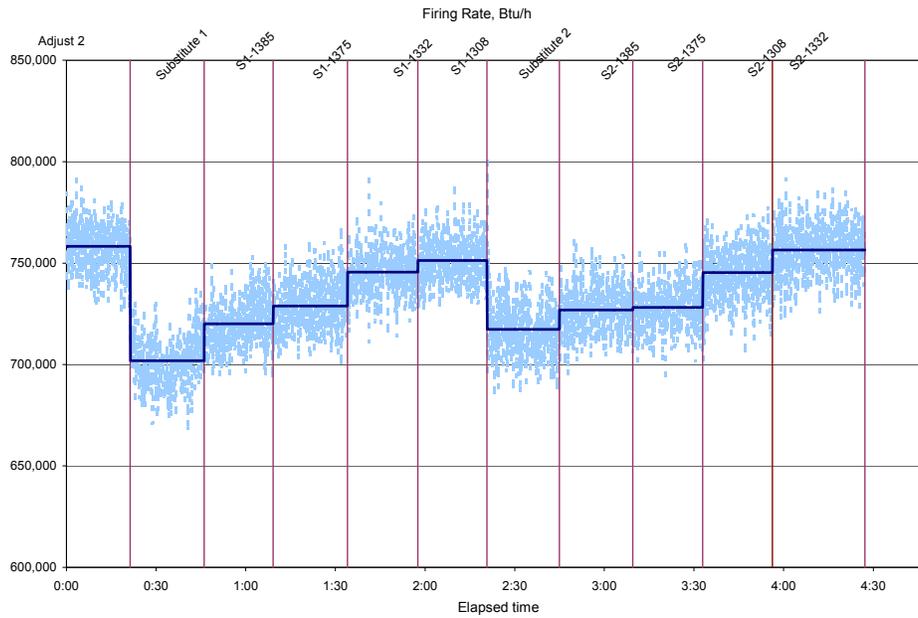


Figure 81. Firing Rate for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 3

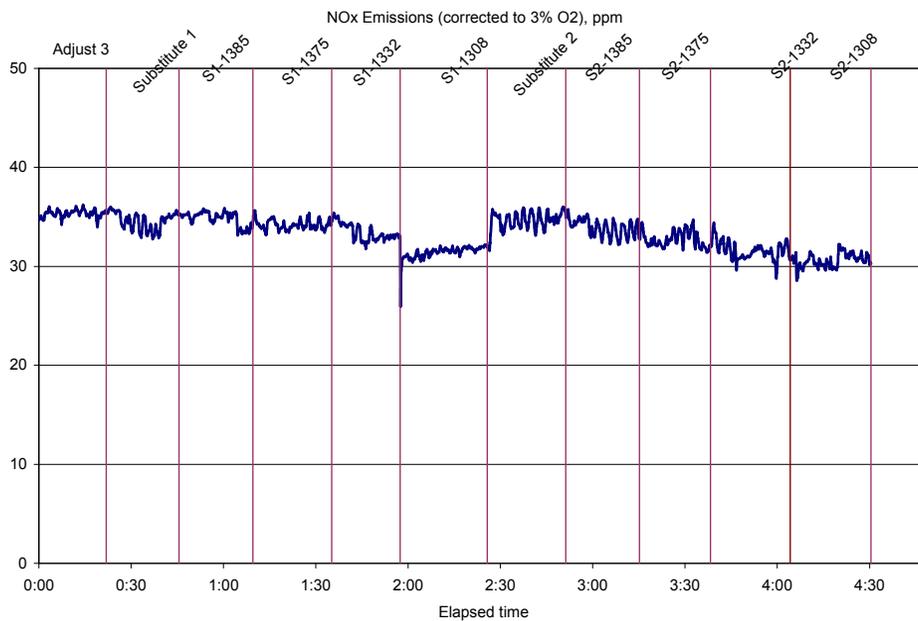


Figure 82. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 2

(Corrected to 3% O₂)

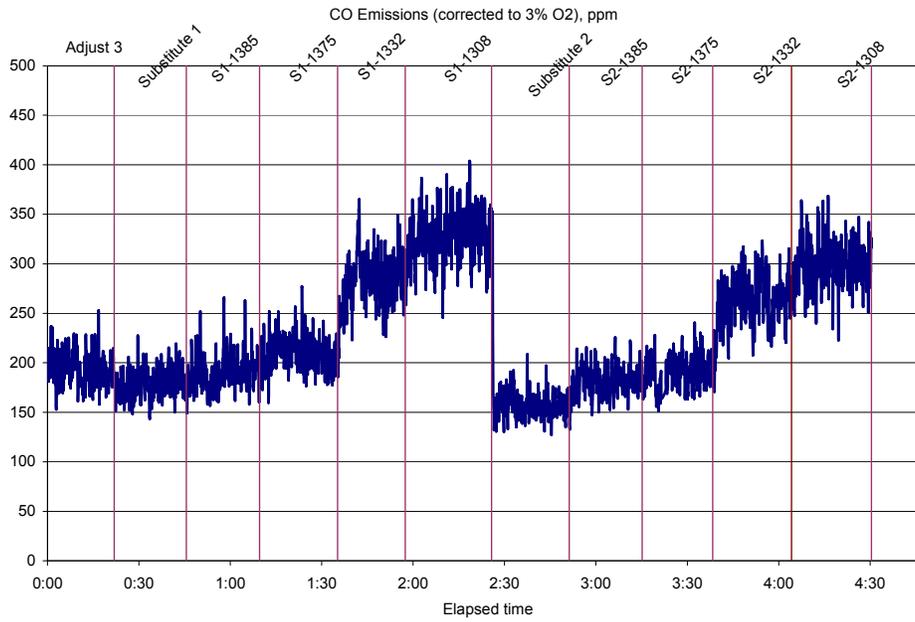


Figure 83. CO Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 3

(Corrected to 3% O₂)

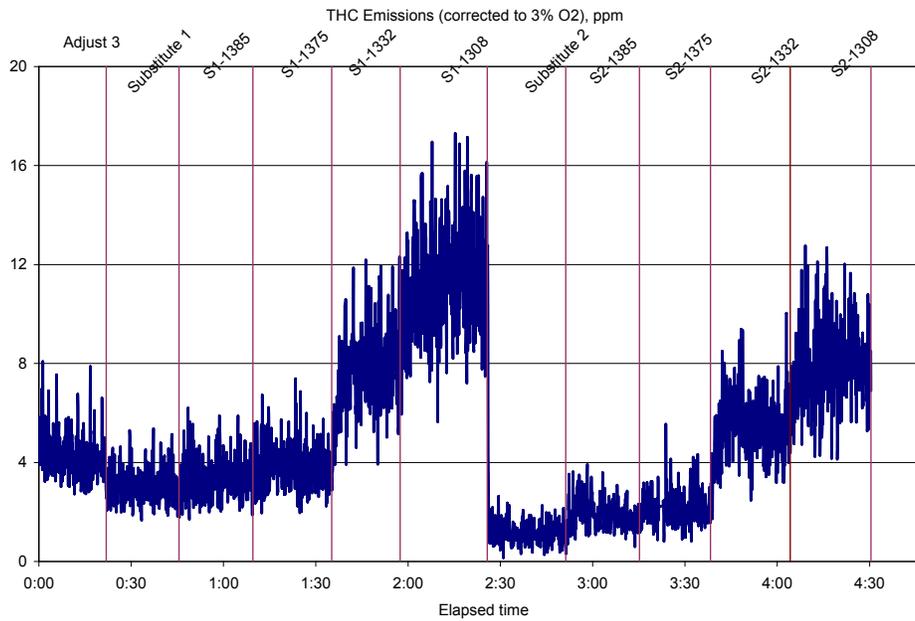


Figure 84. THC Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 3

(Corrected to 3% O₂)

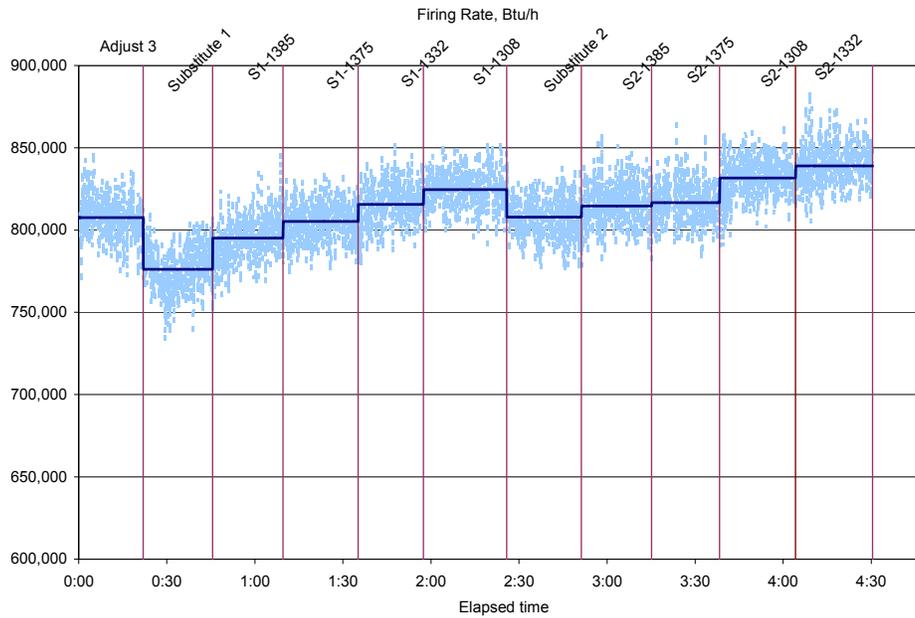


Figure 85. Firing Rate for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 3

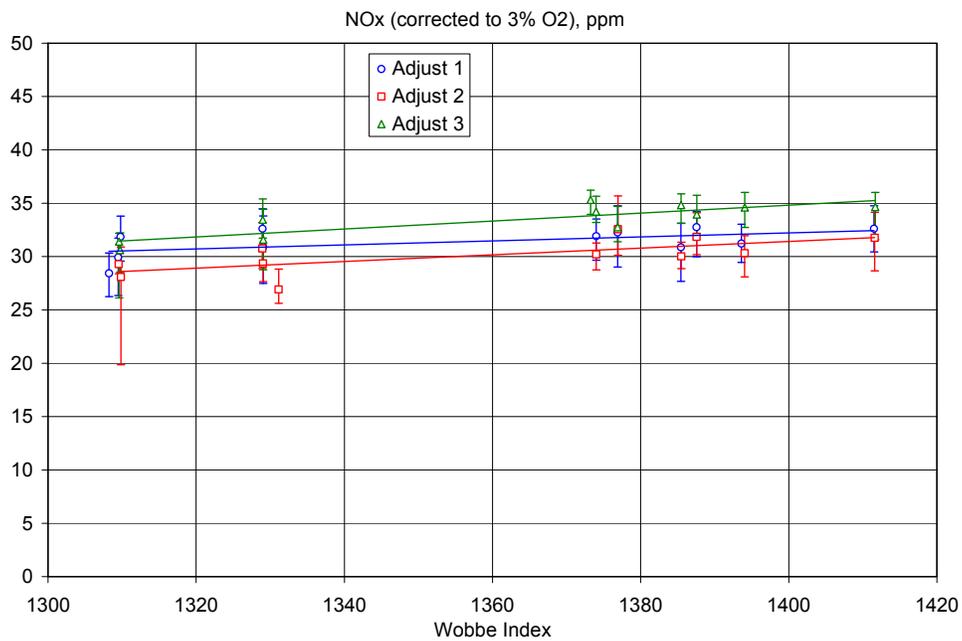


Figure 86. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature

(Corrected to 3% O₂)

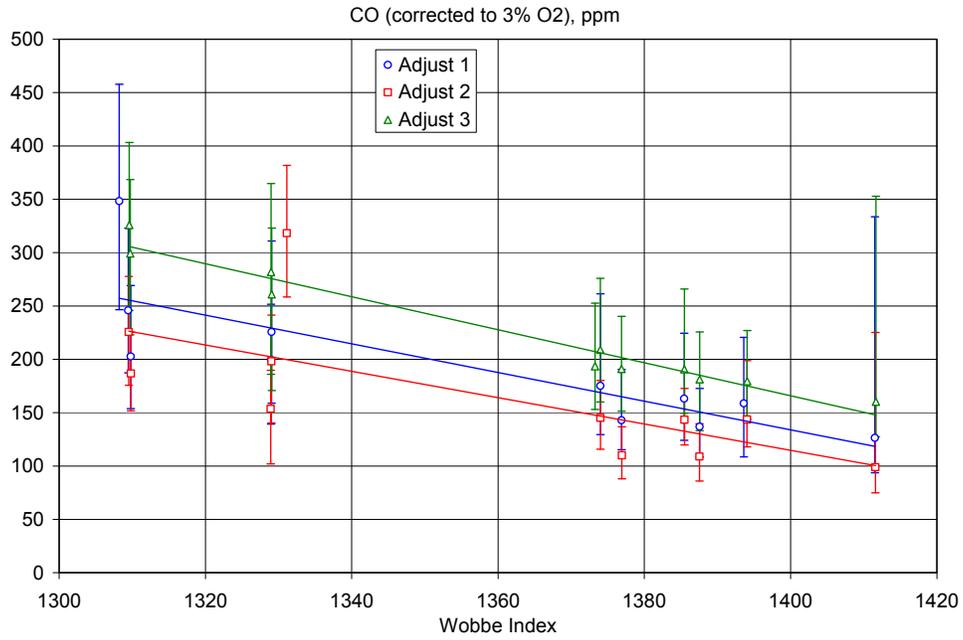


Figure 87. CO Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature

(Corrected to 3% O₂)

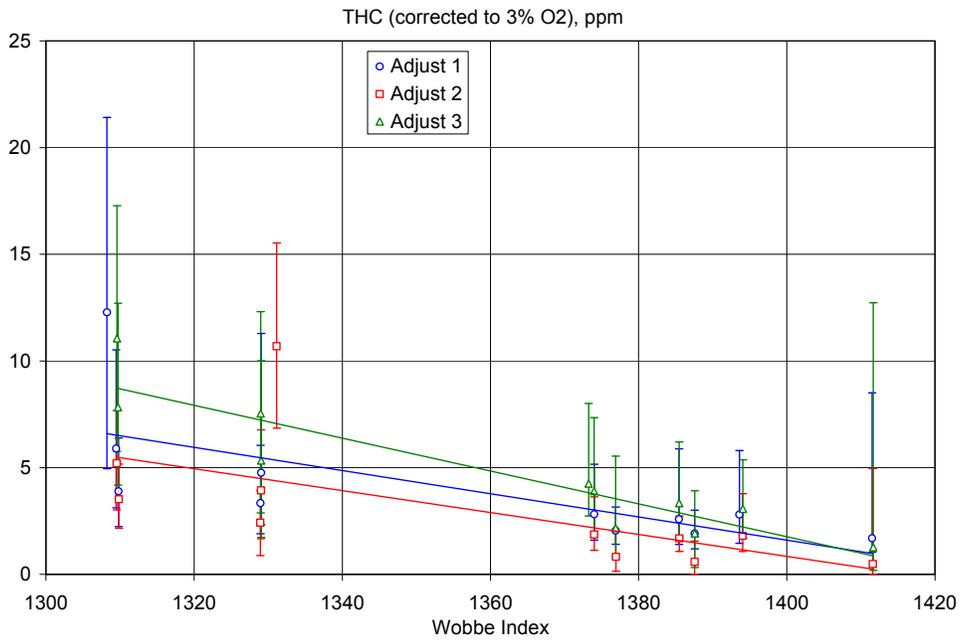


Figure 88. THC Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature

(Corrected to 3% O₂)

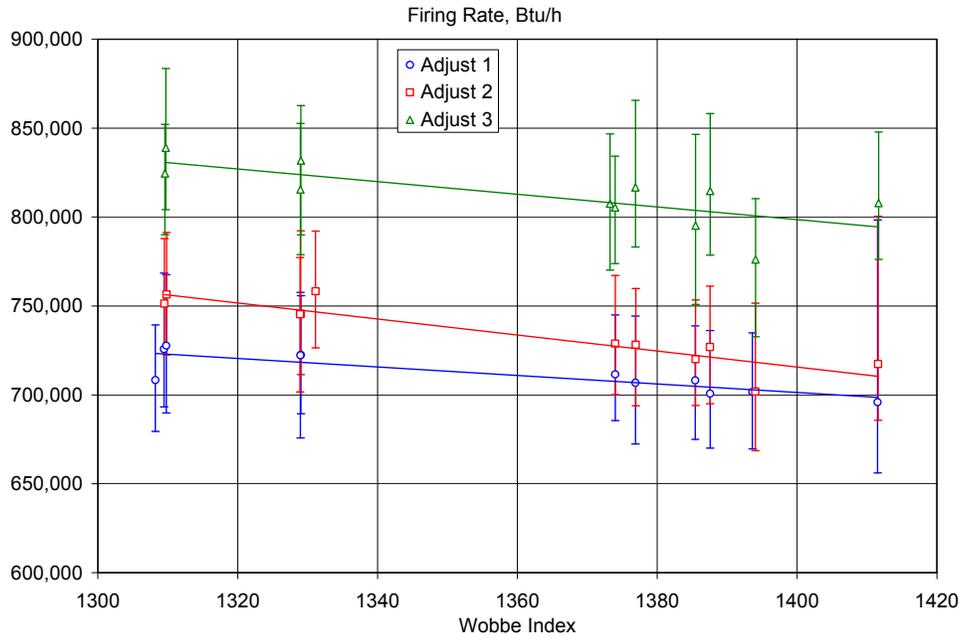


Figure 89. Firing Rate for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature

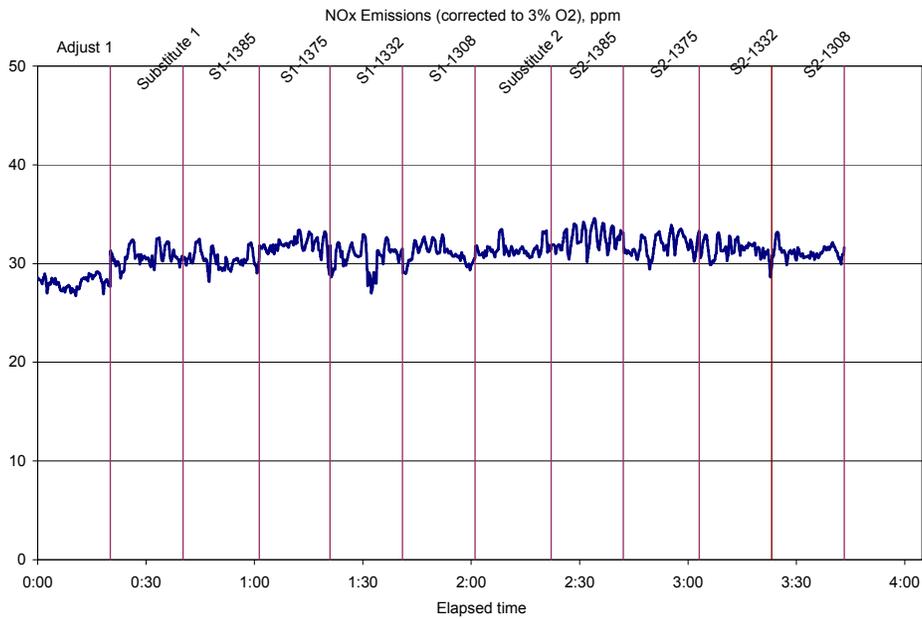


Figure 90. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 1

(Corrected to 3% O₂)

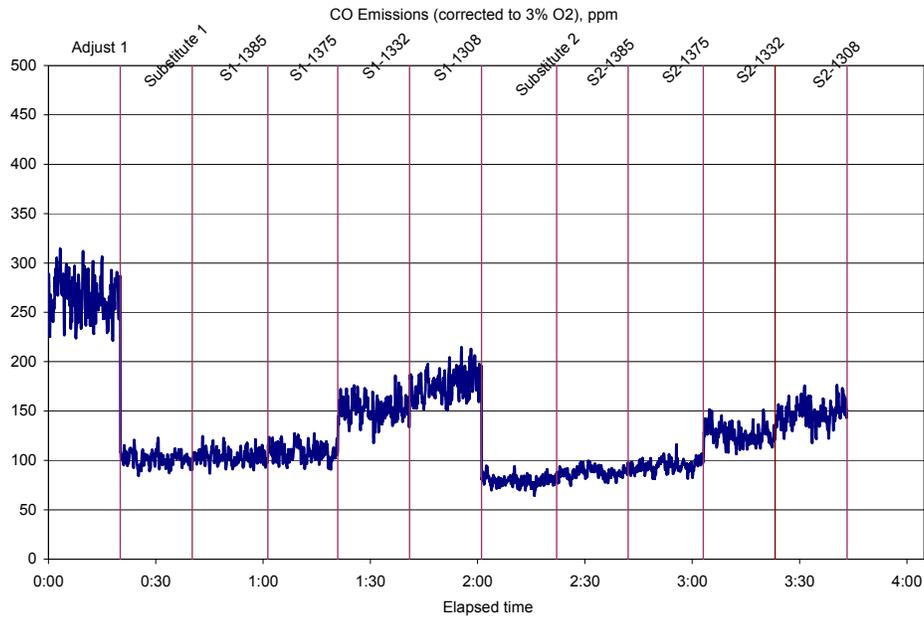


Figure 91. CO Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 1

(Corrected to 3% O₂)

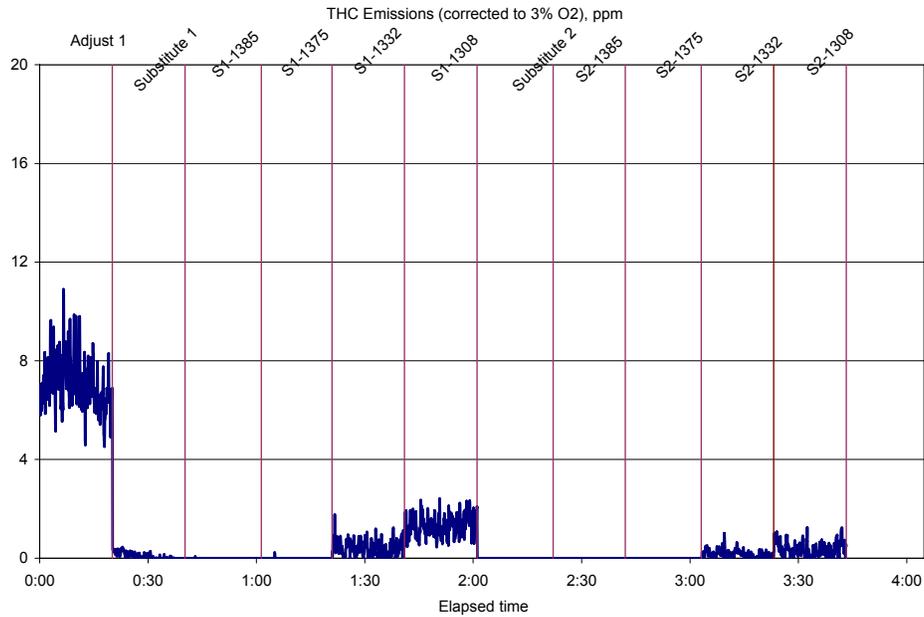


Figure 92. THC Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 2

(Corrected to 3% O₂)

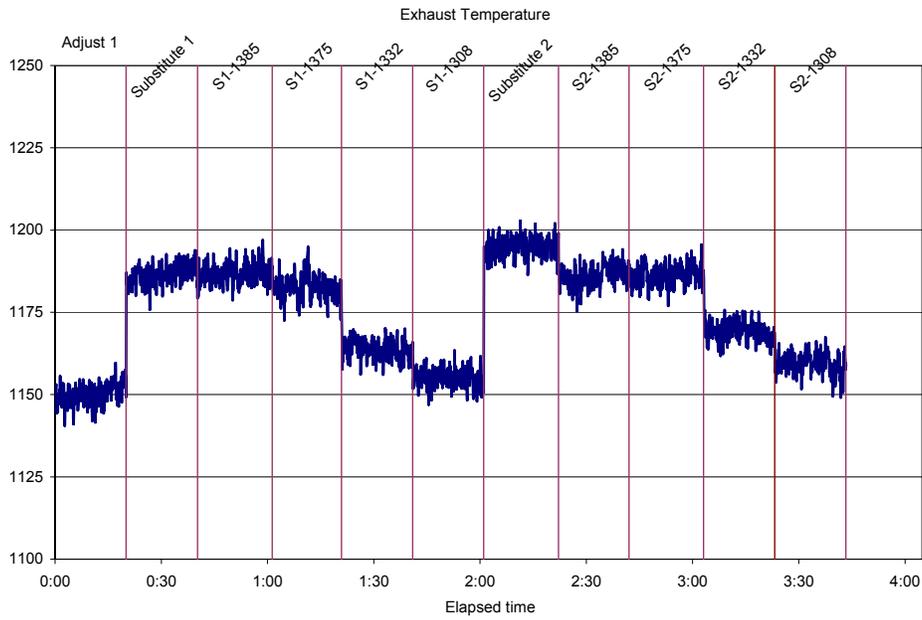


Figure 93. Exhaust Temperature for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 1

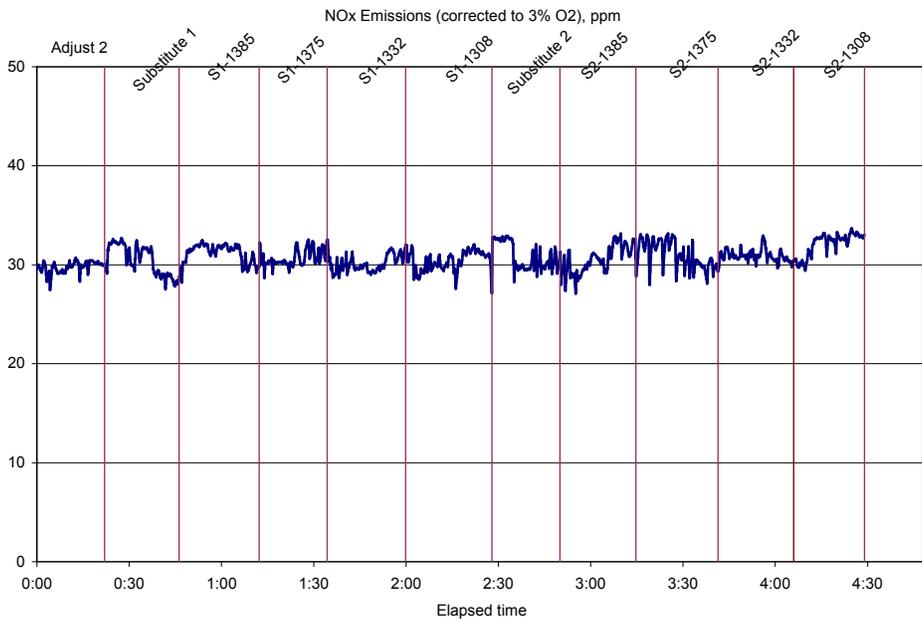


Figure 94. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 2

(Corrected to 3% O₂)

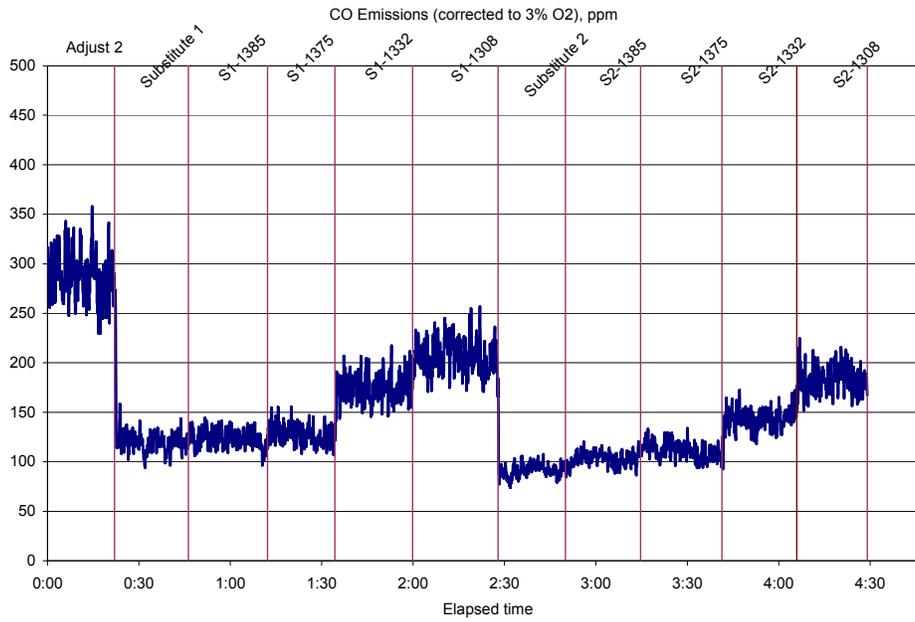


Figure 95. CO Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 2

(Corrected to 3% O₂)

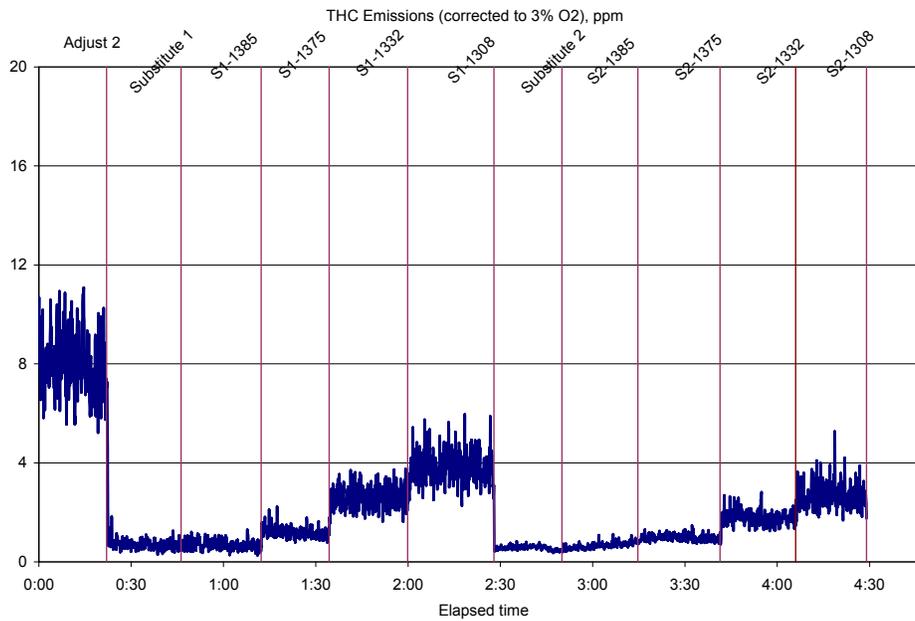


Figure 96. THC Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 3

(Corrected to 3% O₂)

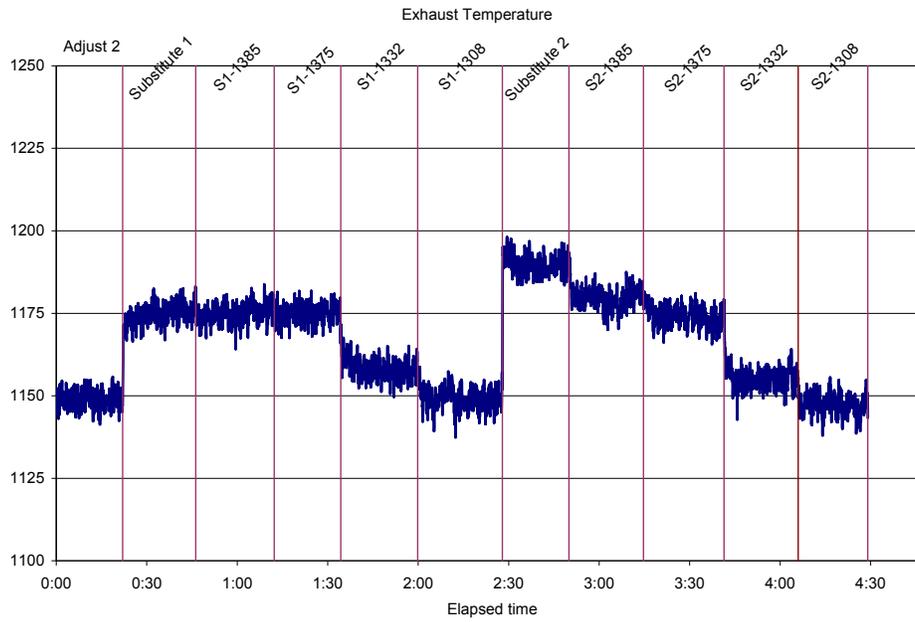


Figure 97. Exhaust Temperature for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 3

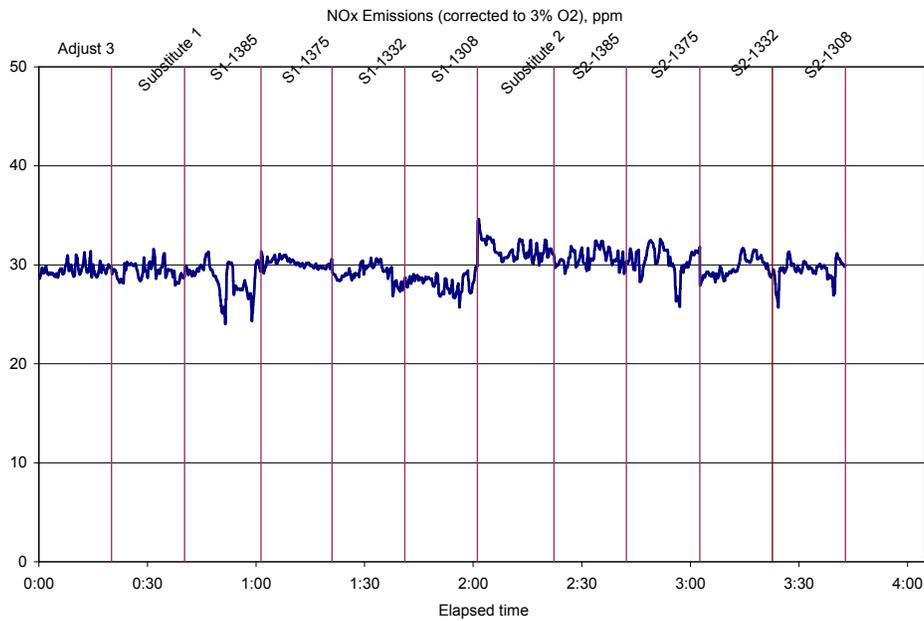


Figure 98. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 2

(Corrected to 3% O₂)

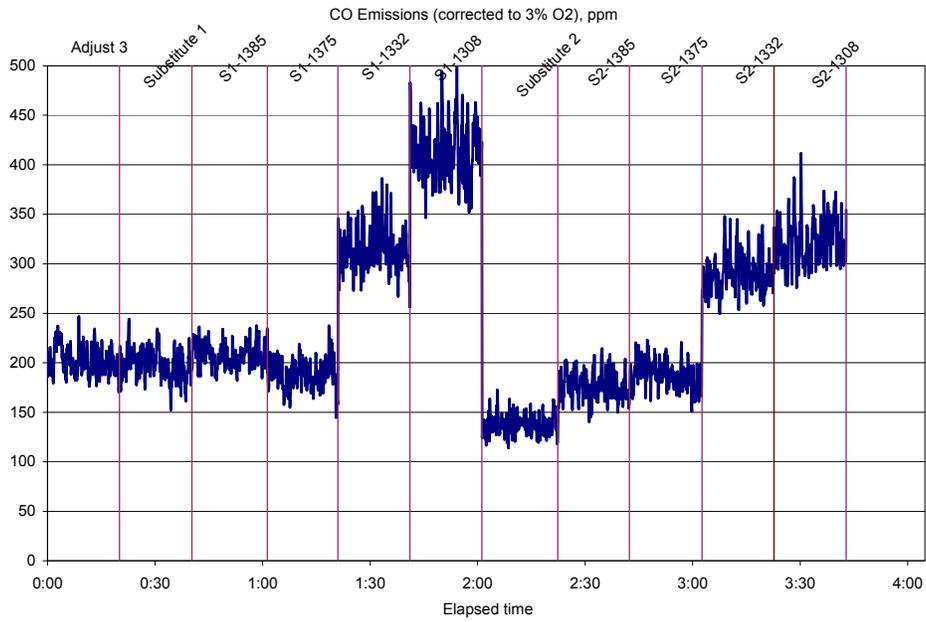


Figure 99. CO Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 3

(Corrected to 3% O₂)

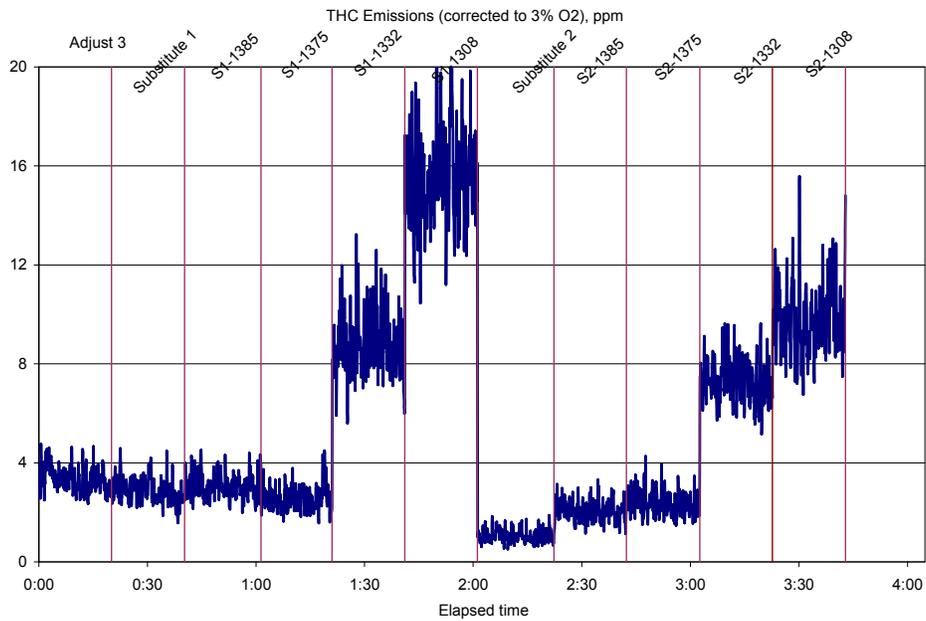


Figure 100. THC Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 3

(Corrected to 3% O₂)

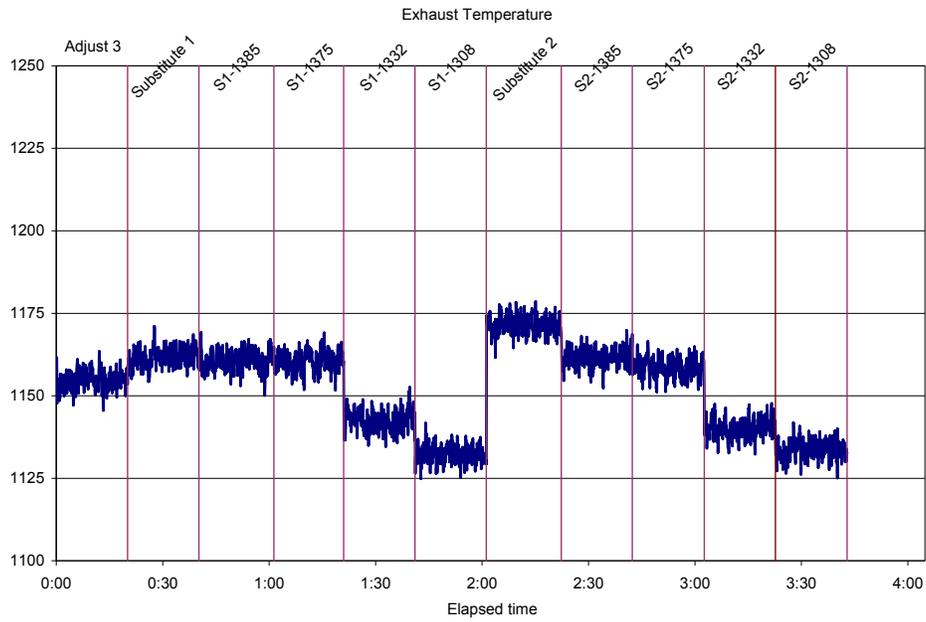


Figure 101. Exhaust Temperature for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 3

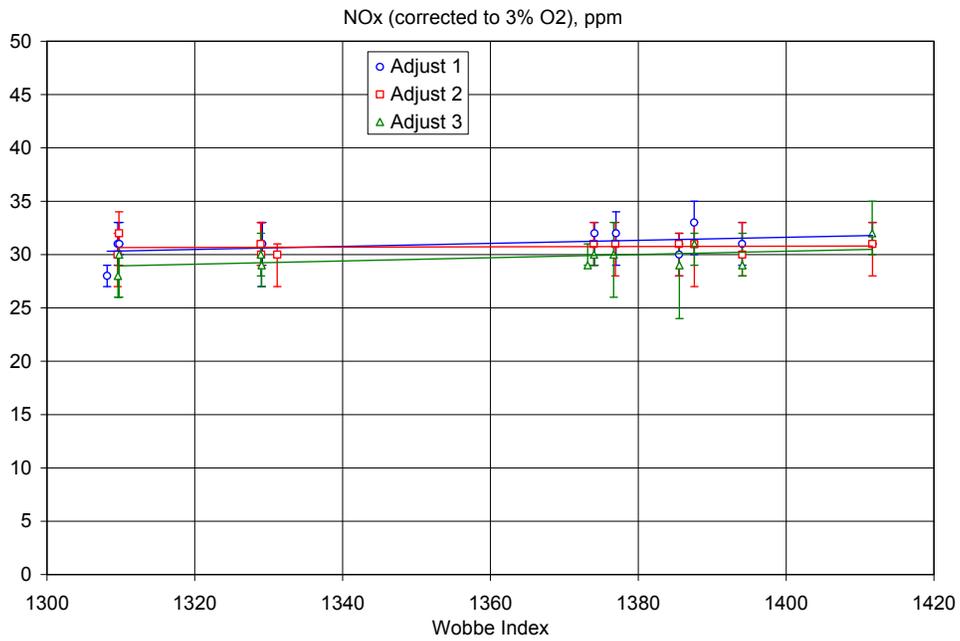


Figure 102. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

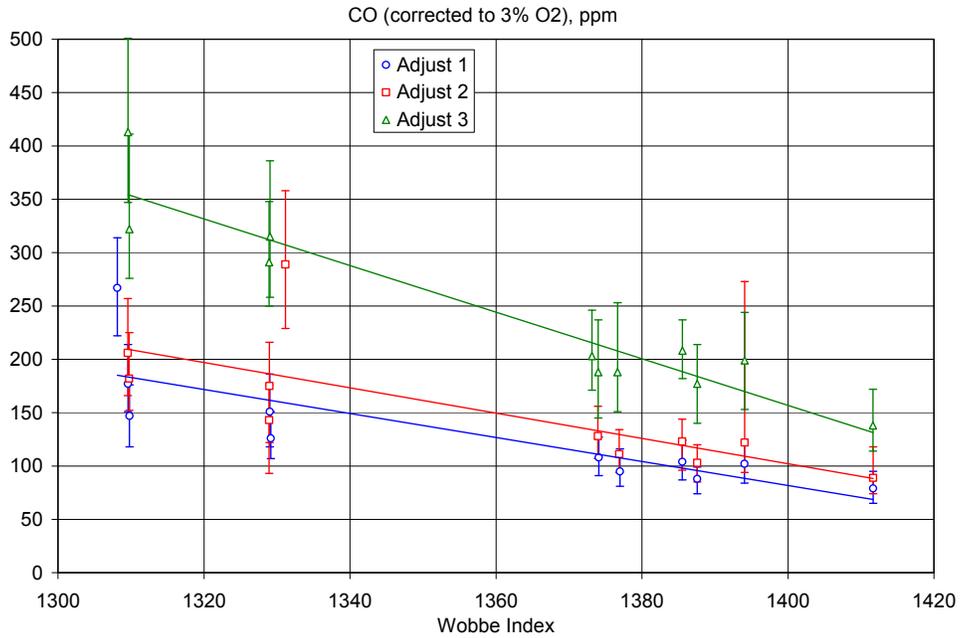


Figure 103. CO Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

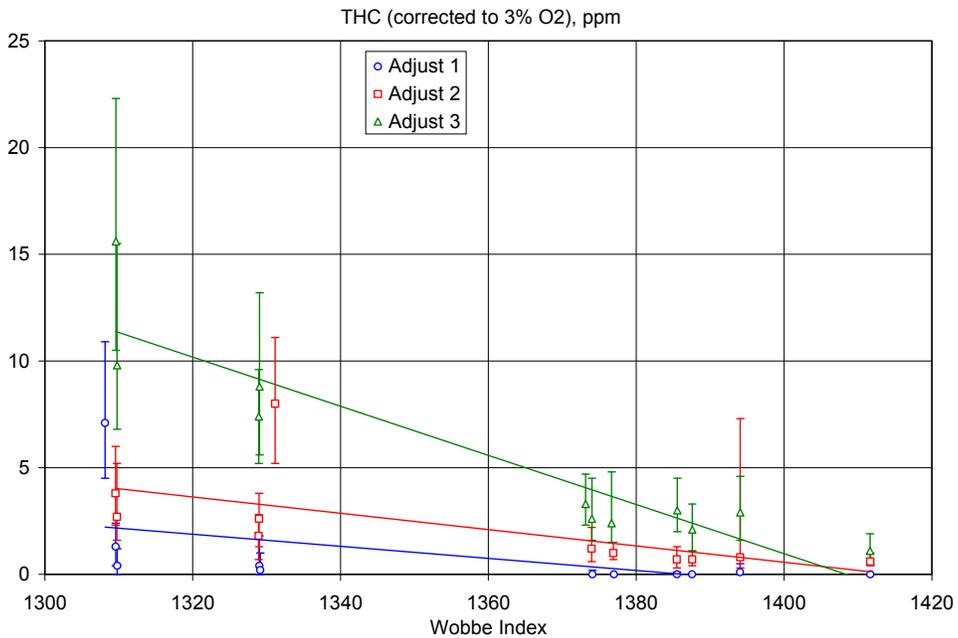


Figure 104. THC Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

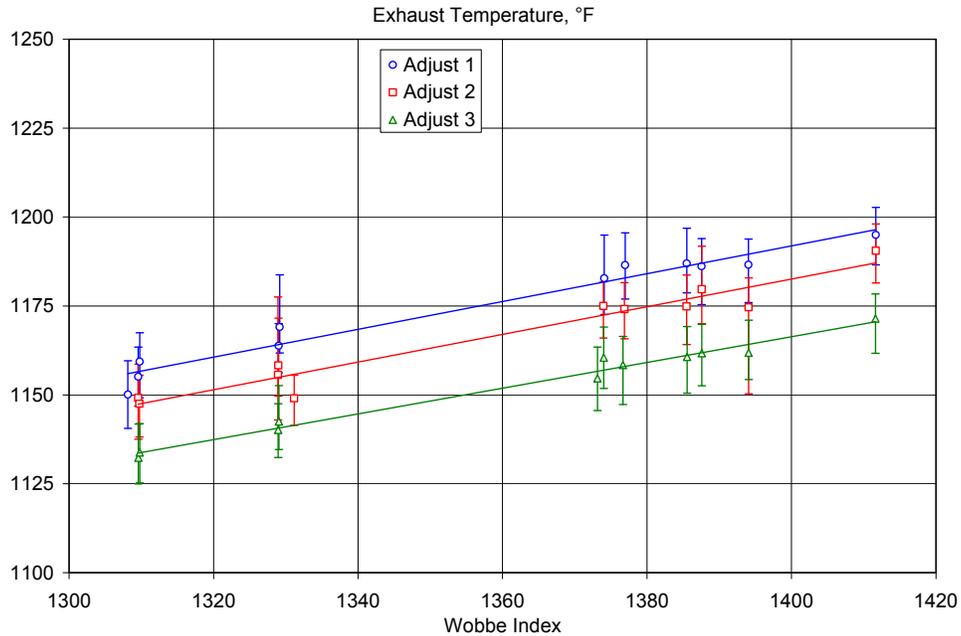


Figure 105. Exhaust Temperature for All Substitute Gases for Continuous Testing with Constant Firing Rate

Calculations

The equation below is the linear correction used to approximately cancel out the analyzer drift;

$$X_{corr} = X_{meas} - \left((Zero\ drift) + (Span\ drift) \frac{X_{meas}}{Span\ value} \right) \frac{T_1}{T_2},$$

where X_{corr} is the corrected emissions value, X_{meas} is the measured value, the drift values are as labeled, T_1 denotes the time elapsed from the previous analyzer calibration, and T_2 denotes the time from the previous analyzer calibration to the next analyzer calibration.

After this correction, the emissions were normalized to 3%O₂ using the formula,

$$X_{3\%O_2} = X_{corr} \left(\frac{21 - 3\%}{21 - \%O_2} \right),$$

where $X_{3\%O_2}$ is the final value after both the correction for drift and the normalization to a common %O₂ in the exhaust.

The Firing Rate was calculated from the actual flow data. The heating value calculation followed the ASTM D 3588 – 98(03) standard at 70°F.

Analysis and Conclusions

The charts and data are analyzed in the same sections below as appear in the Results section.

Ignition Tests

Since all 132 startups (11 gases times 4 ignitions times 3 tuning bases) were successful, comparisons are not possible. With proper setup, the spark ignition does not appear to be affected by the fuel used.

Continuous Tests – Constant Exhaust Temperature

For all three "adjust" gas tunings, "substitute" gases with higher Wobbe indexes yielded slightly higher NO_x emissions, and yielded significantly lower CO and THC emissions.

The firing rate tended to inversely follow the Wobbe index. This was not unexpected since the heat input to the burner is directly tied to Wobbe index.

Continuous Tests – Constant Firing Rate

The CO and THC emissions followed the same trend with Wobbe index as with the constant exhaust temperature tests (lower CO and THC for higher Wobbe indexes). The NO_x emissions did not vary significantly with Wobbe index.

The exhaust temperature tended to follow the Wobbe index. This was not unexpected since the heat input to the burner is directly tied to Wobbe index.

Selected Photographs



Figure 106. High Velocity Burner



Figure 107. Test Chamber



Figure 108. Continuous Emissions Analyzers



Figure 109. Blending Station

**NATURAL GAS IN CALIFORNIA: ENVIRONMENTAL IMPACTS
AND DEVICE PERFORMANCE**

**Industrial Burner Evaluations:
Oxy-Gas Burner Test Report**

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For

California Energy Commission

Contract No. CEC-500-05-026

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Objective

The purpose of the interchangeability tests is to assess the performance of an oxy-gas burner, used primarily in the glass melting industry, when fired with different natural gas compositions. The burner's performance when firing selected Adjust Gases was compared with its performance when firing selected Substitute Gases with and without different levels of nitrogen ballasting.

Approach

The tests used a laboratory setup intended to mimic industrial operating conditions. Operating/Switching tests were then performed. During these tests, the burner was first tuned to operate with an "adjust" gas composition, then several "substitute" gas compositions were fired in sequence on the burner. These tests were then repeated with the other two "adjust" gases as a basis. No ignition tests were performed since this type of burner is typically ignited once and fired continuously for years. Oxygen-gas mixtures are self-igniting at high temperatures, so this type of burner commonly has no need of an ignition source or flame sensor.

Operating tests were performed in two modes, constant chamber temperature and constant firing rate. Both tests used mass flow meters for fuel and oxygen, a control valve for fuel, and computer-based control system to maintain the fuel flow rate proportional to the oxygen flow rate. Constant chamber temperature tests were performed with a PID-loop temperature controller manipulating a control valve for oxygen to maintain the chamber temperature at about 2450°F. Constant firing rate tests were performed with the control valve for oxygen set manually, yielding a firing rate of about 75% or 1,125,000 Btu/hr.

For all test sequences, the chamber was first warmed up on house gas. The fuel was then switched to an "adjust" gas, and the burner was tuned so that the exhaust gases contained 12% O₂.

Table 9 shows the specific performance measurements.

Table 18. Performance Metrics for the Oxy-Gas Burner

BASIC PERFORMANCE METRICS
Gaseous Pollutant Emissions
Chamber Temperature
System or Controller Response upon Switching

Test Apparatus

The oxy-gas burner used for this test was a Primefire 300 by Eclipse, Inc. rated for 1,500,000 Btu/hr. The burner was ignited using a spark ignition rod. The burner assembly is shown in Figure 37.

The test burner fired into a rectangular furnace chamber equipped with a water-cooled panel located on the floor and covering about the first 30% of the floor and a thermocouple protruding through the roof to measure the chamber temperature. This thermocouple was used for temperature control. The overall view of the test rig is shown in Figure 67. Water was flowed through the cooling panel. The water flow rate was measured by a magnetic flow meter. The inlet and outlet water temperatures were measured with thermocouples.

The exhaust duct of the chamber included a damper, which was manually adjusted to maintain a slightly positive pressure inside the chamber. A water-cooled stainless steel sampling probe was installed at the end of the furnace chamber. Due to the high water vapor content of exhaust gases from oxy-gas combustion, a water knock-out trap and peristaltic pump were added after the sampling probe so most of the water condensed from the sampled exhaust gas before sending the gas through a filtering and drying train to a set of continuous emissions analyzers for THC, NO_x, CO₂, CO, and O₂. These are shown in Figure 68.

The oxygen for the burner was supplied from GTI's header, which is fed by a liquid tank. It was regulated down to about 80 psig before the oxygen control valve.

A custom-built blending station was used to provide simulated natural gas compositions to the fuel control valve at 3.2 psig. The blending station allowed for one of two main streams, house gas and cleaned gas, to be selected, to which metered amounts of ethane, propane, butane, and nitrogen could be added. The house gas was the normal natural gas delivered to GTI, and was the basis for all the "adjust" gases. The cleaned gas was the basis for the "substitute" gases. House gas without additions was used for warming up the furnace chamber.

Mass flow meters were used to measure the house gas and cleaned gas flows. Motorized ball valves were used to select one of the two main streams. Mass flow controllers were used to add ethane, propane, butane, and nitrogen to the main stream. Ethane was supplied from a bank of 5 gas cylinders, propane and butane were each supplied from the gaseous outlet of liquid cylinders, and nitrogen was supplied from GTI's header, which is fed by a liquid tank. All gases were regulated down to about 15 psig before or upon entering the blending station except butane, which is delivered unregulated at its saturation vapor pressure of about 14 psig. The selected main stream is further regulated down to about 5 psig before the other gases are blended in. A pressure transmitter and thermocouple were used to monitor the mixed gas pressure and temperature. The blending station with constituent gases is shown in Figure 69.

The chamber and water thermocouples, continuous emissions analyzers, mass flow meters and controllers, and motorized ball valves were connected to a data acquisition and control system. Instruments used to perform this test series are listed in Table 3.

Table 19. Summary of Test Instruments

Instrument	Parameter	Range	Accuracy
National Instruments Field Point Modules	Data logging and control	4-20 mA, 0-5 V, 0-10 V, ± 100 mV, on/off (relay)	16 bit input current; 12 bit input voltage; 12 bit output current; 16 bit temperature
LabView software	Data logging	—	—
Custom software	Control	—	—
Laptop computer	Data logging and control	—	—
Type R thermocouple	Chamber temperature	3218°F	—
ABB Mini-Mag 10D1475W	Water flow rates	26.42 gpm	0.5% of rate @ $\geq 7\%$ full scale
Type T thermocouple	Water temperatures	752°F	—
Rosemount Analytical 400A	THC concentration	0-100 ppm, Span 79 ppm	1% full scale
Rosemount Analytical 755R	O ₂ concentration	0-25%, Span 8.0%	0.01% O ₂ or 1% full scale
Thermo Environmental 42C High Level	NO concentration, NO _x concentration	0-1500 ppm, Span 197.8 ppm	0.5 ppm
Rosemount Analytical 880A	CO concentration	0-1000 ppm, Span 924 ppm	1% full scale
Rosemount Analytical 880A	CO ₂ concentration	0-100%, Span 80.0%	1% full scale
Brooks Instruments 5863S	House gas flow rate	2066 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5863S	Cleaned gas flow rate	1826 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5853S	Ethane gas flow rate	224 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5851S	Propane gas flow rate	68.5 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5851S	Butane gas flow rate	31.4 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5851S	Nitrogen gas flow rate	141 SCFH	0.7% of rate plus 0.2% of full scale
Sierra Instruments 780S	Fuel flow rate	2000 SCFH	1% of rate plus 0.5% of full scale
Magnetrol TA2	Oxygen flow rate	4000 SCFH	1% of rate plus 0.5% of full scale
Wika S-10	Mixed gas pressure	0-200 psig	0.25% of span
Type T thermocouple	Mixed gas temperature	752°F	—

The measured flow rates of the fuel gases supplied from the custom blending station and measured flow rate of oxygen and fuel to the burner were recorded using National Instruments Field Point Modules and a LabView program running on a laptop computer. The fuel gas compositions were commanded through a separate, custom program on the same laptop computer. The custom program used the measured flow rate of the main stream to determine the flow rates of the added gases. A table of ratios of each added gas to the main stream for each "adjust" and "substitute" gas was created for the custom program.

The temperature of the furnace chamber was controlled with a Fuji Electric PXZ4 1/16 DIN PID-loop temperature controller driving the oxygen control valve. Gas from the blending station was controlled with the fuel control valve. The fuel control valve was driven by the above mentioned custom program on the laptop computer. The custom program used the measured flow rate of the oxygen to determine the flow rate of the fuel via a simple proportioning ratio determined during the tuning of the burner. The desired fuel flow rate was sent to a process controller which drove the fuel control valve.

Test Gases

Test gases were selected to match compositions distributed in California, and international compositions that may be imported into California. The compositions distributed in California are designated "adjust gases" for the purpose of tuning the burner for optimum performance on each of them. The remaining gases are designated "substitute gases" for the purpose of comparing the performance with substitute gases to the performance with the adjust gases. Table 4 summarizes the gas compositions. Adjust 1 represents natural gas in the Sacramento area, Adjust 2 is an average value for the state of California, and Adjust 3 is representative of some areas in California with higher Btu content due to local natural gas production. The two substitute gases, Sub 1 and Sub 2, were selected from a set of potential LNG compositions available to California; Sub 1 has a relatively low Wobbe Number (1408) compared with other LNG compositions, and Sub 2 has a relatively high Wobbe Number (1425). Because it is possible that these "substitute" gases will be conditioned with nitrogen prior to distribution in California, additional compositions with nitrogen are added to make the Wobbe Number match those of the selected "adjust" gases.

Table 20. Summary of Adjust and Substitute Gases

Name	Gas Composition, mol %							HHV	Wobbe
	C1	C2	C3	C4	C5+	N2	CO2		
Adjust 1	93.2	2.52	0.41	0.14	0.093	2.691	0.920	1010	1309
Adjust 2	94.5	2.55	0.42	0.14	0.094	1.361	0.931	1024	1332
Adjust 3	90.61	2.45	3.41	1.25	0.094	1.305	0.893	1094	1374
Sub 1	92.4	4.9	1.9	0.79	0.0	0.0	0.0	1099	1408
@1385	91.3	4.8	1.9	0.79	0.0	1.2	0.0	1086	1387
@1375	90.7	4.8	1.9	0.79	0.0	1.9	0.0	1080	1375
@1332	88.3	4.8	1.8	0.79	0.0	4.4	0.0	1053	1331
@1308	87.8	4.6	1.8	0.70	0.0	5.5	0.0	1036	1308
Sub 2	89.4	7.1	2.5	1.04	0.0	0.0	0.0	1131	1426
@1385	87.5	7.0	2.4	1.00	0.0	2.1	0.0	1106	1387
@1375	86.9	6.9	2.4	1.00	0.0	2.7	0.0	1098	1376
@1332	84.5	6.7	2.4	1.00	0.0	5.4	0.0	1070	1330
@1308	83.6	6.6	2.3	1.00	0.0	6.5	0.0	1057	1310

For small-scale testing (up to about 40,000 Btu/h), it is practical to purchase cylinders with these exact compositions, with only nitrogen being blended in as needed. For medium-scale testing (up to about 200,000 Btu/h), it is practical to create these compositions from cylinders of pure gases using a blending station. For large-scale testing (over 1,000,000 Btu/h), the amount of pure methane needed requires a tube trailer, but none were available from GTI's gas supplier during the time of the test campaign. The "adjust" gases could be simulated (same heating value and Wobbe index) by blending in ethane, propane and butane from cylinders, and nitrogen from a liquid tank into GTI's house gas. However, the pure "substitute" gases and conditioned (nitrogen-diluted) "substitute" gases with higher Wobbe indexes could not be simulated this way because of the amount of inerts (CO₂ and N₂) in the house gas.

For another project, GTI assembled a CO₂ stripper which utilized three columns (towers) to remove the CO₂ from the house gas. The first tower performed the function of absorbing the CO₂ from the desired amount of house gas and an additional amount of house gas. The desired amount of cleaned gas went onto the burner being tested, while the additional amount went through the second tower, a heater, and the third tower before being vented or flared. The third tower performed the function of desorbing the CO₂ from the absorbent using the heated gas, while the second tower was being cooled

by the cleaned gas. The towers rotated their function every 3 hours, so the process was regenerative.

The cleaned gas with the heavy molecular weight CO₂ removed was then used as the basis for simulating the "adjust" gases and the conditioned "substitute" gases. The pure "substitute" gases were still not quite reached, so the points of maximum heating value and Wobbe index, along the same lines as the conditioned "substitute" gases, were used in their place. The final compositions are shown in Table 12.

Table 21. Summary of Test Gases

Name	Gas Composition, mol %						HHV	Wobbe
	House Gas	Cleaned Gas	Ethane	Propane	Butane	Nitrogen		
Adj1Q	97.28%	0.00%	0.00%	0.84%	0.00%	1.89%	1010.0	1309.0
Adj2Q	98.49%	0.00%	0.00%	0.90%	0.00%	0.61%	1024.0	1332.0
Adj3Q	92.02%	0.00%	4.62%	1.95%	0.81%	0.59%	1094.0	1374.0
Sub1QM	0.00%	93.62%	3.99%	1.69%	0.70%	0.00%	1090.3	1394.3
Sub1Q-Hi	0.00%	93.17%	3.97%	1.68%	0.69%	0.49%	1085.0	1385.5
Sub1Q-A3	0.00%	92.57%	3.95%	1.67%	0.69%	1.12%	1078.0	1374.1
Sub1Q-A2	0.00%	90.20%	3.85%	1.63%	0.67%	3.65%	1050.4	1329.2
Sub1Q-A1	0.00%	89.16%	3.80%	1.61%	0.66%	4.76%	1038.3	1309.7
Sub2QM	0.00%	90.82%	5.75%	2.43%	1.00%	0.00%	1122.0	1411.9
Sub2Q-Hi	0.00%	89.58%	5.67%	2.40%	0.99%	1.36%	1106.8	1387.7
Sub2Q-A3	0.00%	89.03%	5.64%	2.38%	0.98%	1.96%	1100.0	1377.0
Sub2Q-A2	0.00%	86.56%	5.48%	2.32%	0.96%	4.68%	1069.3	1329.2
Sub2Q-A1	0.00%	85.56%	5.42%	2.29%	0.95%	5.79%	1056.9	1309.9

Figure 42 illustrates the fuel heating values and Wobbe indexes used for the oxy-gas burner testing.

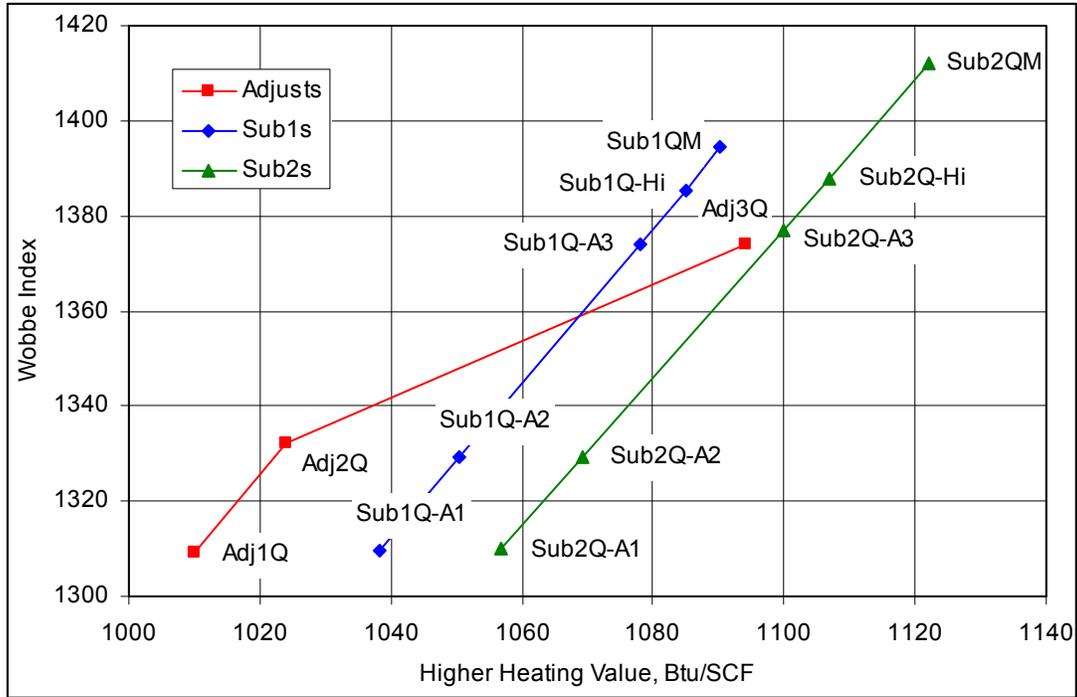


Figure 110. Wobbe Indexes and Heating Values for Oxy-Gas Burner Tests

Test Schedule

Performance tests with constant chamber temperature were performed first for all three "adjust" gases. These were followed by performance tests with a constant firing rate for all three "adjust" gases. Ignition tests were not performed because this type of burner is typically ignited once and fired continuously for years.

Figure 45 illustrates the overall setup, testing, and analysis schedule. Table 13 shows the schedule of test sequences. Each sequence of tests (each column in Table 13) was performed during a single day.

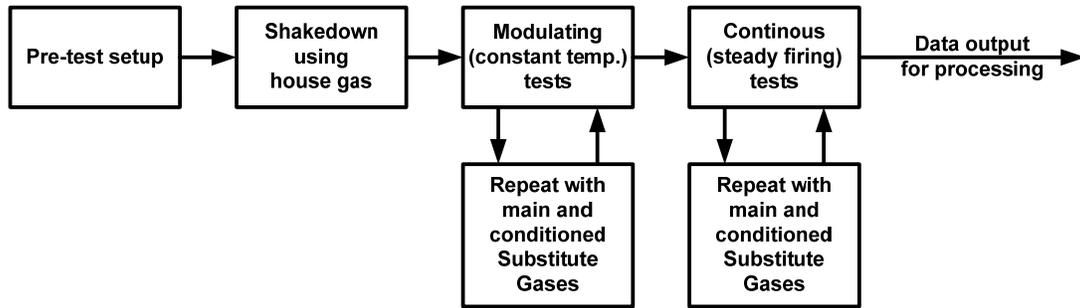


Figure 111. Test Schedule for the Oxy-Gas Burner

Table 22. Test Schedule

Type	Constant Exhaust Temperature			Constant Firing Rate		
	Adj2Q	Adj1Q	Adj3Q	Adj3Q	Adj2Q	Adj1Q
Basis	Adj2Q	Adj1Q	Adj3Q	Adj3Q	Adj2Q	Adj1Q
Subs	Sub1Q	Sub1Q	Sub1Q	Sub1Q	Sub1Q	Sub1Q
	Sub1Q-Hi	Sub1Q-Hi	Sub1Q-Hi	Sub1Q-Hi	Sub1Q-Hi	Sub1Q-Hi
	Sub1Q-A3	Sub1Q-A3	Sub1Q-A3	Sub1Q-A3	Sub1Q-A3	Sub1Q-A3
	Sub1Q-A2	Sub1Q-A2	Sub1Q-A2	Sub1Q-A2	Sub1Q-A2	Sub1Q-A2
	Sub1Q-A1	Sub1Q-A1	Sub1Q-A1	Sub1Q-A1	Sub1Q-A1	Sub1Q-A1
	Sub2Q	Sub2Q	Sub2Q	Sub2Q	Sub2Q	Sub2Q
	Sub2Q-Hi	Sub2Q-Hi	Sub2Q-Hi	Sub2Q-Hi	Sub2Q-Hi	Sub2Q-Hi
	Sub2Q-A3	Sub2Q-A3	Sub2Q-A3	Sub2Q-A3	Sub2Q-A3	Sub2Q-A3
	Sub2Q-A2	Sub2Q-A2	Sub2Q-A2	Sub2Q-A2	Sub2Q-A2	Sub2Q-A2
	Sub2Q-A1	Sub2Q-A1	Sub2Q-A1	Sub2Q-A1	Sub2Q-A1	Sub2Q-A1

Activities Performed

Setup

Preliminary tests with the typical manufacturer-recommended burner setup were conducted to verify ignition of the burner on house gas and to determine typical chamber temperatures at various firing rates on house gas and cleaned gas, fuel and oxygen delivery pressures, the functionality of the blending station (by switching between the different gases), the functionality of the continuous emissions analyzers, and the functionality of the data acquisition system.

Continuous Tests – Constant Chamber Temperature

The continuous tests with constant chamber temperature measured how the controller responds, i.e., how the firing rate varies, when various "substitute" gases are fired with a system with a fixed operating condition with the burner tuned for a particular "adjust" gas. These tests are useful for predicting how a system will respond when there is feedback control.

The test plan was to calibrate the continuous emissions analyzers, fire the burner on house gas, bring the test chamber up to an operating condition with a chamber temperature of about 2450°F, switch to an "adjust" gas, tune the burner on the "adjust" gas by adjusting the oxygen/fuel ratio, and connect the temperature controller to the oxygen control valve. Next was to allow the firing rate to settle and then collect firing rate and emissions data for twenty minutes. The blending station was then switched to one of the "substitute" gases. The emissions were allowed to settle and then firing rate and emissions data were collected for twenty minutes. This series of switching gases and collecting data was repeated with the nine other "substitute" gases. The sampling trains for the continuous emission analyzers were purged as needed between "substitute" gases. The calibration of the continuous emissions analyzers was then checked.

The above process was repeated for the second "adjust" gas and all 10 "substitute" gases, and then repeated again with the third "adjust" gas and all 10 "substitute" gases.

For all of the above sequences with constant chamber temperature, the response of the controller's performance in terms of firing rate was recorded with the emissions data at 5 second intervals.

Continuous Tests – Constant Firing Rate

The continuous tests with constant firing rate measured how the system responds, i.e., how the chamber temperature varies, when various "substitute" gases are fired at a fixed rate with the burner tuned for a particular "adjust" gas. These tests are useful for predicting how a system will respond when there is no feedback control.

The test plan was to calibrate the continuous emissions analyzers, fire the burner on house gas, bring the test chamber up to an operating temperature of about 2450°F, switch to an "adjust" gas, tune the burner on the "adjust" gas by adjusting the oxygen/fuel ratio, and set the firing rate to around 75% of the burner nominal rated capacity (1,125,000 Btu/hr) by manually setting the oxygen control valve. Next was to allow the chamber temperature to settle somewhat and then collect chamber temperature and emissions data for twenty minutes. The blending station was then switched to one of the "substitute" gases. The emissions were allowed to settle and then chamber temperature and emissions data were collected for twenty minutes. This series of switching gases and collecting data was repeated with the nine other "substitute" gases. The sampling trains for the continuous emission analyzers were purged as needed between "substitute" gases. The calibration of the continuous emissions analyzers was then checked.

The above process was repeated for the second "adjust" gas and all 10 "substitute" gases, and then repeated again with the third "adjust" gas and all 10 "substitute" gases.

For all of the above sequences with constant firing rate, the response of the system's performance in terms of chamber temperature was recorded with the emissions data at 5 second intervals.

Results

Continuous Tests – Constant Chamber Temperature

The major results from the continuous tests with constant chamber temperature are the emissions and the fuel flow rate (the controller's response) when the burner is tuned for a particular "adjust" gas, and the fuel is switched to various "substitute" gases. Figure 75 through Figure 86 show the emissions and firing rate data over the 20 minute data collection intervals for each of the three "adjust" gas tunings separately. Figure 47 through Figure 90 show the affect of Wobbe Number on emissions and firing rate data for the three different tunings combined.

Continuous Tests – Constant Firing Rate

The major results from the continuous tests with constant firing rate are the emissions and the chamber temperature (the system's response) when the burner is tuned for a particular "adjust" gas, and the fuel is switched to various "substitute" gases. Figure 91 through Figure 102 show the emissions and chamber temperature data over the 20 minute data collection intervals for each of the three "adjust" gas tunings separately. Figure 103 through Figure 106 show the affect of Wobbe Number on emissions and chamber temperature data for the three different tunings combined.

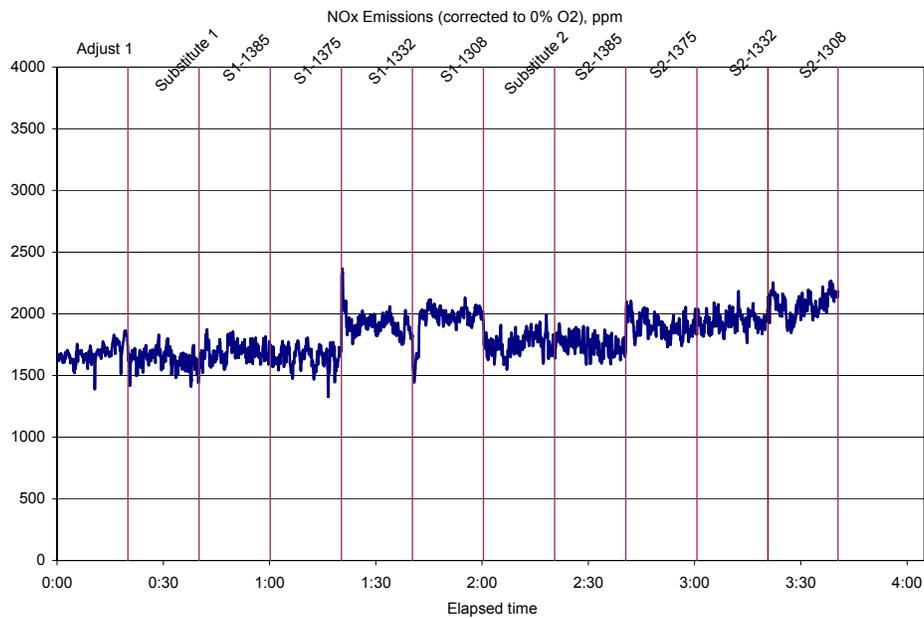


Figure 112. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Chamber Temperature with Burner Tuned for Adjust 1

(Corrected to 0% O₂)

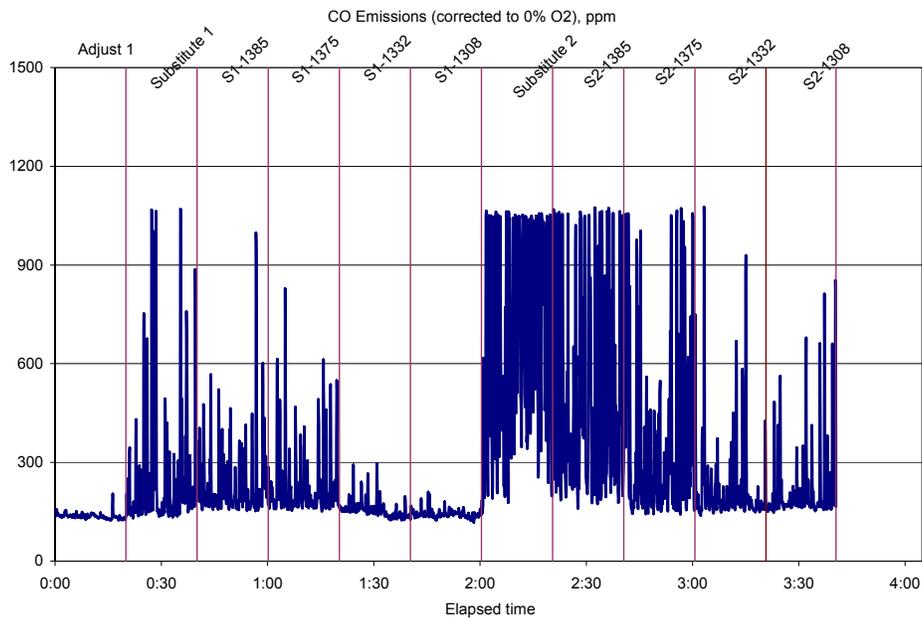


Figure 113. CO Emissions for All Substitute Gases for Continuous Testing with Constant Chamber Temperature with Burner Tuned for Adjust 1

(Corrected to 0% O₂)

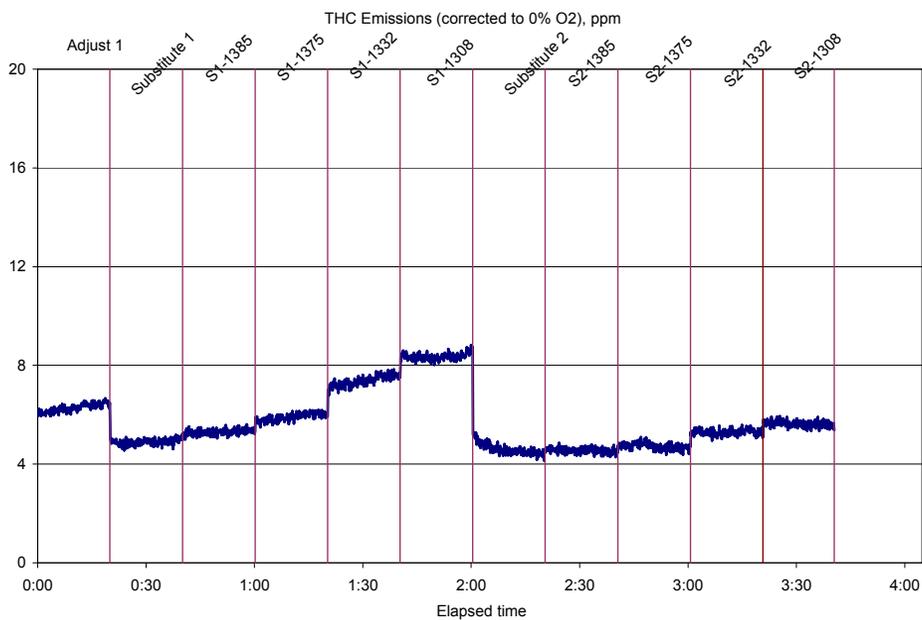


Figure 114. THC Emissions for All Substitute Gases for Continuous Testing with Constant Chamber Temperature with Burner Tuned for Adjust 1

(Corrected to 0% O₂)

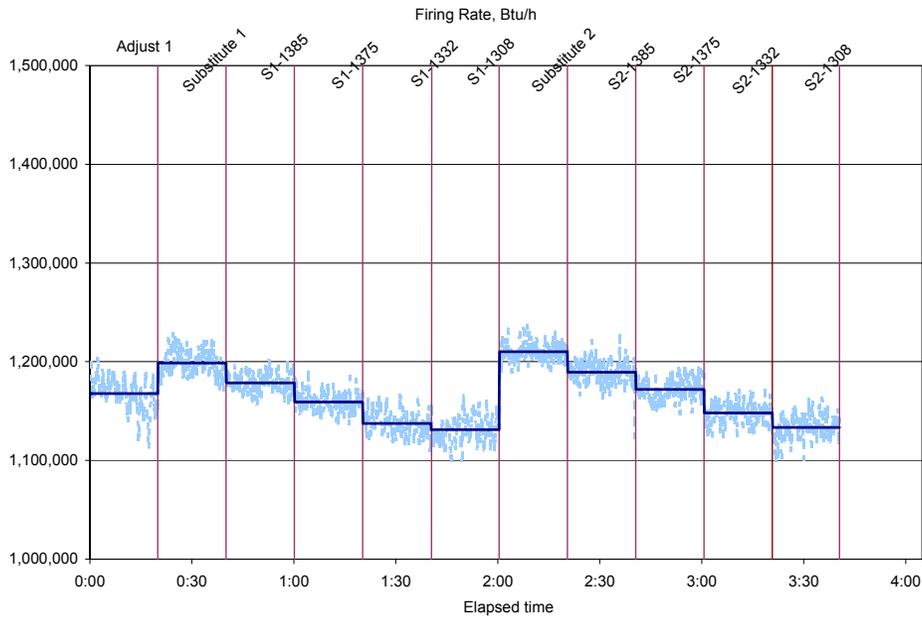


Figure 115. Firing Rate for All Substitute Gases for Continuous Testing with Constant Chamber Temperature with Burner Tuned for Adjust 1

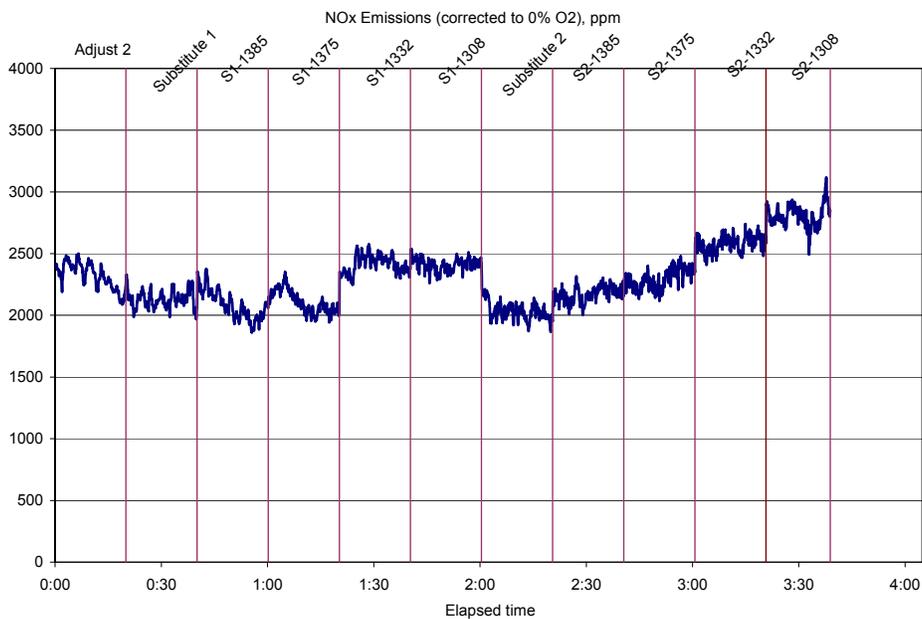


Figure 116. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Chamber Temperature with Burner Tuned for Adjust 2

(Corrected to 0% O₂)

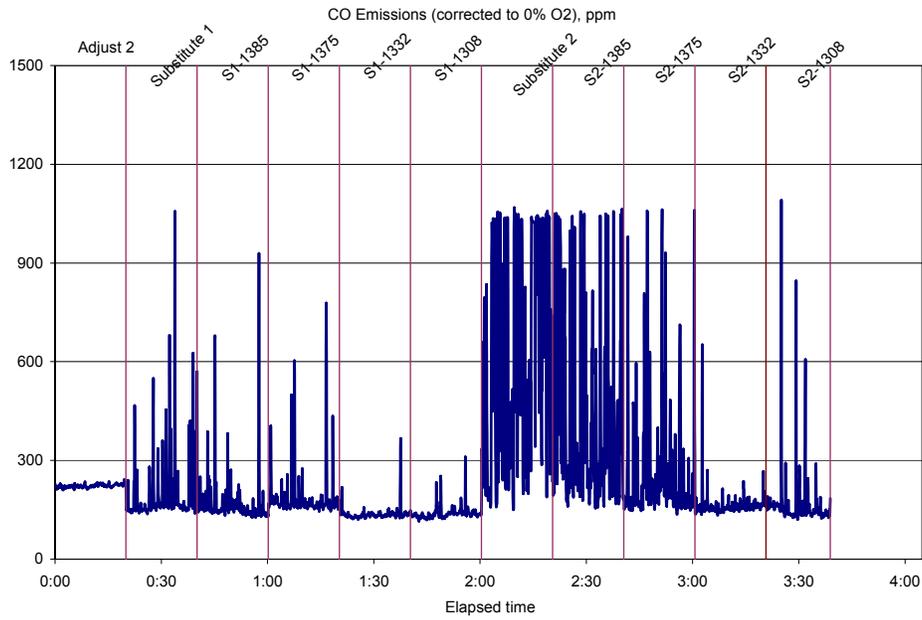


Figure 117. CO Emissions for All Substitute Gases for Continuous Testing with Constant Chamber Temperature with Burner Tuned for Adjust 2

(Corrected to 0% O₂)

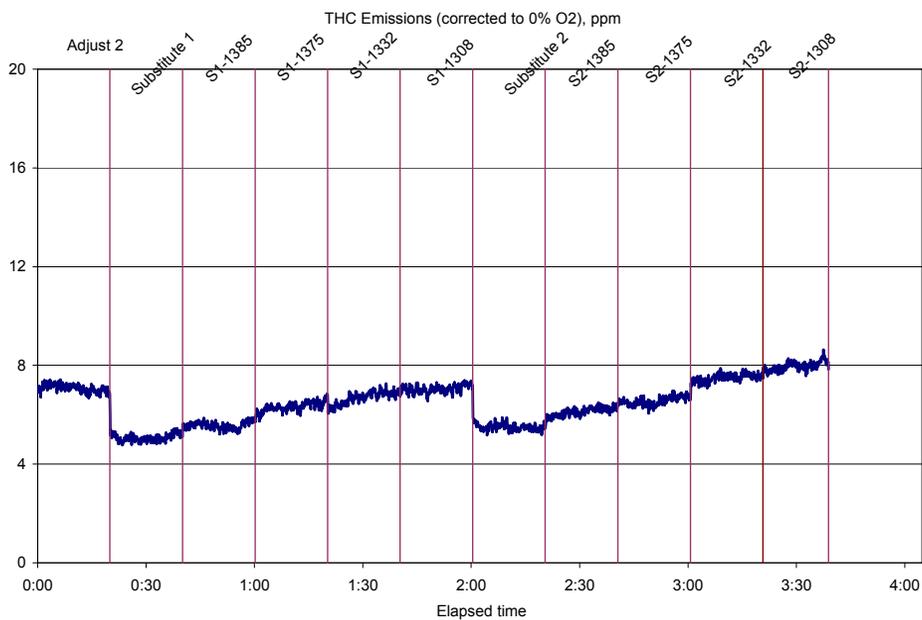


Figure 118. THC Emissions for All Substitute Gases for Continuous Testing with Constant Chamber Temperature with Burner Tuned for Adjust 2

(Corrected to 0% O₂)

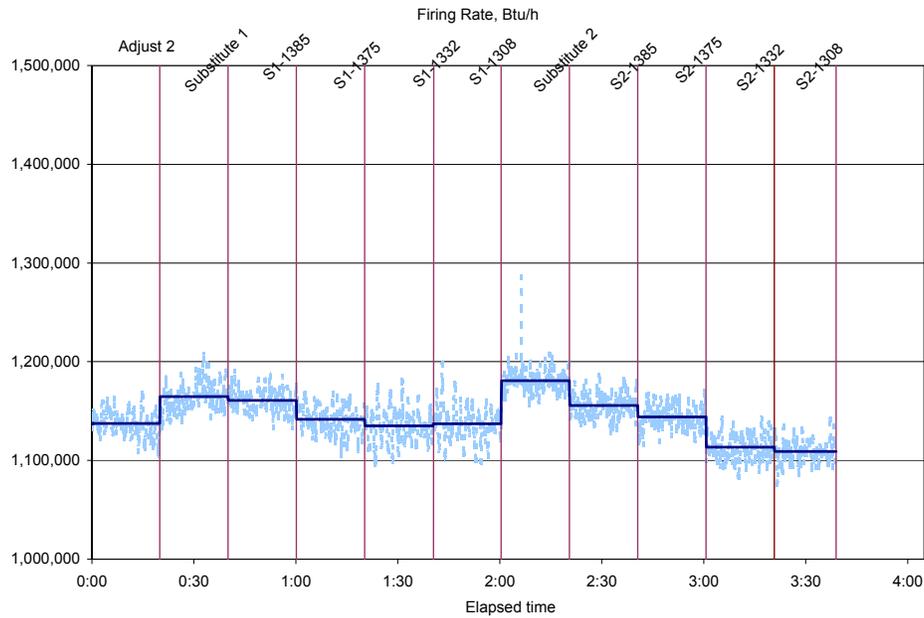


Figure 119. Firing Rate for All Substitute Gases for Continuous Testing with Constant Chamber Temperature with Burner Tuned for Adjust 2

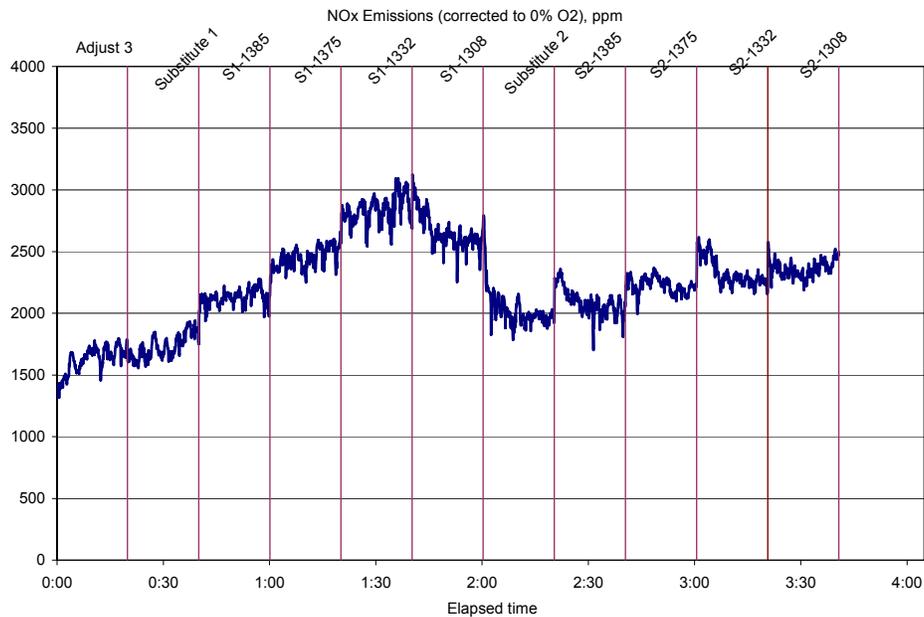


Figure 120. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Chamber Temperature with Burner Tuned for Adjust 3

(Corrected to 0% O₂)

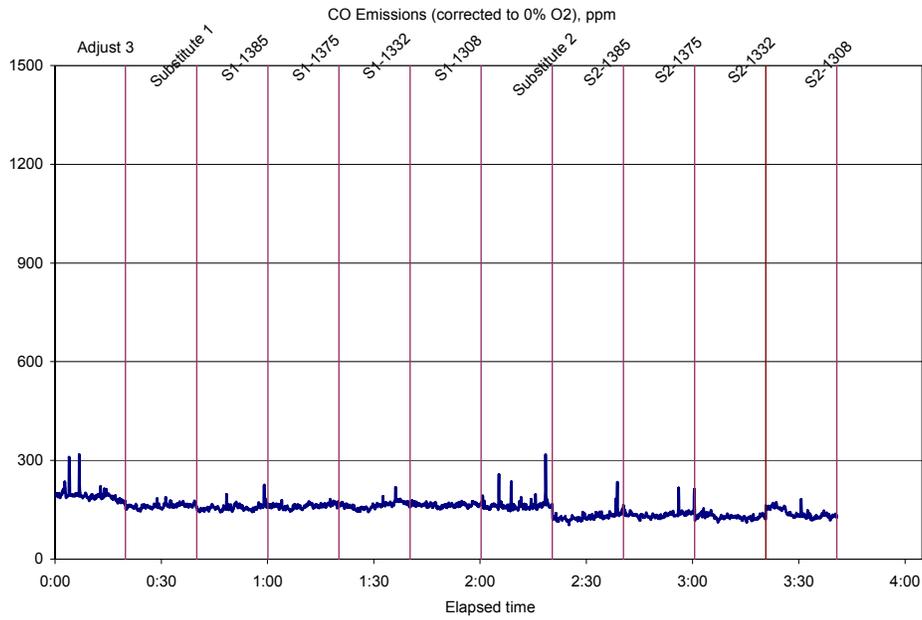


Figure 121. CO Emissions for All Substitute Gases for Continuous Testing with Constant Chamber Temperature with Burner Tuned for Adjust 3

(Corrected to 0% O₂)

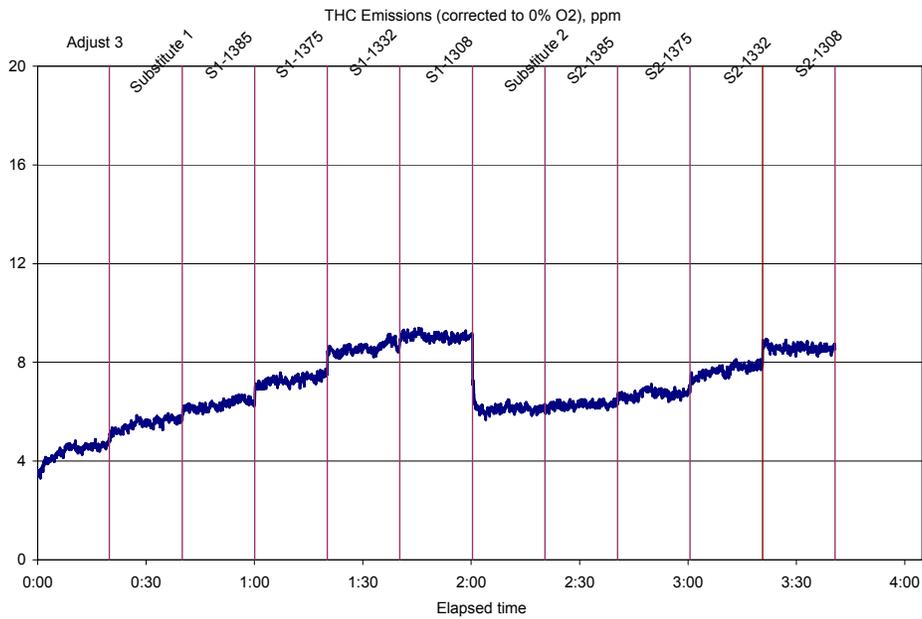


Figure 122. THC Emissions for All Substitute Gases for Continuous Testing with Constant Chamber Temperature with Burner Tuned for Adjust 3

(Corrected to 0% O₂)

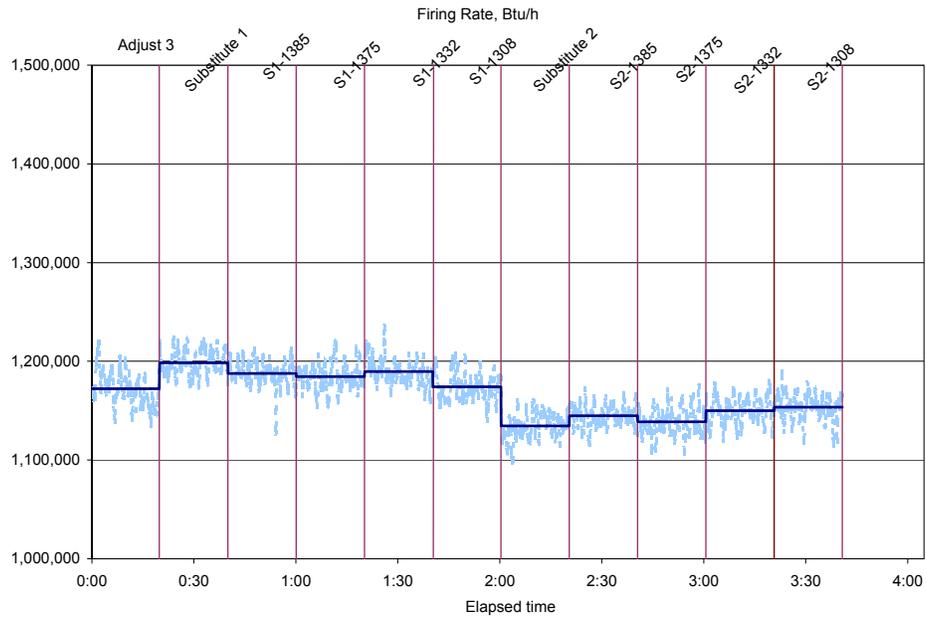


Figure 123. Firing Rate for All Substitute Gases for Continuous Testing with Constant Chamber Temperature with Burner Tuned for Adjust 3

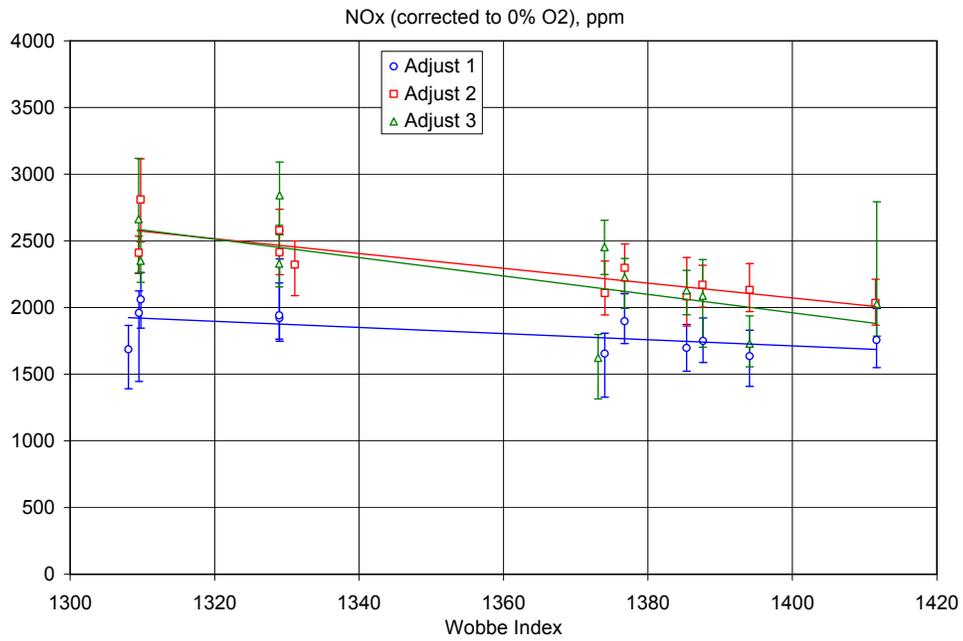


Figure 124. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Chamber Temperature

(Corrected to 0% O₂)

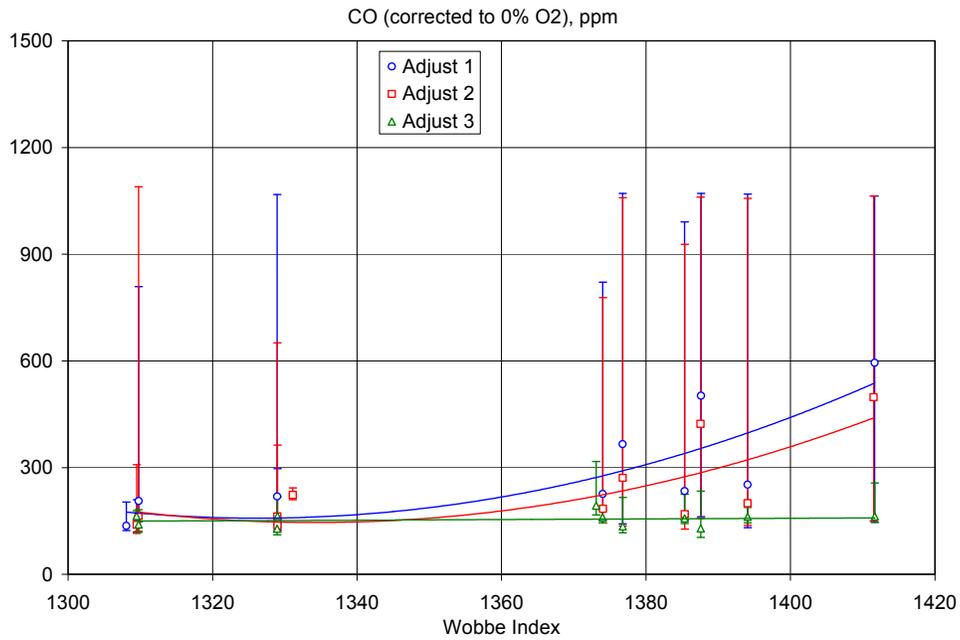


Figure 125. CO Emissions for All Substitute Gases for Continuous Testing with Constant Chamber Temperature

(Corrected to 0% O₂)

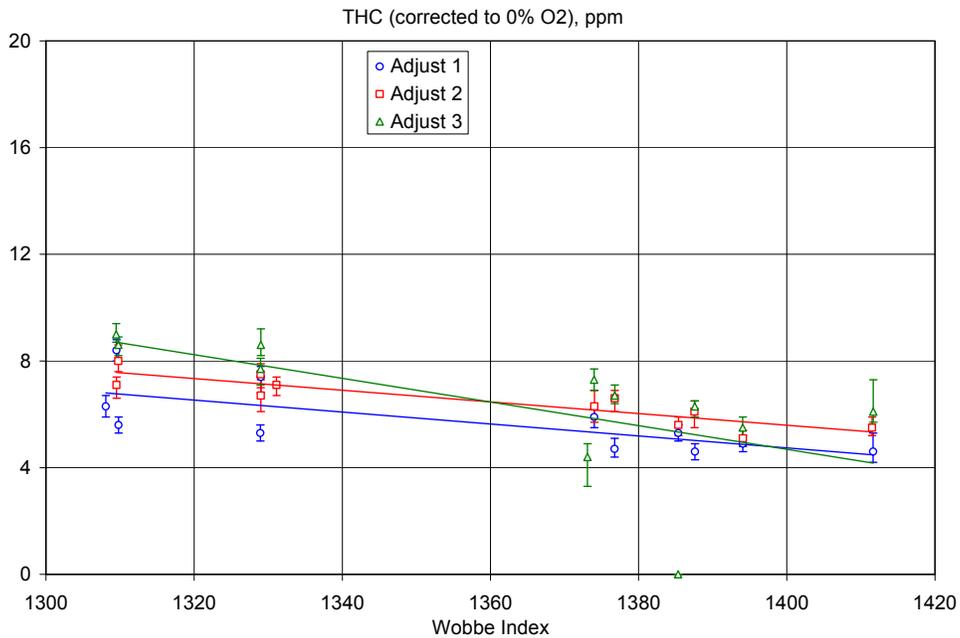


Figure 126. THC Emissions for All Substitute Gases for Continuous Testing with Constant Chamber Temperature

(Corrected to 0% O₂)

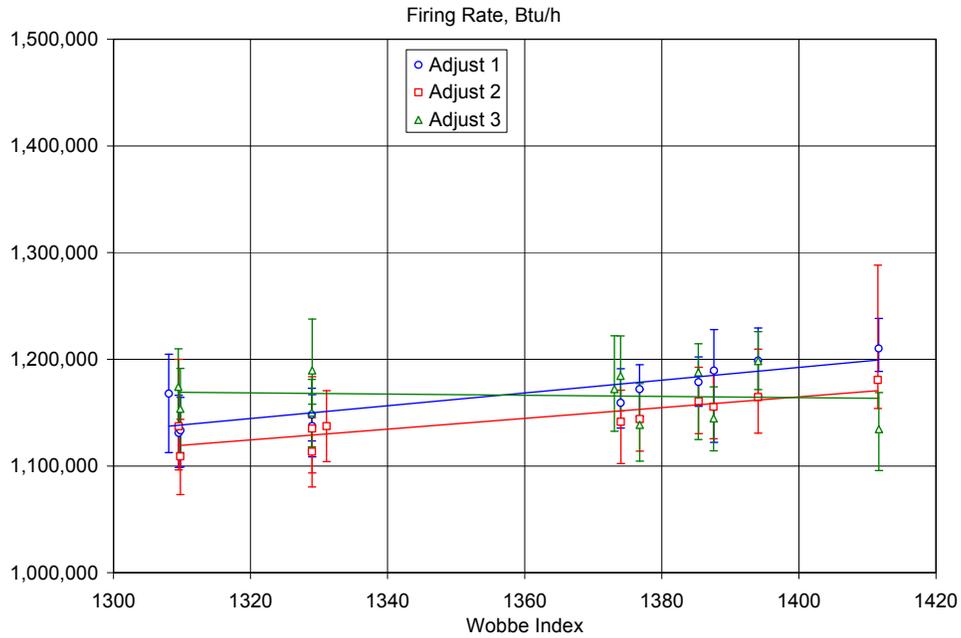


Figure 127. Firing Rate for All Substitute Gases for Continuous Testing with Constant Chamber Temperature

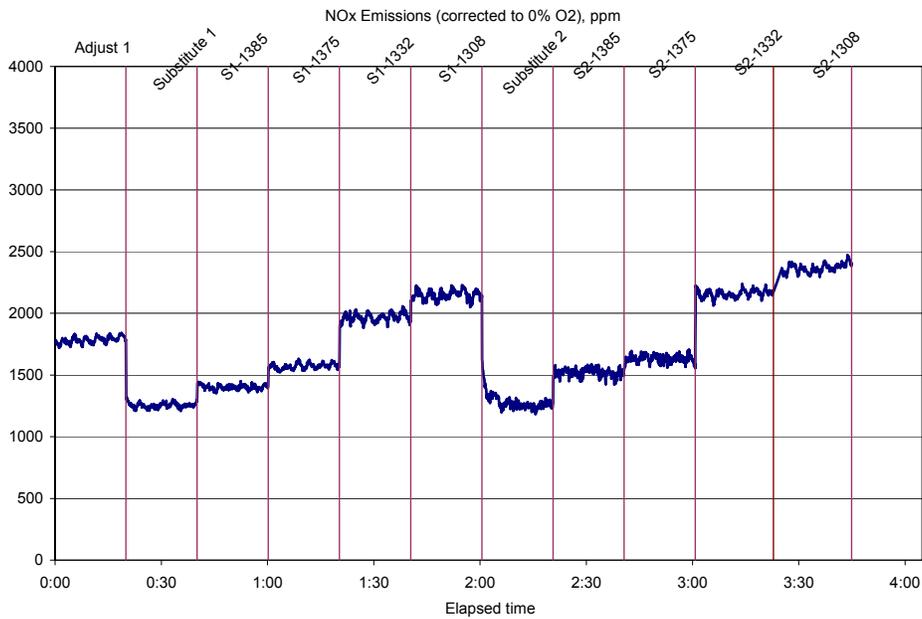


Figure 128. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 1

(Corrected to 0% O₂)

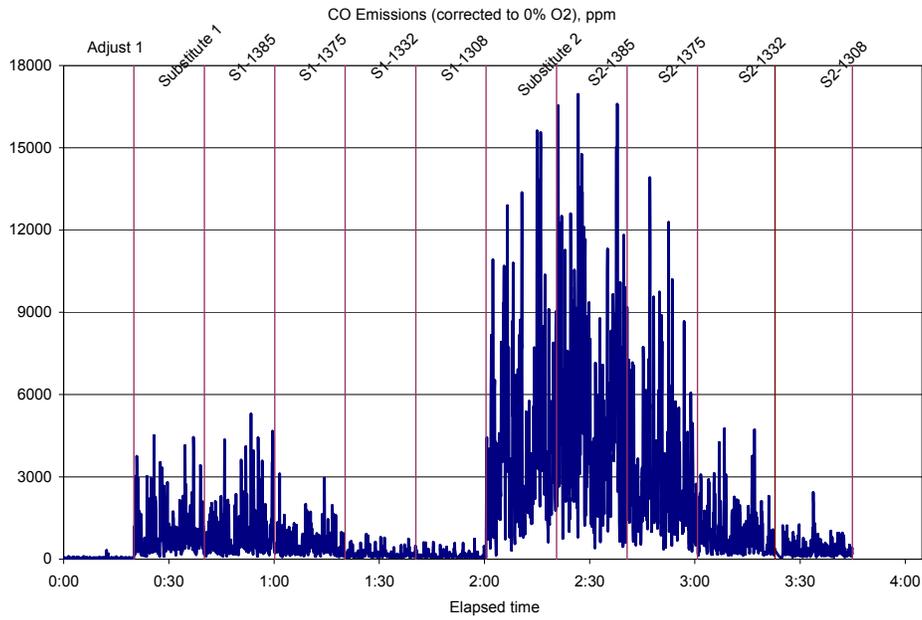


Figure 129. CO Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 1

(Corrected to 0% O₂)

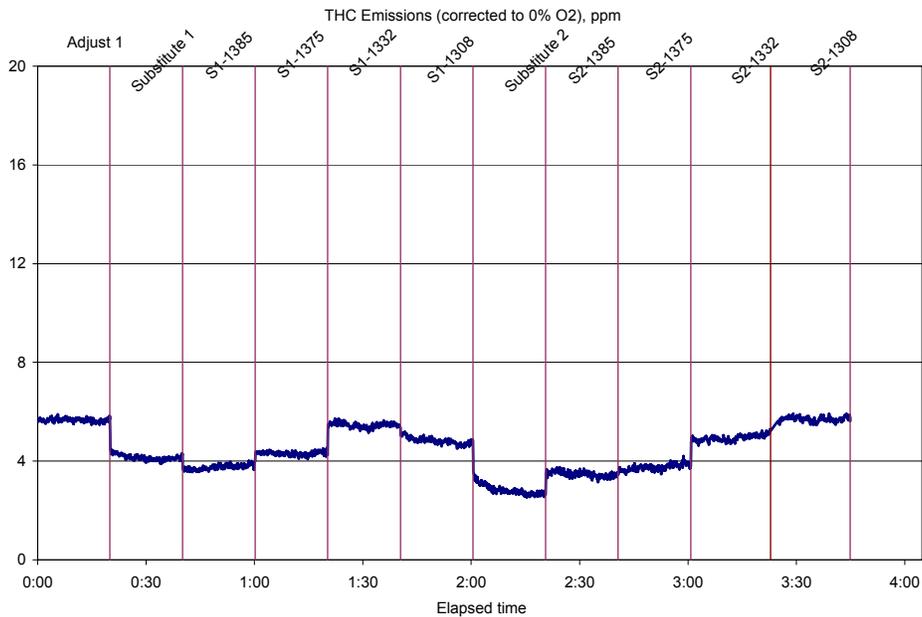


Figure 130. THC Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 1

(Corrected to 0% O₂)

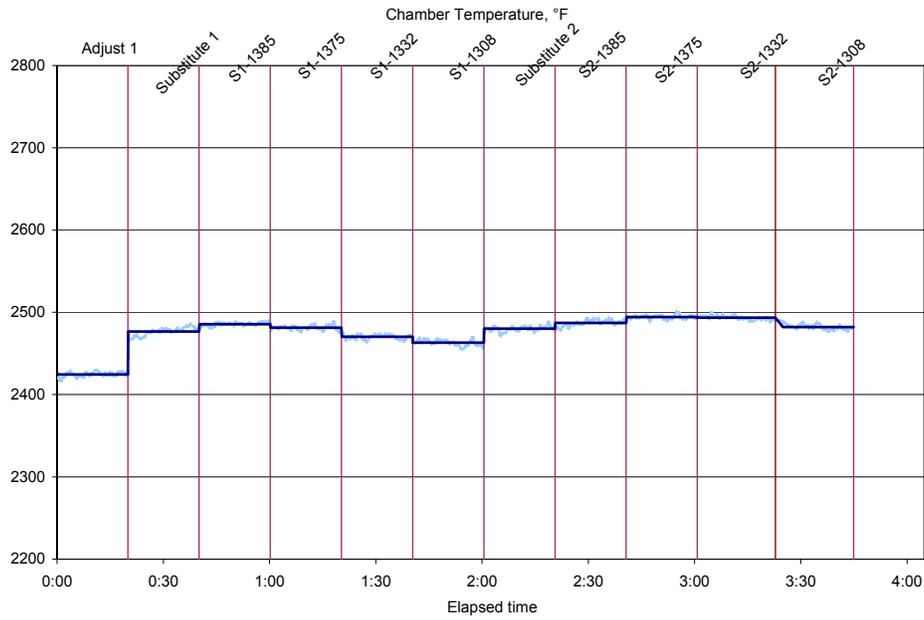


Figure 131. Chamber Temperature for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 1

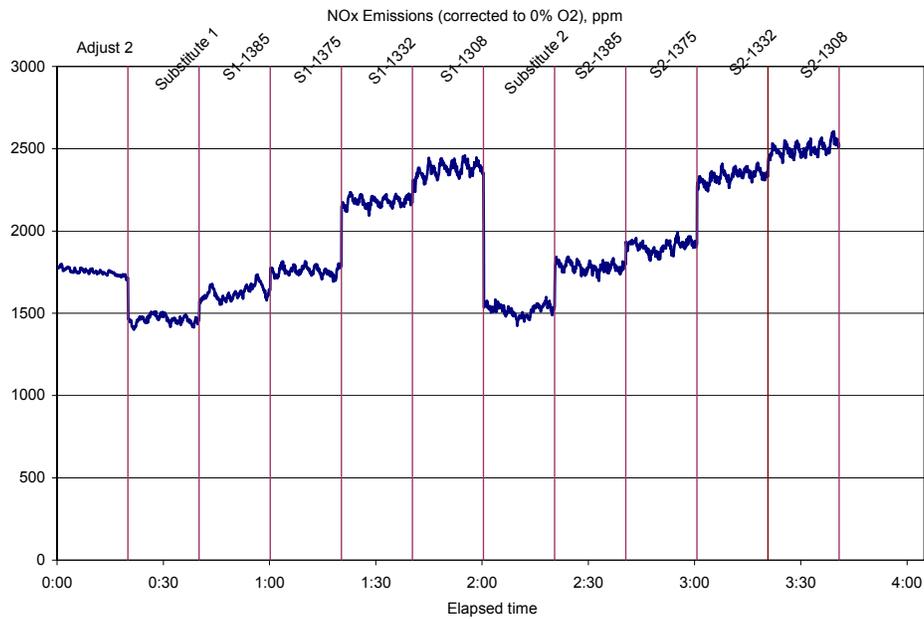


Figure 132. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 2

(Corrected to 0% O₂)

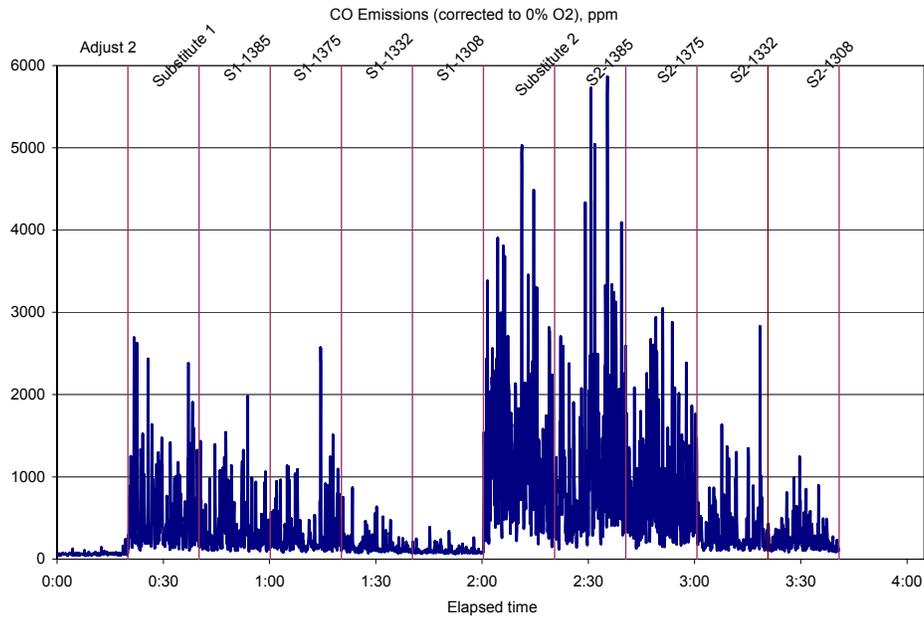


Figure 133. CO Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 2

(Corrected to 0% O₂)

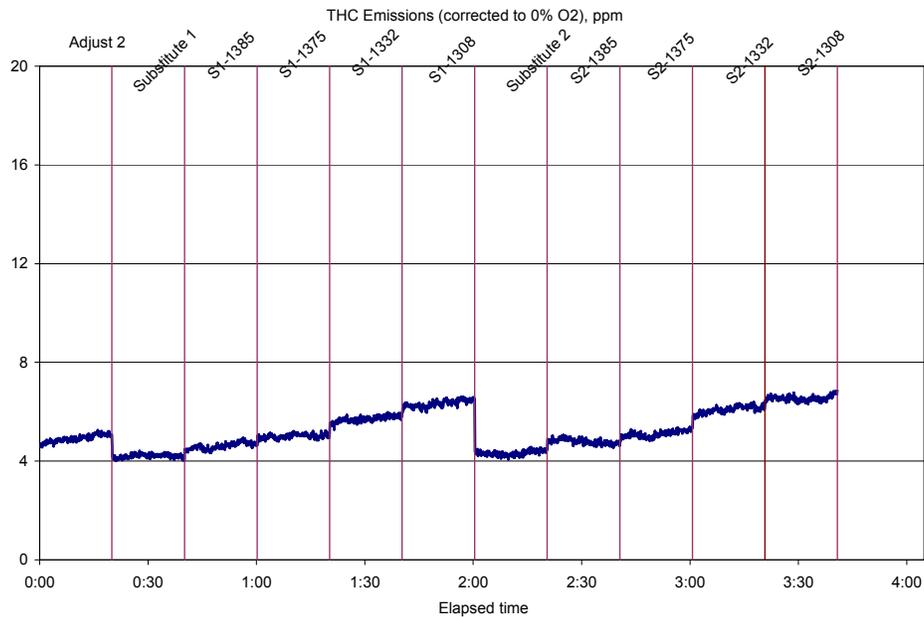


Figure 134. THC Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 2

(Corrected to 0% O₂)

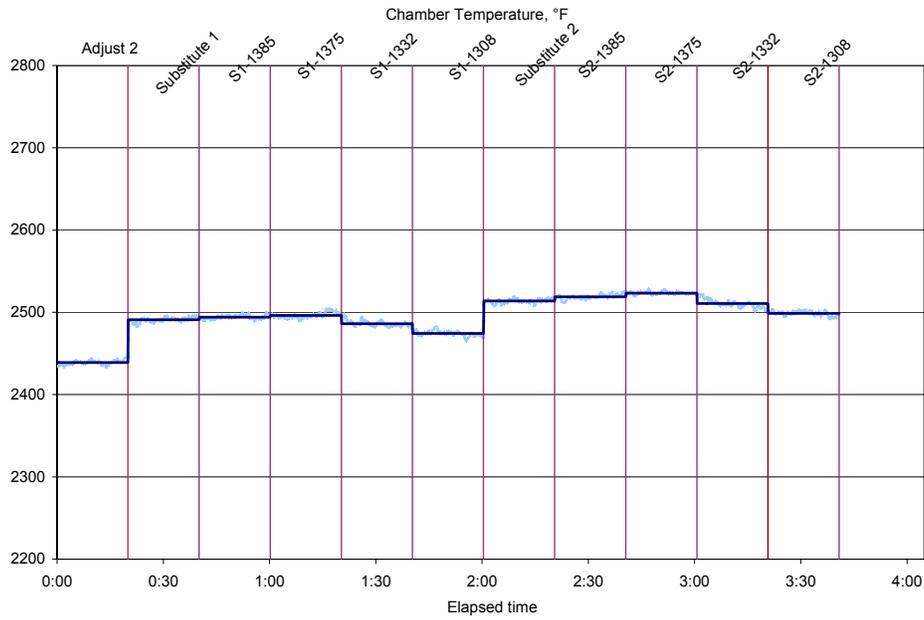


Figure 135. Chamber Temperature for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 2

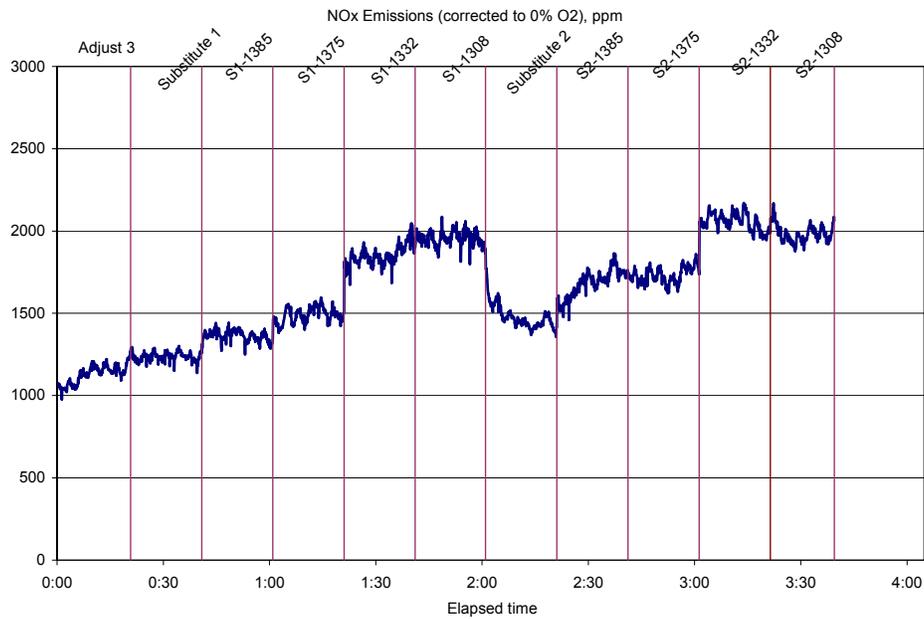


Figure 136. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 3

(Corrected to 0% O₂)

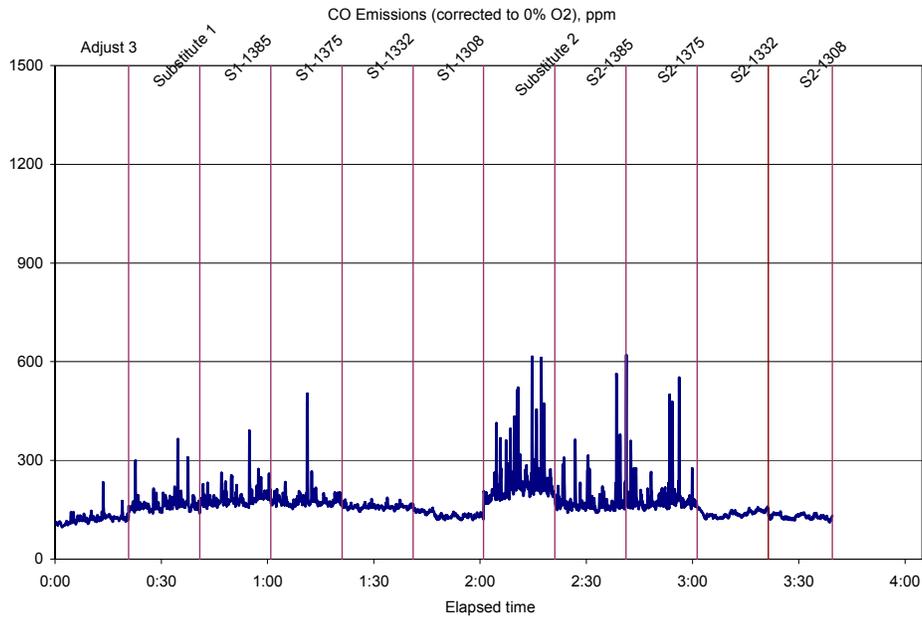


Figure 137. CO Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 3

(Corrected to 0% O₂)

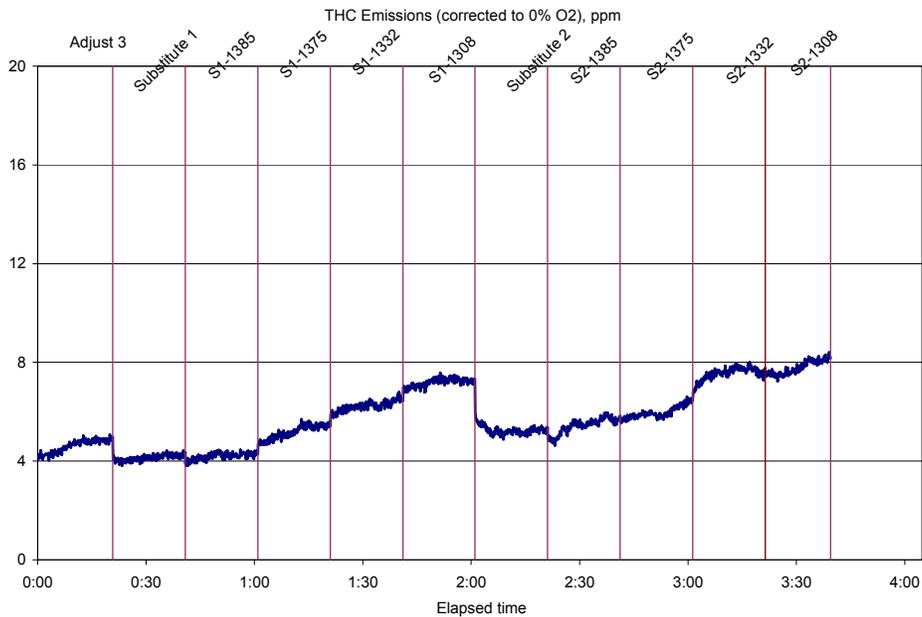


Figure 138. THC Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 3

(Corrected to 0% O₂)

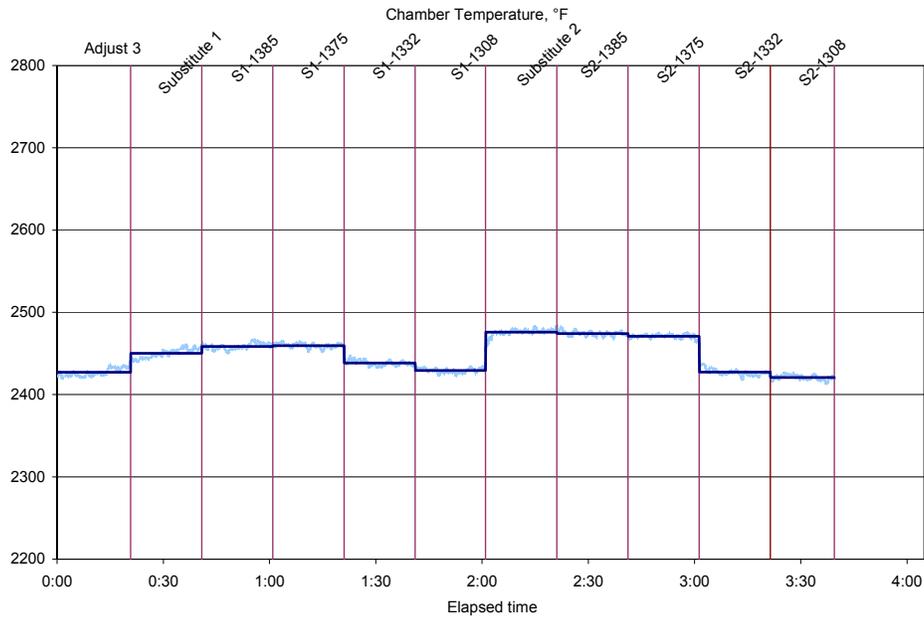


Figure 139. Chamber Temperature for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 3

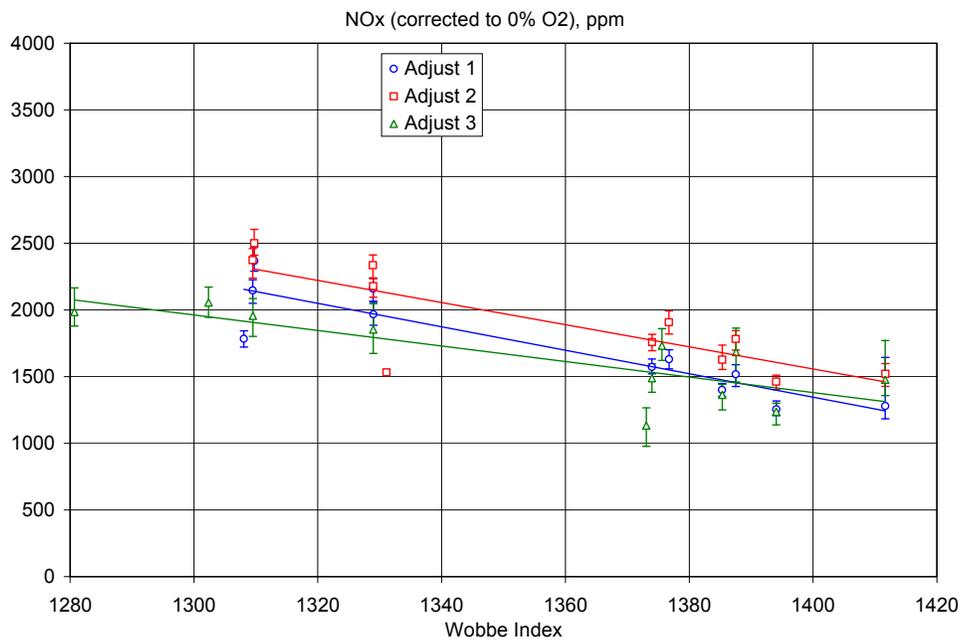


Figure 140. NO_x Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 0% O₂)

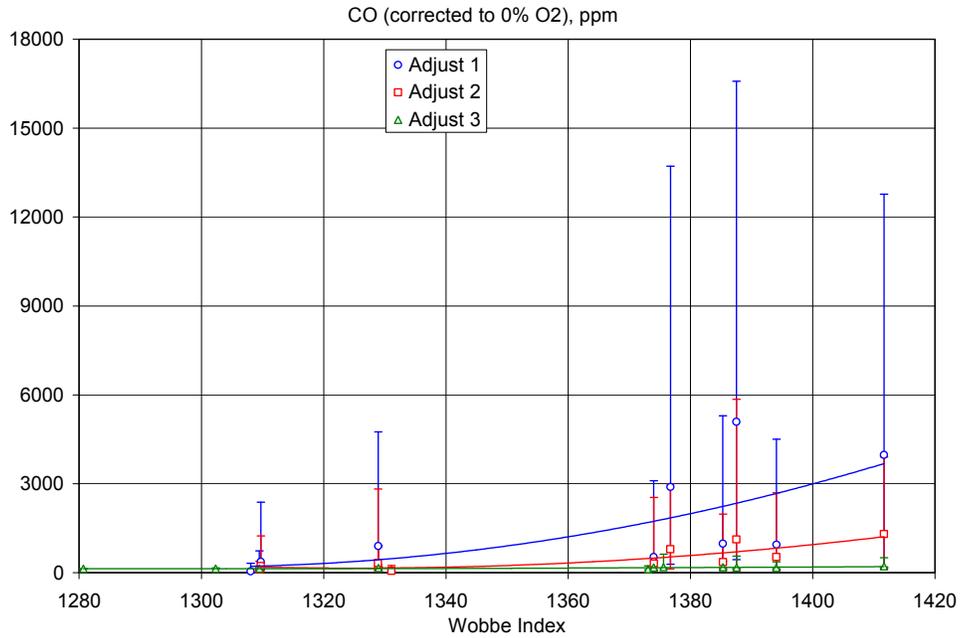


Figure 141. CO Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 0% O₂)

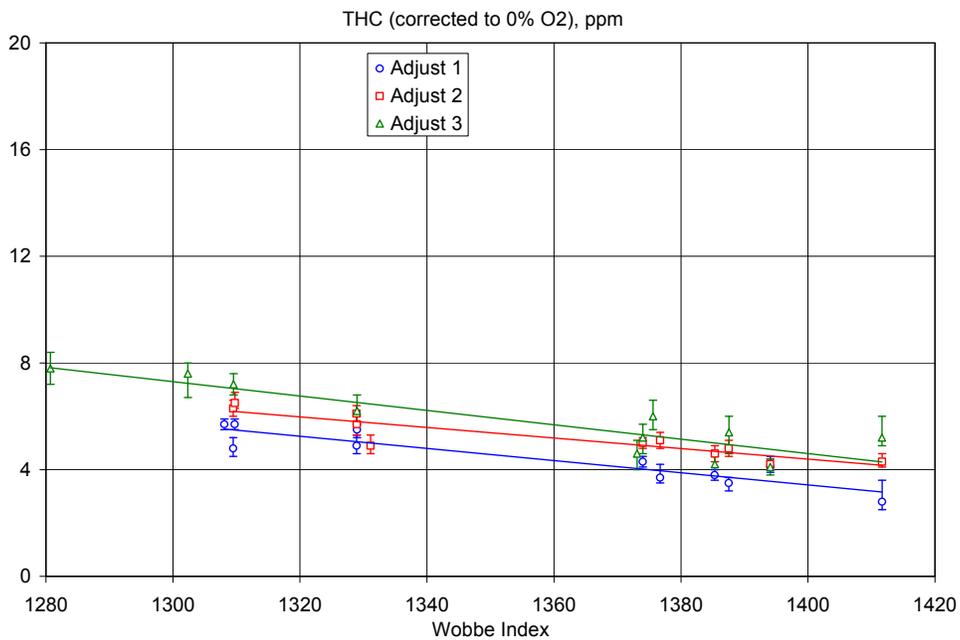


Figure 142. THC Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 0% O₂)

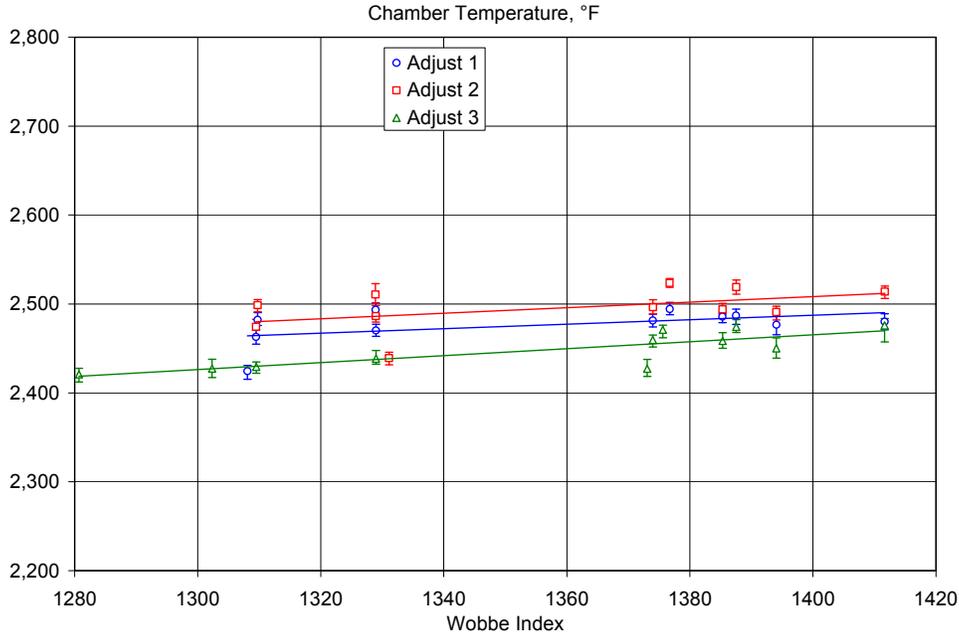


Figure 143. Chamber Temperature for All Substitute Gases for Continuous Testing with Constant Firing Rate

Calculations

The equation below is the linear correction used to approximately cancel out the analyzer drift;

$$X_{corr} = X_{meas} - \left((Zero\ drift) + (Span\ drift) \frac{X_{meas}}{Span\ value} \right) \frac{T_1}{T_2},$$

where X_{corr} is the corrected emissions value, X_{meas} is the measured value, the drift values are as labeled, T_1 denotes the time elapsed from the previous analyzer calibration, and T_2 denotes the time from the previous analyzer calibration to the next analyzer calibration.

After this correction, the emissions were normalized to 0%O₂ using the formula,

$$X_{0\%O_2} = X_{corr} \left(\frac{100\% - 0\%}{100\% - \%O_2} \right),$$

where $X_{0\%O_2}$ is the final value after both the correction for drift and the normalization to a common %O₂ in the exhaust. This formula uses 100% as the minuend in the numerator and denominator of the normalizing ratio instead of 21% because of the use of oxygen instead of air as the oxidant for combustion. The normalization basis used here is 0%O₂ (the subtrahend in the numerator) instead of 3%O₂ due to industry conventions.

The Firing Rate was calculated from the actual flow data. The heating value calculation followed the ASTM D 3588 – 98(03) standard at 70°F.

Analysis and Conclusions

The charts and data are analyzed in the same sections below as appear in the Results section.

Continuous Tests – Constant Chamber Temperature

For all three "adjust" gas tunings, "substitute" gases with higher Wobbe indexes yielded slightly lower NO_x and THC emissions. For the two lower Wobbe "adjust" gas tunings, "substitute" gases with higher Wobbe indexes yielded significantly higher CO emissions. For the highest Wobbe "adjust" gas tuning, "substitute" gases with higher Wobbe indexes had virtually no effect on CO emissions.

For the two lower Wobbe "adjust" gas tunings, the firing rate trended higher with "substitute" gases with higher Wobbe indexes. This may have been due to incomplete combustion as indicated by the higher CO emissions. For the highest Wobbe "adjust" gas tuning, the firing rate tended to inversely follow the Wobbe index. This was not unexpected since the heat input to the burner is directly tied to Wobbe index.

Continuous Tests – Constant Firing Rate

The NO_x, CO, and THC emissions followed the same trend with Wobbe index as with the constant chamber temperature tests (lower NO_x and THC for higher Wobbe indexes and higher CO for higher Wobbe indexes except for the highest Wobbe "adjust" gas tuning).

The chamber temperature tended to follow the Wobbe index. This was not unexpected since the heat input to the burner is directly tied to Wobbe index.

The low Wobbe numbers for Adjust3 were due to a shortage of ethane gas. This did not affect the trends observed in the data.

Selected Photographs



Figure 144. Oxy-Gas Burner



Figure 145. Test Chamber



Figure 146. Continuous Emissions Analyzers



Figure 147. Blending Station

**NATURAL GAS IN CALIFORNIA: ENVIRONMENTAL IMPACTS
AND DEVICE PERFORMANCE**

**Industrial Burner Evaluations:
Radiant Tube Burner Interchangeability
Test Report**

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For

California Energy Commission

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Objective

The purpose of the radiant tube burner interchangeability tests is to assess the performance of a radiant tube burner and industrial control system when fired with different natural gas compositions. The burner's performance when firing selected Adjust Gases was compared with its performance when firing selected Substitute Gases with and without different levels of nitrogen ballasting.

Approach

The tests used a laboratory setup intended to mimic industrial operating conditions. The burner was first tuned to operate with an "adjust" gas composition. Ignition tests and operating/switching tests were then performed. During these tests several "substitute" gas compositions were fired in sequence on the burner. Ignition tests were performed from the same start conditions with an approximately 200°F furnace, and operating tests were performed with the furnace maintained at 1600°F by a high/low firing control scheme was selected. These tests were then repeated with the other "adjust" gases as a basis.

Table 23. Performance Metrics for the Infrared Burner

BASIC PERFORMANCE METRICS
Pollutant emissions, including ultrafine particles
Flame shape
Temperature distribution on the radiant tube
Controller response during steady operation
Rate of temperature rise during ignition

Test Apparatus

The radiant tube burner used for this test was a North American Evenglow 4725-3-E rated for 300,000 Btu/hr. It and the rest of the experimental setup are shown in Figure 37 through Figure 182. The burner fires into a 4-inch diameter radiant U-tube that extends approximately 59 inches from the inner wall of the furnace to its turn. The U-tube is one of three radiant tubes inside of GTI's full size heat treat furnace; it is the north U-tube, with supplementary heat available from a second U-tube installed in the south half of the furnace, plus a 7" diameter single-ended radiant tube and burner installed above and between the U-tubes.

The air supply for the furnace is coupled to the fuel flow through a North American Bulletin 7218-1 air/gas ratio regulator. The air flow is controlled by using a motorized valve to select “high fire” or “low fire”. The setpoint temperature is entered into a Honeywell UDC3000 Universal Digital Controller; a hysteresis, or deadband, range of 0.5% (8°F) above or below the setpoint was selected. A Honeywell UDC2000 Mini-Pro Universal Digital Controller in Limit Control Mode was used as the high limit controller.

A separate fuel supply line was added upstream of the air/gas ratio regulator for the subject burner, and a solenoid shutoff valve for the new line was connected in parallel to the existing gas solenoid valve on the furnace. This separated its fuel supply from the south burner, which always fired GTI’s house natural gas. Simulated natural gas compositions from a custom blending station were regulated to 2 psig upstream of the subject burner’s air/fuel ratio regulator. The burner adjustment was to 3% O₂ in the exhaust: a butterfly valve adjusted the air flow, and fuel flow was set using a limiting orifice. The high firing rate was 250,000 Btu/hr for two test cases and 150,000 Btu/hr for the other. The burner firing House Gas was purposely adjusted to match the subject burner, with the intent that any observed effect would be approximately twice as large as is recorded for these experiments.

The air-to-fuel ratio was different at low fire—for all of the Adjust Gases the low-fire regime, with firing rate 80,000 or 110,000 Btu/hr, had approximately 1.8% to 2% O₂ in the exhaust. The burner was spark-ignited and the spark was manually shut off as soon as ignition was achieved. Industry practice would be to either operate a flame monitor or spark continuously until the furnace temperature reached 1400°F; instead periodic visual checks were made; the continuous spark disrupts the signals for data collection. Instruments used to perform this test are listed in Table 3; they will be described below.

The measured compositions of the fuel gas supplied from the blending station to the burner were recorded using National Instruments Field Point Modules. The fuel gas compositions were commanded through a separate program that was dedicated to the blending station and its user interface. The radiant tube temperature distribution was recorded using type K thermocouples placed at selected locations along the tube, and the exhaust temperature was measured using a type R thermocouple placed in the exhaust stack.

The temperature data and the emissions data were collected simultaneously. A 1/4” diameter stainless steel probe was inserted just downstream of the type R thermocouple, and the emissions sample was drawn from inside the stack. About 3 to 5 scfh of the exhaust sample traveled to the combustion emissions analyzers, and another 17 to 23 scfh (8 to 11 lpm) of exhaust traveled through the Dekati fine particle sampler to be conditioned and diluted prior to size separation and counting in the TSI devices. Dilution ratio was calculated from the pressure drop across parts inside of the Dekati, but the temperature of the fuel gas varied by as much as 200°C, which affects the density of the flow and thus the accuracy of the flow measurement. The gas chromatograph was used to better measure the dilution ratio; the method is described in a later section.

Table 24. Summary of Test Instruments

Instrument	Parameter	Range	Accuracy
LabView software, National Instruments Field Point Modules, and laptop	Datalogging	—	—
Opto 22 Data Acquisition System	Datalogging	—	—
Type K thermocouple	Radiant tube surface temperature	K up to 2282°F	Greater of 2°F or 0.4% of value
Type R thermocouple	Burner exhaust temperature	R 32°F to 2642°F	Greater of 1°F or 0.1% of value
Horiba PG-250 Portable Gas Analyzer	ppmv NO _x , % O ₂ % CO ₂ ppmv CO	Span gases: 197.8 ppmv NO _x 7.924% O ₂ 17.90% CO ₂ 144.3 ppmv CO	±2% full scale
Rosemount Analytical 400A	ppm THC	Span 79.7 ppm	1% full scale
Thermo Environmental 42C	ppm NO _x	0-0.05 ppm to 100 ppm	±0.4 ppb / 500 ppb
Rosemount Analytical 755	% O ₂	Span 3.92%	
Rosemount Analytical 880A	ppm CO	Span 830 ppm	1% full scale
Rosemount Analytical 880A	% CO ₂	Span 18.0%	1% full scale
Dekati Fine Particle Sampler	Sampling and dilution	Dilution ratio to be measured	To be measured
TSI Ultrafine condensation particle counter	Particle size and number	3 nm-20µm	±10%
Varian CP-4900 Gas Chromatograph	ppm CO ₂ , ppm O ₂	Depends on calibration gas; can detect as low as 1ppm	<0.5% relative standard deviation under constant conditions

Test Gases

The test gases were selected to match natural gas compositions distributed in California, and international compositions that may be imported into California. The compositions distributed in California are designated “Adjust Gases” and the burner was adjusted for optimum performance on each of them. The remaining gases are designated “Substitute Gases;” they were fired on the burner to compare performance with the Substitute Gases to performance with the Adjust Gases. Table 4 summarizes the gases used. Adjust 1 is representative of natural gas in the Sacramento area, Adjust 2 is an average value for the state of California, and Adjust 3 is representative of natural gas in the Southern California area. The two Substitute Gases, Sub 1 and Sub 2, were selected from a set of potential LNG compositions available to California; Sub 1 has a relatively low Wobbe Number (1408) compared with the other LNG compositions, and Sub 2 has a relatively high Wobbe Number (1425). Because it is possible that these gases will be conditioned with nitrogen prior to distribution in California, additional compositions with nitrogen added to make the Wobbe Number match those of the selected adjust gases were also

test-fired. These are labeled in the table with “@####” where the numbers indicate the Wobbe number of the Substitute Gas when conditioned with the indicated amount of nitrogen. The values listed are the commanded values; actual values may fluctuate by around $\pm 2\%$ of the instrument’s full scale but remain near the commanded values.

Table 25. Summary of Test Gases

Name	Gas Composition, mol %							HHV	Wobbe
	C1	C2	C3	C4	C5+	N2	CO2		
Adjust 1	93.2	2.52	0.41	0.14	0.093	2.691	0.920	1010	1309
Adjust 2	94.5	2.55	0.42	0.14	0.094	1.361	0.931	1024	1332
Adjust 3	90.61	2.45	3.41	1.25	0.094	1.305	0.893	1094	1374
Sub 1	92.4	4.9	1.9	0.79	0.0	0.0	0.0	1099	1408
@1385	91.3	4.8	1.9	0.79	0.0	1.2	0.0	1086	1387
@1375	90.7	4.8	1.9	0.79	0.0	1.9	0.0	1080	1375
@1332	88.3	4.8	1.8	0.79	0.0	4.4	0.0	1053	1331
@1308	87.8	4.6	1.8	0.70	0.0	5.5	0.0	1036	1308
Sub 2	89.4	7.1	2.5	1.04	0.0	0.0	0.0	1131	1426
@1385	87.5	7.0	2.4	1.00	0.0	2.1	0.0	1106	1387
@1375	86.9	6.9	2.4	1.00	0.0	2.7	0.0	1098	1376
@1332	84.5	6.7	2.4	1.00	0.0	5.4	0.0	1070	1330
@1308	83.6	6.6	2.3	1.00	0.0	6.5	0.0	1057	1310

Test Schedule

The ignition tests were performed separately from the performance tests, because otherwise heat-up and cooldown time would be prohibitive. Figure 3 illustrates the schedule.

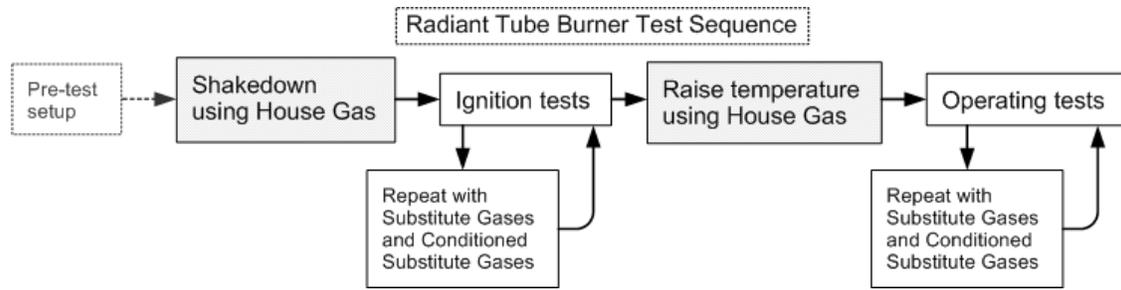


Figure 148. Test schedule for the radiant tube burner

Activities Performed

Firing Rate

The fuel use with different fuels is observed by recording the actual flow through the mass flow controllers used to simulate the selected LNG compositions.

Observation of Controller Response

Pressure changes in the mixing manifold of about $\pm 12\%$ occurred during switching from one gas composition to the next in a previous test for a different burner. With pressure variation upstream, the burner's transient response to rapid changes in gas composition could not be distinguished from the response to the pressure impulse. The controller response test was instead changed to measure the steady-state cycling of firing rate over at least five cycles; one cycle took approximately 20 minutes. This steady response was recorded for three different gas compositions, mostly to compare for fuel use and the total duration of high fire compared to low fire periods.

Exhaust Composition and Ultrafine Particle Emissions Measurements

With the burner firing and the controller maintaining a 1600°F ($\pm 8^{\circ}\text{F}$) furnace temperature, a $\frac{1}{4}$ " diameter probe was inserted near the base of the radiant tube exhaust stack to sample emissions at the exhaust flow velocity. Part of the flow was diverted to a Nafion dryer assembly and then to the emissions analyzers listed in Table 3. The remaining flow was diluted with nitrogen, cooled, and then sent to the ultrafine particle counter. The number of particles must be multiplied to account for dilution: to determine the dilution ratio, the $\%O_2$ and the $\%CO_2$ in the dry emissions were compared with the $\%O_2$ and the $\%CO_2$ from the diluted sample; the diluted sample was passed through a drying train prior to entering a gas chromatograph.

Ignition Tests

The ignition tests measure whether the burner lights and the rate of heating. Attempts to re-light, if there were any, were noted. The furnace was cooled to approximately 200°F between tests.

Tube Temperature Distribution

The temperature distribution on the radiant tube is one measure of burner performance. Radiation is the primary mode of heat transfer in a radiant tube furnace, so the more even the surface temperature of the heat source—the radiant tube—the more uniform the heat transfer to the parts. The temperature distribution along the tube was measured with seven thermocouples (visible in Figure 37 and Figure 38). The thermocouple placement is illustrated in Figure 150; distances are given from the interior of the furnace wall.

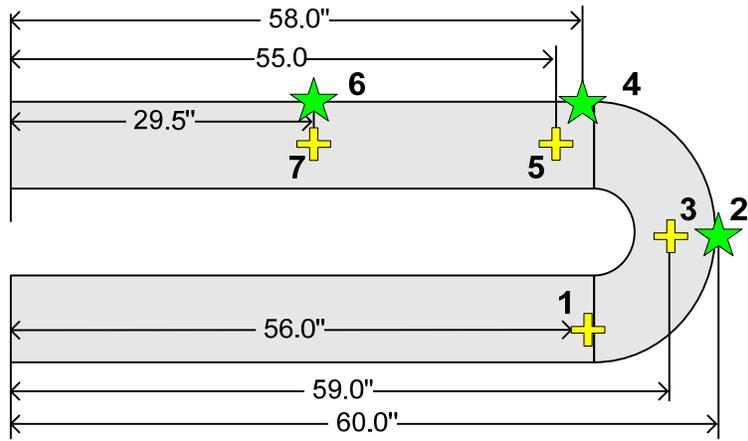


Figure 149. Thermocouple placement on the radiant U-Tube

Results

Data for each of the three tests, with the burner tuned for Adjust 1, Adjust 2, and Adjust 3, are presented in this section.

Continuous Test Results

During the continuous-firing tests, emissions data were collected either by hand every two minutes, or later during the testing electronically every 5 seconds. Ultrafine particle sampling took about four minutes per set of three samples (a set of 3 were averaged to one data point), and burner temperature and firing rate were automatically recorded every five seconds.

Firing Rate

The furnace control system switches between two rates: High Fire and Low Fire, to maintain the 1600°F setpoint. During the continuous test, at least one firing cycle was run using the Adjust Gas after having fully adjusted the burner, and at least one cycle of each of the Substitute Gases was run. Table 5 shows the average high and low firing rates of the burners for the different gas compositions. The tests for Adjust 1 and Adjust 3 were performed on the same day, and a higher firing rate was selected than when tuning to Adjust 2. These same data are also presented in Table 28 and Figure 4 as a percent difference with respect to the Adjust Gas.

Figure 5, through Figure 8 show the firing rate of the radiant tube burner during the entire test. In Figure 5, the grayed area indicates a time period when butane flow was not as expected. The flow was switched to Adjust 3 and the problem solved prior to continuing. Figure 152 shows the relative time spent at high and low fire during one period.

Table 26. Average High and Low Firing Rates over at Least 1 Cycle During Continuous Operation

Sub [Ⓢ] \ Adj [Ⓢ]	Average High and Low Firing Rate (Btu/hr)					
	Adjust 1		Adjust 2		Adjust 3	
	High	Low	High	Low	High	Low
Adjust	217,770	101,129	132,464	79,835	228,632	122,474
Sub1-1308	224,342	104,051	132,979	79,353	223,262	118,393
Sub2-1308	227,164	106,284	135,115	80,404	225,495	119,016

Sub2-1332	229,666	108,232	136,675	82,038	228,563	121,307
Sub1-1332	225,619	105,678	135,221	80,930	225,376	119,467
Sub1-1375	233,792	104,125	130,112	85,875	231,389	124,100
Sub2-1375	235,847	111,193	140,400	83,375	234,785	123,072
Sub1-1385	241,416	119,298	140,862	83,127	235,067	126,030
Sub2-1385	236,948	110,617	141,807	84,909	235,779	125,404
Sub1	245,713	114,022	141,940	84,390	238,342	129,715
Sub2	241,475	112,186	144,980	87,615	235,167	127,644

Table 27. Percent Difference from Adjust Firing Rate over at Least 1 Cycle During Continuous Operation

Sub [Ⓢ] \ Adj [Ⓢ]	Average High and Low Firing Rate Percent Difference					
	Adjust 1		Adjust 2		Adjust 3	
	High	Low	High	Low	High	Low
Adjust	0.0%	0.00%	0.0%	0.0%	0.0%	0.0%
Sub1-1308	3.0%	2.89%	0.4%	-0.6%	-2.3%	-3.3%
Sub2-1308	4.3%	5.10%	2.0%	0.7%	-1.4%	-2.8%
Sub2-1332	5.5%	7.02%	3.2%	2.8%	0.0%	-1.0%
Sub1-1332	3.6%	4.50%	2.1%	1.4%	-1.4%	-2.5%
Sub1-1375	7.4%	2.96%	-1.8%	7.6%	1.2%	1.3%
Sub2-1375	8.3%	9.95%	6.0%	4.4%	2.7%	0.5%
Sub1-1385	10.9%	17.97%	6.3%	4.1%	2.8%	2.9%
Sub2-1385	8.8%	9.38%	7.1%	6.4%	3.1%	2.4%
Sub1	12.8%	12.75%	7.2%	5.7%	4.2%	5.9%
Sub2	10.9%	10.93%	9.4%	9.7%	2.9%	4.2%

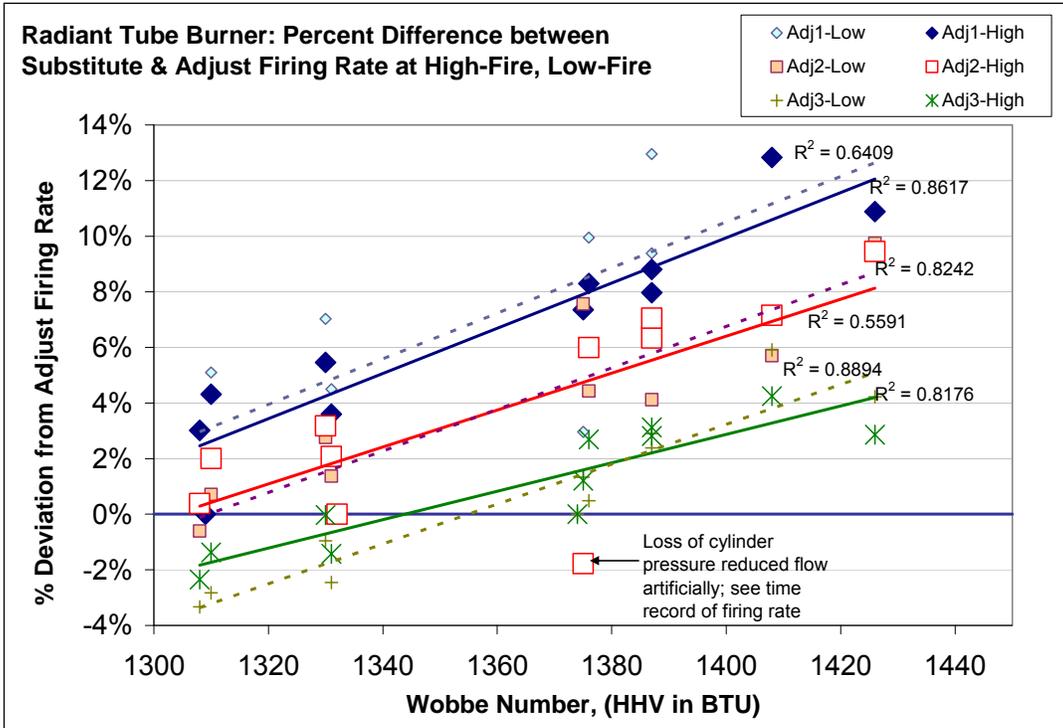


Figure 150. Percent difference from the Adjust Gas to each Substitute Gas firing rate

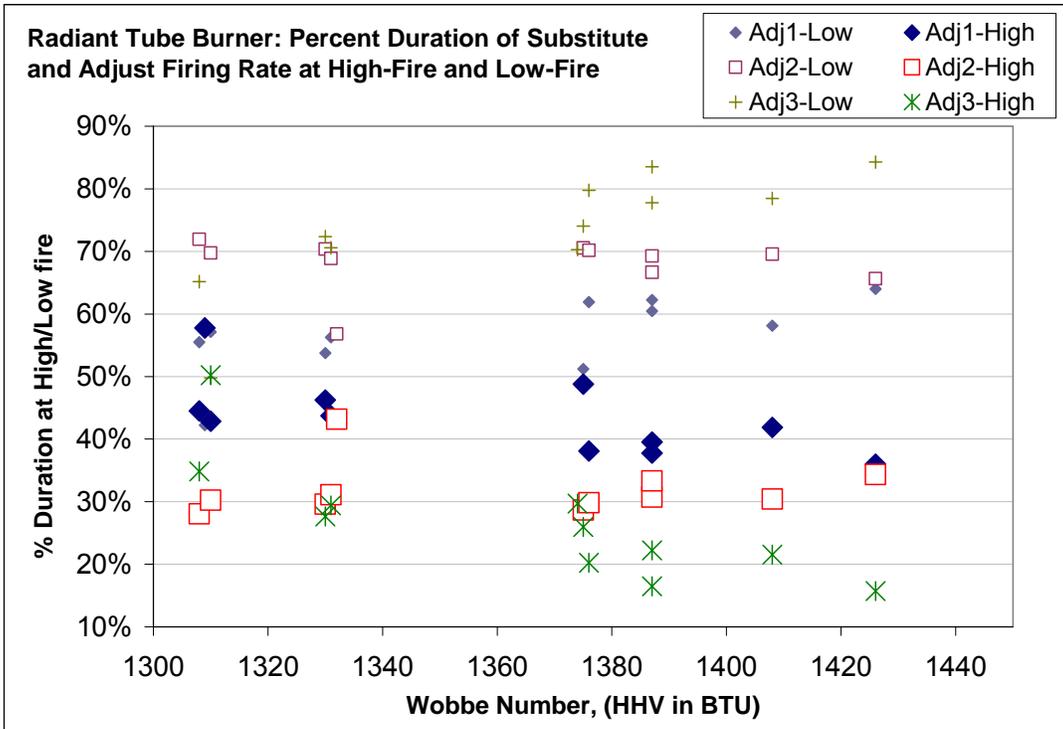


Figure 151. Percent of period spent at High Fire/Low Fire at all burner adjustments

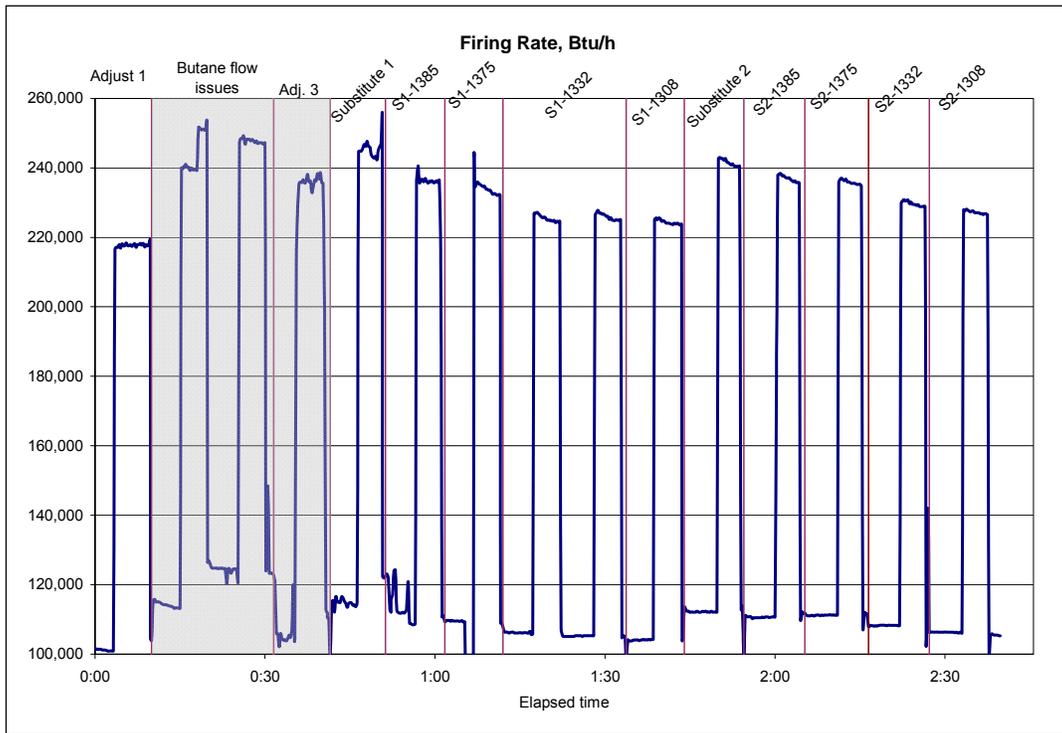


Figure 152. Continuous test, tuned to Adjust 1: Radiant tube burner firing rate

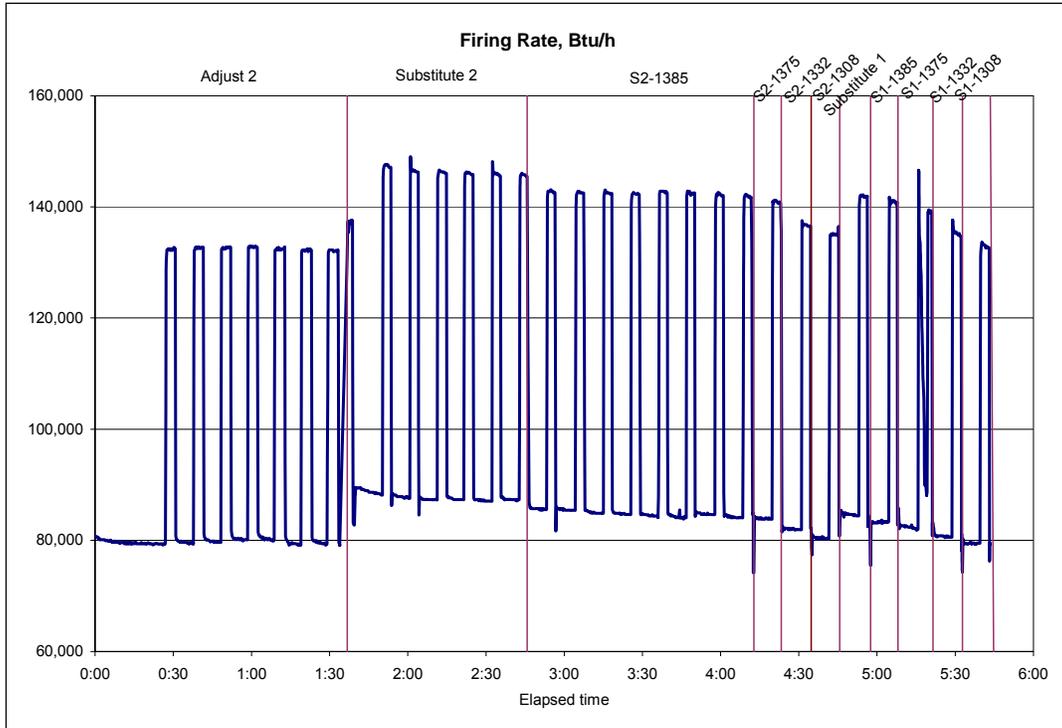


Figure 153. Continuous test, tuned to Adjust 2: Radiant tube burner firing rate

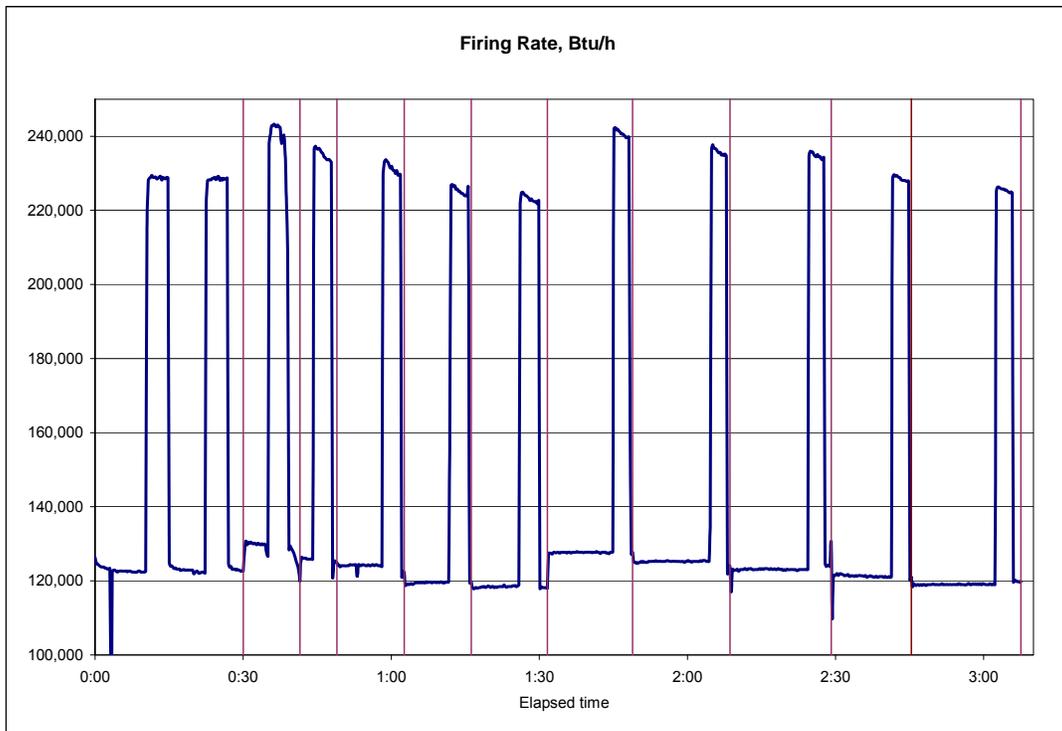


Figure 154. Continuous test, tuned to Adjust 3: Radiant tube burner firing rate

Controller response

The longer duration controller response tests give a clearer picture of how a change in fuel composition affects fuel usage and frequency and duration of switching between High Fire and Low Fire. Table 29 shows the controller response data for the three long-duration tests with the burner tuned to Adjust 2. Baseline performance is compared with Substitute 2, with a Wobbe Number of 1425, and S2-1385 with a Wobbe Number of 1385. S2-1385 is Substitute 2 diluted with nitrogen.

Table 28. Controller Response Data for the Three Long-Duration Tests

	Wobbe		Firing rate		Duration, 5 cycles		% high fire	
		% diff	Btu	% diff.	minutes	% diff.	% high	% diff.
Adj 2	1332		80,980		51:45		36.50%	
S2-1385	1385	3.98%	84,213	3.99%	52:15	0.97%	31.30%	-14.2%
Sub 2	1425	6.98%	86,774	7.15%	53:30	3.38%	31.90%	-12.6%

The furnace was run with automatic control for 5 cycles to collect enough data for comparison. Only the named gases were run to conserve fuel and time. Adjust 2 was selected because it represents the California average composition. Substitute 2 was selected because it is the most different from Adjust 2 of any of the Substitute Gases and any change in performance would be more dramatic. At the time of the tests 1385 was the highest allowable Wobbe Number natural gas permitted in California. Figure 156 presents the burner's firing rate as a function of time, and Figure 157 shows that firing rate integrated to become the fuel consumption over the period examined.

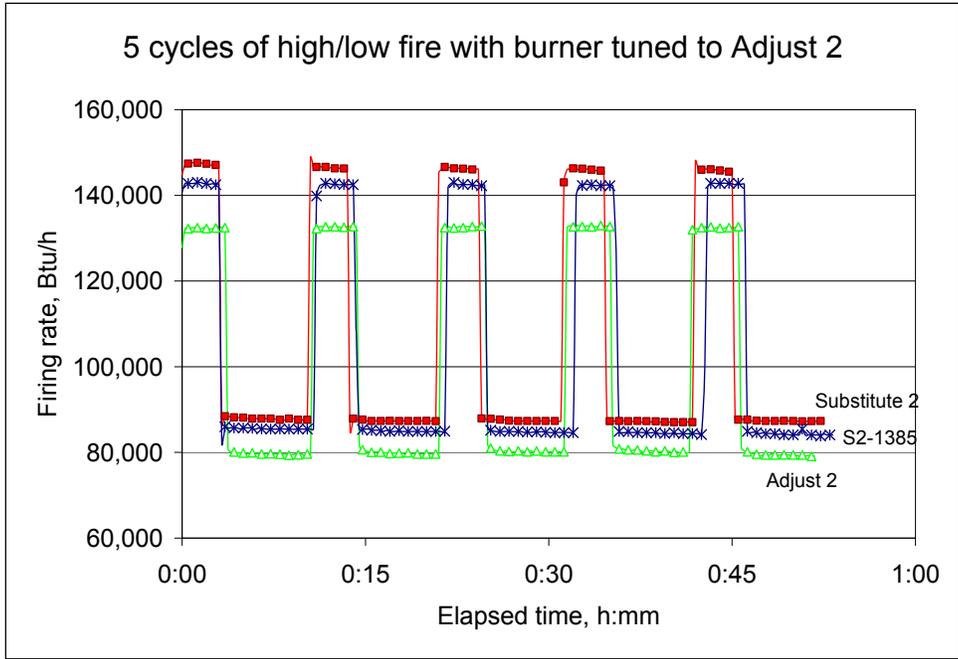


Figure 155. Firing rate as a function of time for the Continuous Tests, with the burner tuned to Adjust 2

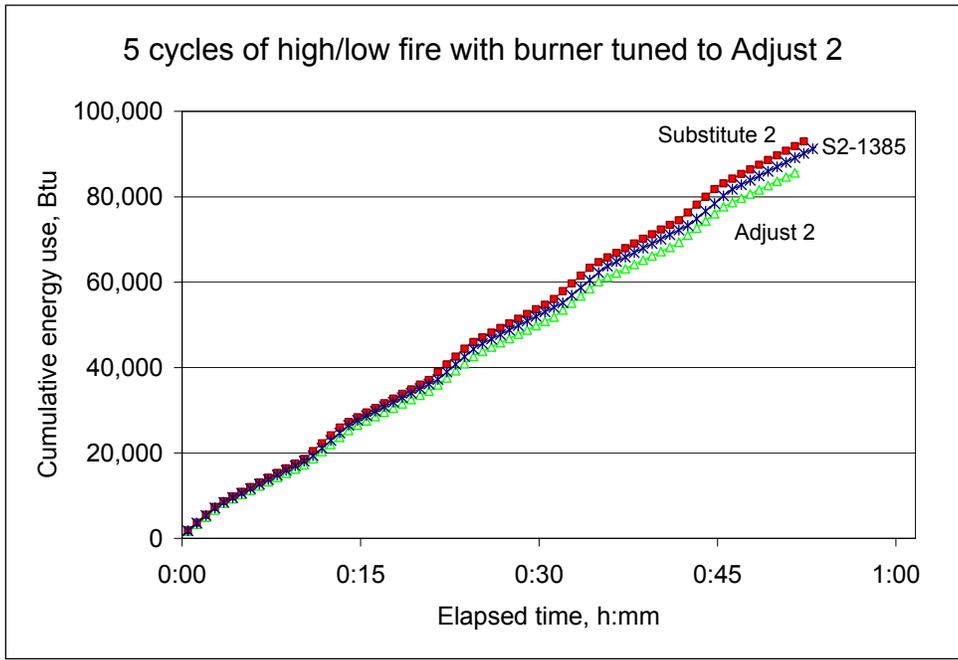


Figure 156. Cumulative fuel consumed as a function of time for the Continuous Tests, with the burner tuned to Adjust 2

Emissions

Emissions data were collected online during the continuous firing tests. The air-to-fuel ratio during High Fire was different from that during Low Fire, so emissions are separated, but presented on the same charts. High Fire data are designated with larger, darker icons than the Low Fire data. A one minute lag was presumed between a change in firing rate and the change in emissions, meaning the averaging window used for the emissions data lagged the measured change in firing rate by one minute. It is still the change in fuel composition, and not the beginning of the averaging window, that is denoted by the vertical separating lines in Figure 9 through Figure 20. Total hydrocarbon data are not reported; the measured values were nearly always below the detection limit; only occasionally did the instrument read anything besides a negative number. When the carbon monoxide readings saturated the instrument (at 5000 ppmv), total hydrocarbon readings were positive.

Tuning of the radiant tube burner was performed only on the High Fire setting. The Low Fire setting was allowed to follow naturally, although it is possible to “tighten up” the fuel-to-air ratio by adjusting a part on the air/fuel ratio regulator. Tuning only at High Fire is not an uncommon industry practice. First, after successful ignition the furnace was placed in manual override and set to High Fire. A butterfly valve on the air line, downstream of the mechanized control valve and the air/fuel ratio regulator, was adjusted to set the air flow to the desired rate. A limiting orifice on the fuel line was then adjusted to obtain 3% O₂ in the exhaust. This value tends to decrease slightly from morning into the afternoon. With the air/fuel ratio regulator’s settings left untouched, the oxygen in the burner exhaust at low fire was about 1.5% O₂ to 2% O₂.

Figure 9 through Figure 20 show the volume fraction (dry) of the %O₂ and chemical pollutant emissions from the burner, as a function of the Wobbe Number. The time-history of the data is also presented to show emissions at both High Fire and Low Fire; it will also help with interpretation of data in the next section of this report. Figure 21 through Figure 23 show the concentration of ultrafine particles in the exhaust; the detection range is between 12 nm and 673 nm. Error bars for both particle and gas emissions show the entire range of data collected, not a standard deviation.

For the ultrafine particle measurement, the sample temperature upstream of the first dilution ranged from about 350°F to 500°F, and the second dilution brought sample temperatures below about 100°F, with a goal of room temperature; around 76°F. A dilution ratio of 17 was commanded. The commanded ratio, which is measured by comparing pressures at different locations in the probe, does not agree with the dilution ratios of between 25:1 and 45:1 were calculated by comparing the carbon dioxide content in the sample stream before and after dilution; the stream was diluted with nitrogen instead of the usual air in order to allow this calculation.

Calculations using O₂ were less repeatable than the CO₂ measurements, and indicated impossible dilution ratios—sometimes below 1. As can be seen from Figure 9 through Figure 11 there was often little O₂ in the exhaust stream to begin with, meaning

a diluted sample may have been near the detection limit of the gas chromatograph. CO₂ measurements were more repeatable, so the CO₂ dilution ratios were used and the O₂ ratios discarded to determine particle count. Each data point in the figures is averaged from between one and three sets of three two-minute scans. The dilution ratios for Adjust 3 (in green) in Figure 23 were estimated because the gas chromatograph was not functioning reliably during the test. The commanded ratio was steady at 9, and the previous commanded ratio of 7 yielded a relatively consistent ratio of 33 to 38. The Air sample for Adjust 2 was drawn from the static air in the radiant tube once the dilution nitrogen had been turned off; the Air sample for Adjust 3, however, was drawn from the hot radiant tube immediately after the gas had been turned off.

Certain difficulties were encountered with the ultrafine particle sampling probe. First, isokinetic sampling was not fully controlled—the flow rate of the sampling equipment was set and variations in firing rate were not accounted for. It was also difficult to maintain the proper temperature ranges inside the ultrafine particle probe. The probe was to sample from the exhaust stack at around 900°F and then dilute and cool the air to about 100°F. In reality, cooling was insufficient even at its maximum to properly lower the temperature. The consequence of this is that some particles may not have formed that would have otherwise. Another consequence was that during testing the temperature inside the probe varied as different attempts were made to cool its outside. These attempts at cooling may have altered the functioning of the dilution device and thus may have affected measurement.

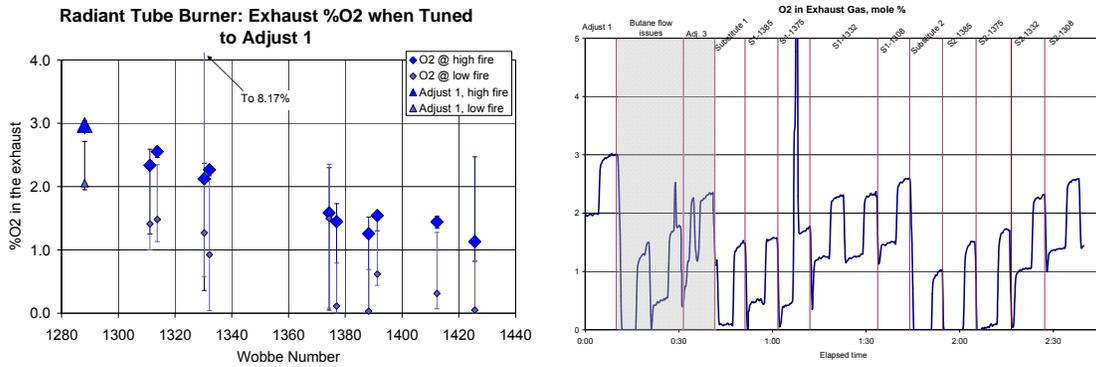


Figure 157. Volume %O₂ in dry exhaust, with the burner tuned to Adjust 1

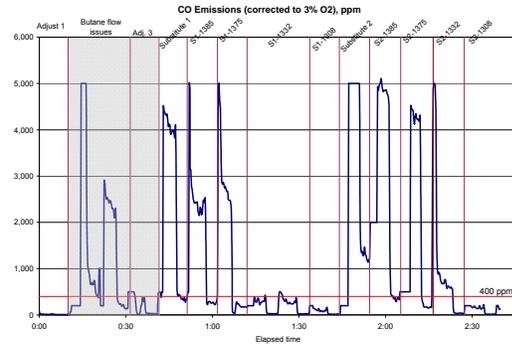
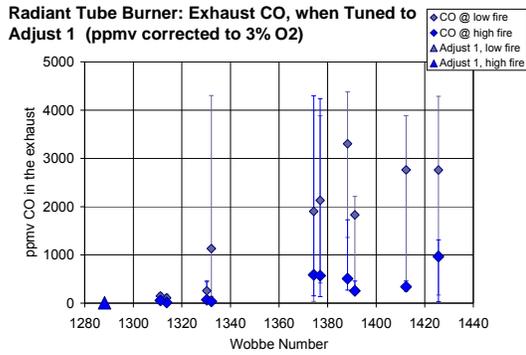


Figure 160. CO concentration in the exhaust with the burner tuned to Adjust 1, corrected to 3% O₂

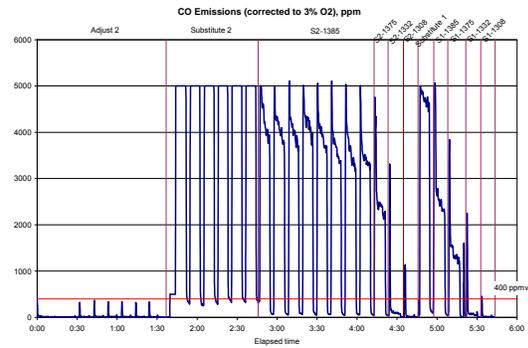
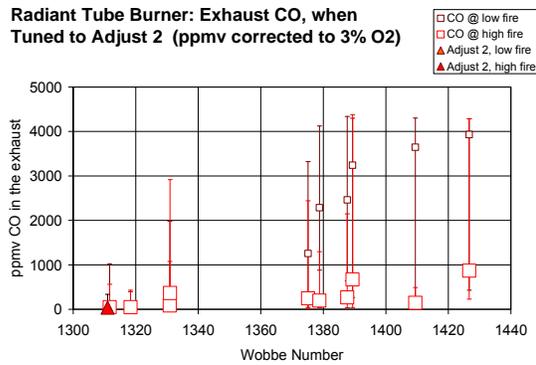


Figure 161. CO concentration in the exhaust with the burner tuned to Adjust 2, corrected to 3% O₂

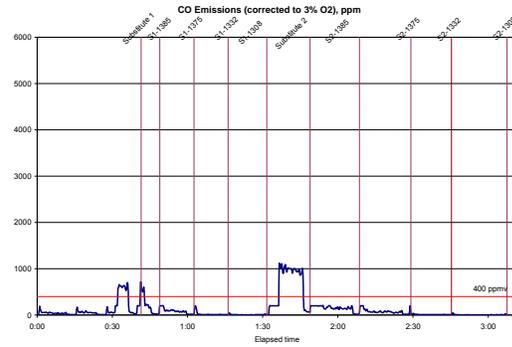
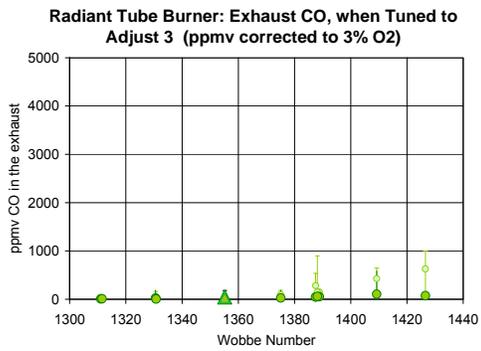
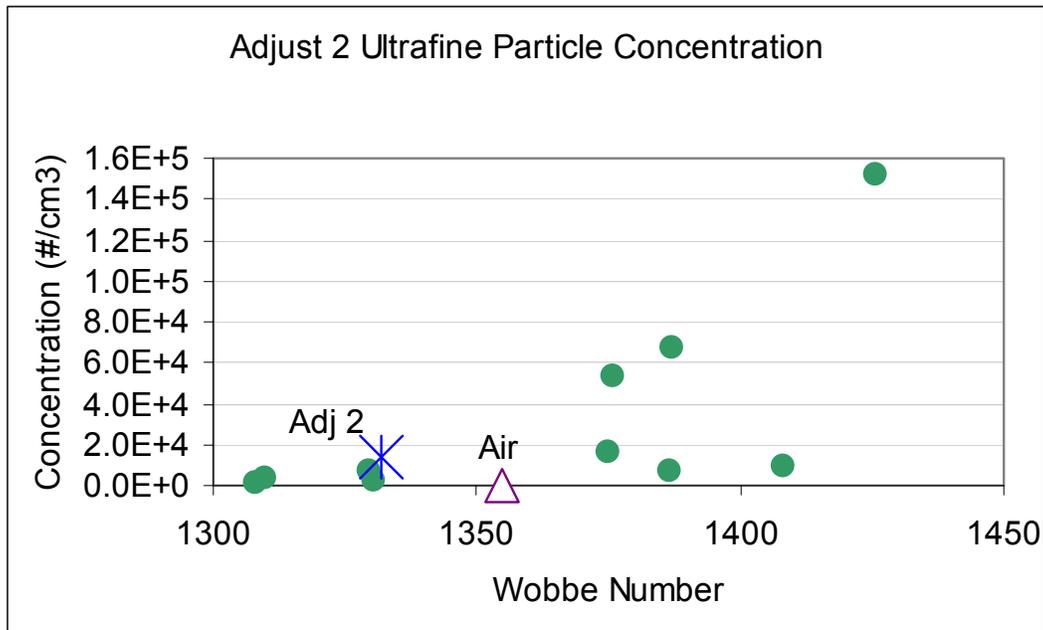
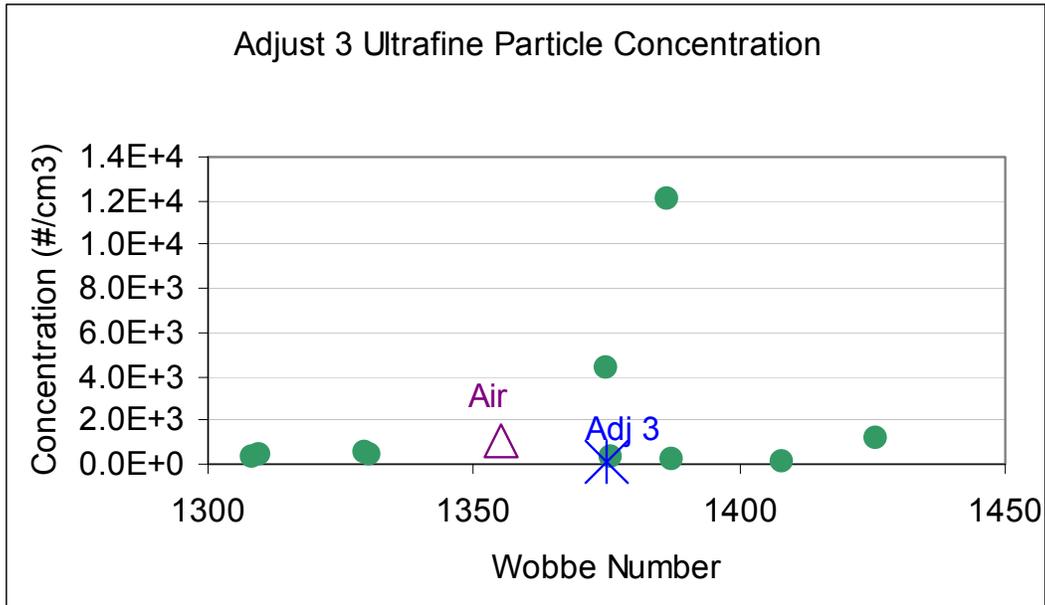


Figure 162. CO concentration in the exhaust with the burner tuned to Adjust 3, corrected to 3% O₂



	Fuel	Wobbe	Dilution ratio, calculated from %CO ₂ in diluted and undiluted stream	Average diluted concentration(#/cm ³)	Estimated Undiluted Concentration (#/cm ³)
Adjust 2	Adj2	1332	97.1	143	13,861
	Sub1	1408	53.8	166	8,953
	Sub1-1385	1387	41.0	172	7,037
	Sub1-1375	1375	39.5	407	16,092
	Sub1-1332	1331	38.2	53	2,009
	Sub1-1308	1308	38.0	23	881
	Sub2	1426	38.5	3946	151,782
	Sub2-1385	1387	53.8	1252	67,386
	Sub2-1375	1376	38.8	1375	53,343
	Sub2-1332	1330	38.6	183	7,059
	Sub2-1308	1310	38.3	101	3,881
	Air	---	---	38.3	1

Figure 167. Particle emissions with burner tuned for Adjust 2



	Fuel	Wobbe	Dilution ratio, assumed; command = 12	Average diluted concentration(#/cm ³)	Estimated Undiluted Concentration (#/cm ³)
Adjust 3	Adj3	1375	42	2	92
	Sub1	1408	42	3	111
	Sub1-1385	1387	42	289	12,119
	Sub1-1375	1375	42	106	4,434
	Sub1-1332	1331	42	11	447
	Sub1-1308	1308	42	8	330
	Sub2	1426	42	28	1,161
	Sub2-1385	1387	42	4	172
	Sub2-1375	1376	42	7	306
	Sub2-1332	1330	42	12	484
	Sub2-1308	1310	42	11	460
	Air	---	42	24	1,023

Figure 168. Particle emissions with burner tuned for Adjust 3

Ignition Test Results

Ignition

Figure 170 through Figure 172 show the furnace temperature (200°F to about 600°F) and the exhaust temperature (to 1600°F) during the ignition tests. The figures show an initial period where the burner was tuned to the selected adjust gas and then eleven short periods of temperature rise where ignition was tested. The firing rate at ignition was around 300,000 Btu/hr; the burner's rated capacity. It is unusual to ignite at High Fire and much safer to light at Low Fire. High Fire was thus chosen specifically to present the most problematic situation to the burner. The sequence of testing was: Adjust Gas, Substitute 1 unconditioned, Substitute 1 conditioned to 1385, 1375, 1332, and 1308 Wobbe, Substitute 2 unconditioned, and Substitute 2 conditioned to 1385, 1375, 1332, and 1308 Wobbe. Only the time slices when the burner was firing are presented in the figures. The remaining time in between ignitions, when the furnace was cooling, are not included in the plot. The back door of the furnace was left open during the ignition tests to allow faster cooling between runs; this presents a bigger load to the furnace during ignition. In addition, a blower was attached to a side port on the furnace, and run between ignition tests to speed cooling.

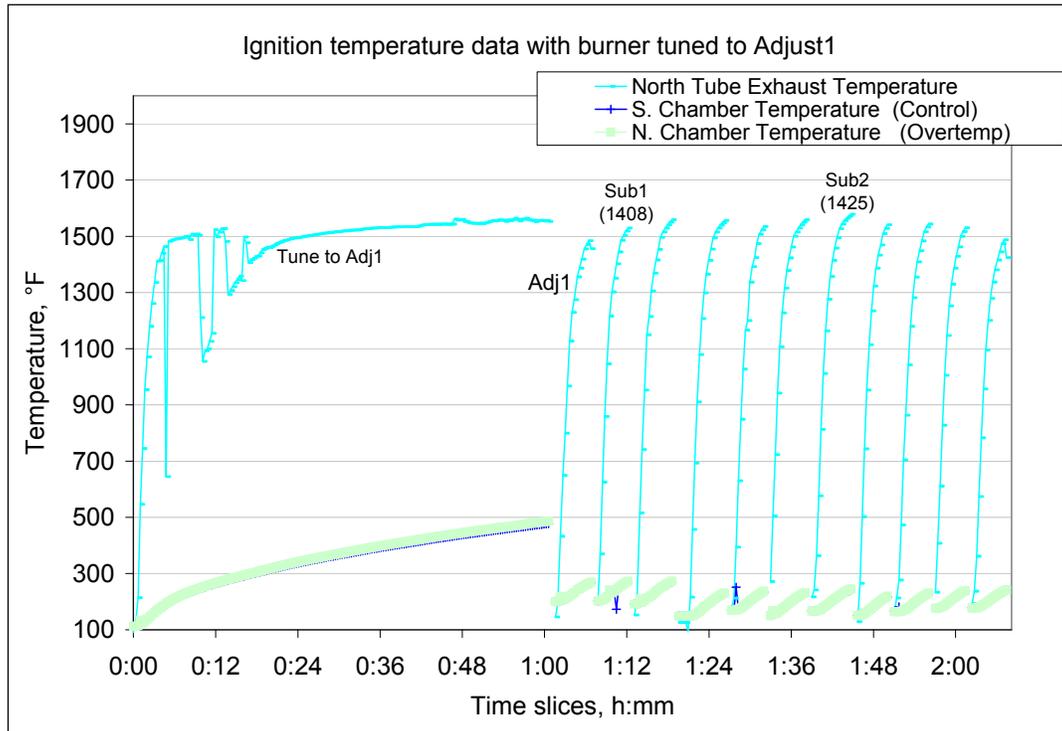


Figure 169. Ignition Tests with Radiant Tube Burner Tuned to Adjust 1

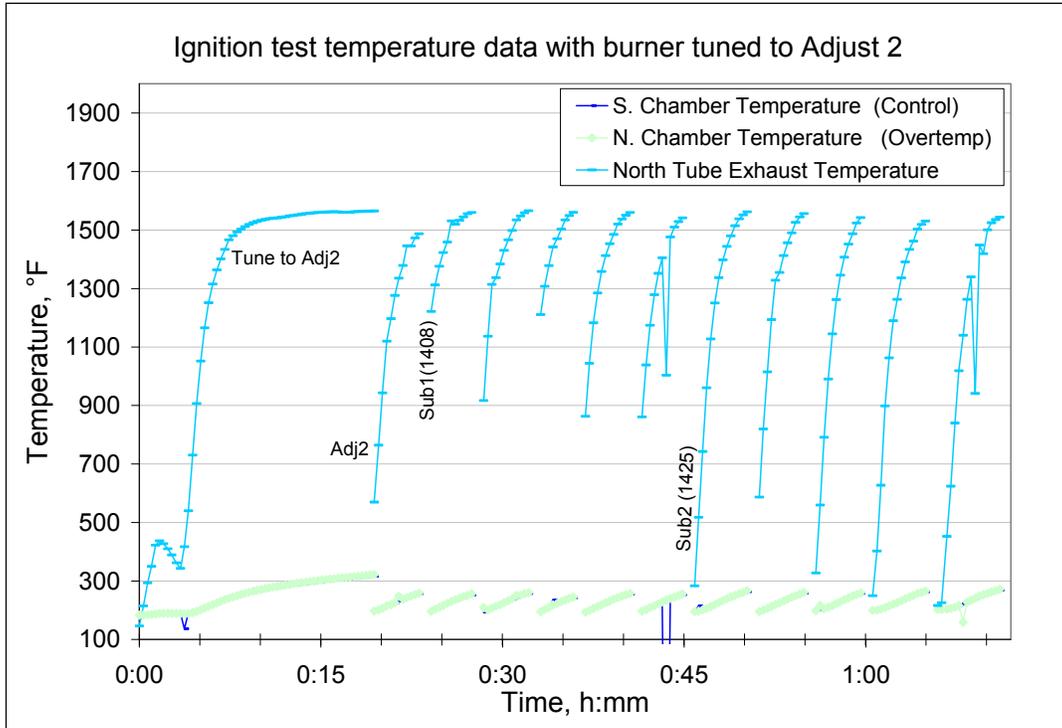


Figure 170. Ignition Tests with Radiant Tube Burner Tuned to Adjust 2

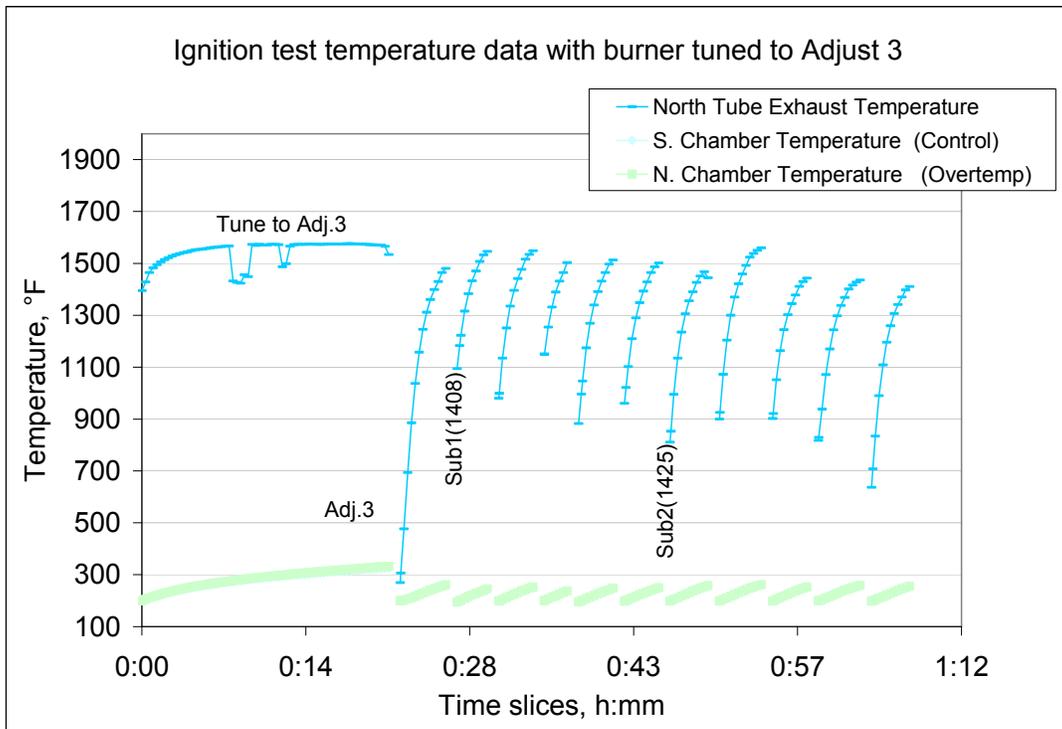


Figure 171. Ignition Tests with Radiant Tube Burner Tuned to Adjust 3

Tube temperature distribution

The tube temperatures at the seven discrete locations along the tube (see Figure 150 for placement) were recorded during the ignition tests and are displayed in Figure 173 through Figure 175. They are presented the same way as the data for the ignition tests, as slices of time condensed onto one plot. Overlaying the temperatures all on one time interval as in Figure 176, or plotting a set of tube temperature profiles for a single instant in time as in Figure 177 both provide less qualitative information than in Figure 173 through Figure 175. Figure 176 shows an example of furnace temperature overlaid for all gases tested when the burner was tuned to Adjust 3. Figure 177 shows the instantaneous tube temperature distribution overlaid for all gases tested with the burner tuned to Adjust 3. The instants were selected to have a temperature at Position #1 near 825°F.

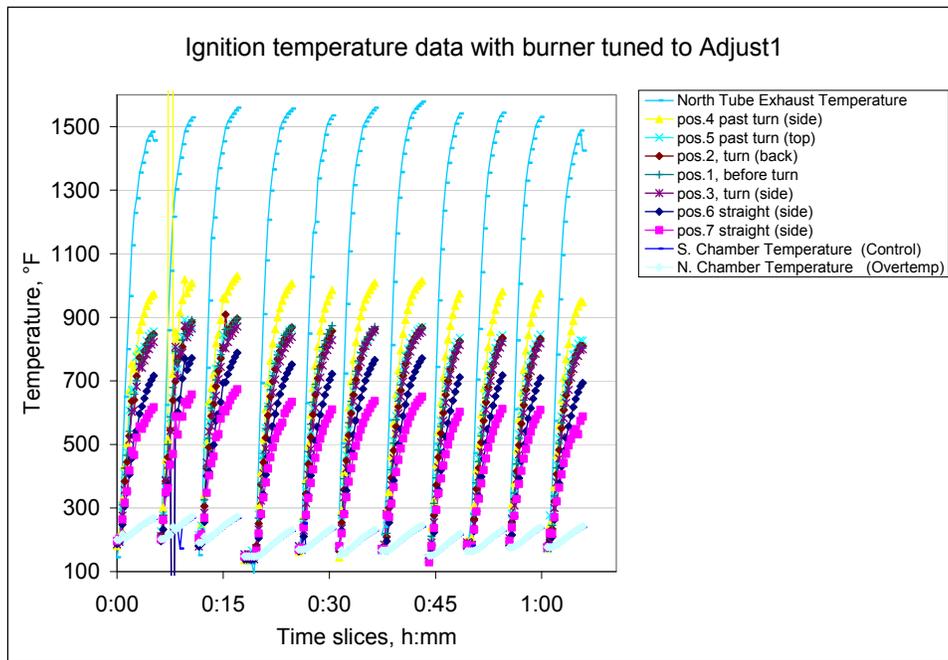


Figure 172. Tube temperature distribution during Ignition Tests with the radiant tube burner tuned to Adjust 1

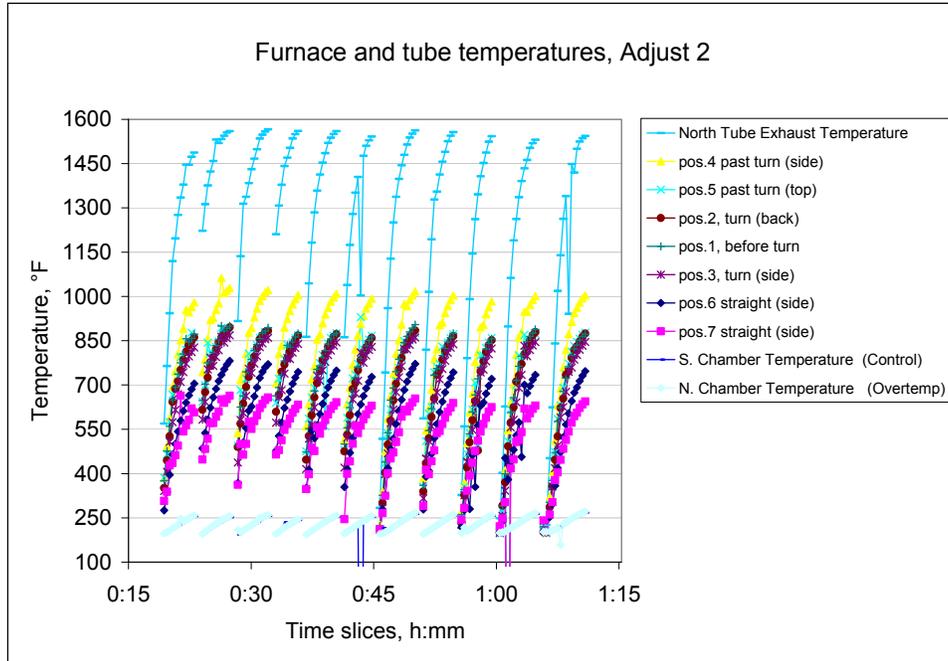


Figure 173. Tube temperature distribution during ignition tests with the radiant tube burner tuned to Adjust 2

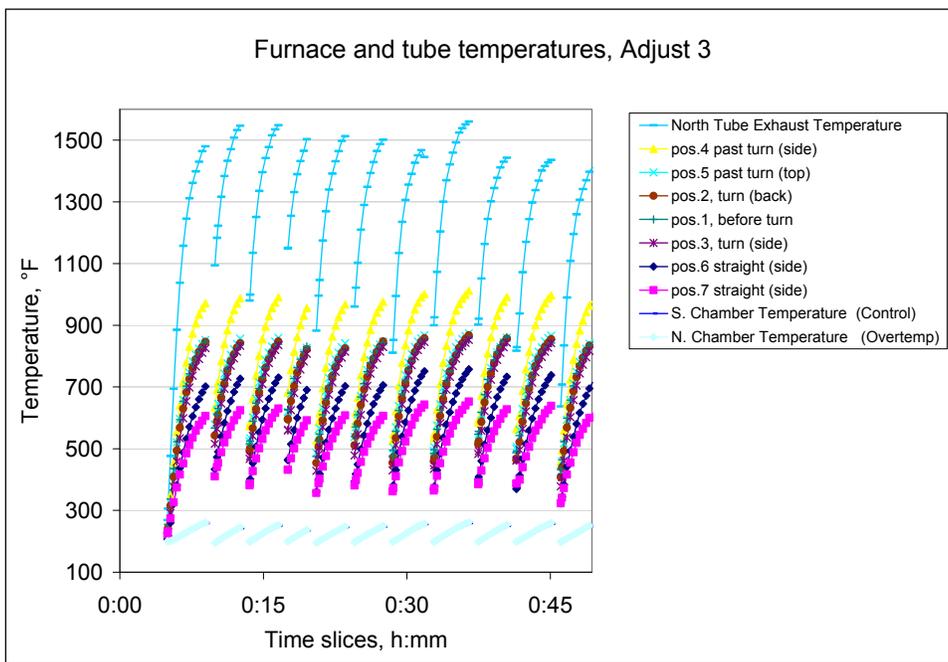


Figure 174. Tube temperature distribution during ignition tests with the radiant tube burner tuned to Adjust 3

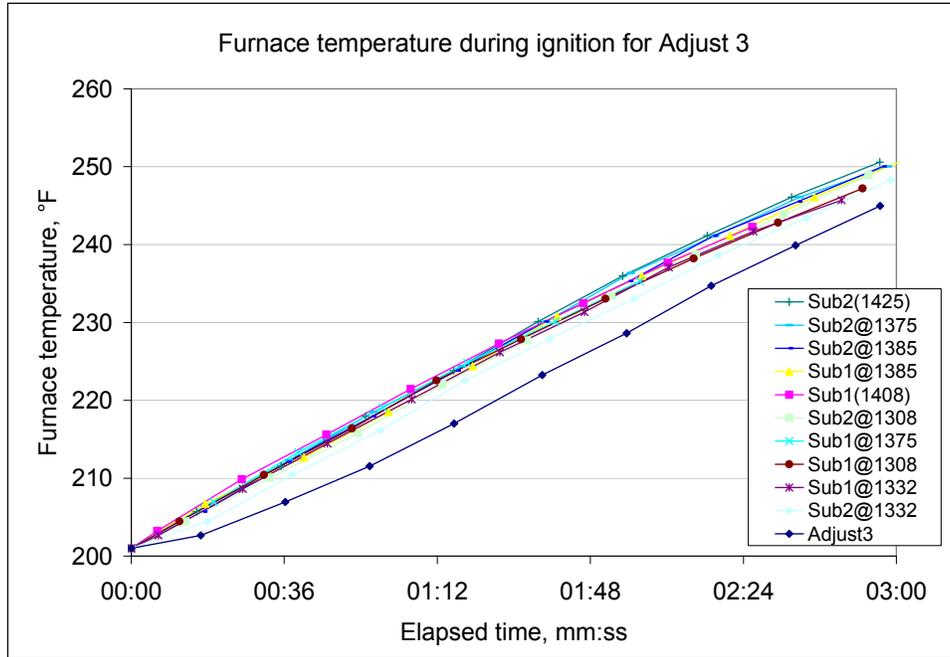


Figure 175. Furnace temperature rise during ignition, with radiant tube burner tuned to Adjust 3

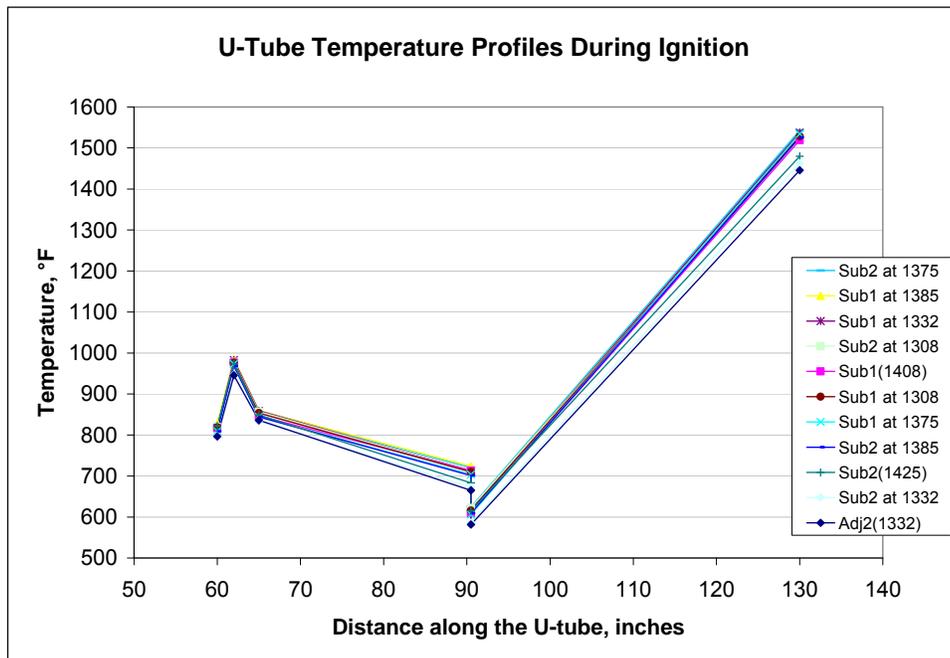


Figure 176. Tube temperature distribution during ignition tests, with radiant tube burner tuned to Adjust 3

Analysis

The charts and data are analyzed in the same sections below as appear in the Results section.

Continuous Test Analysis

Firing rate

The percent variation in the firing rate with respect to Wobbe Number, presented in Table 28 and Figure 4, are shown with a linear fit overlaid. The linear fits drawn have R-squared values of between 5.6 and 8.9; one outlying data point, labeled in Figure 4, occurred because a methane cylinder ran out before it was exchanged for a new one. It was not included in the linear fit.

Figure 152 presents the percent duration of High-Fire and Low-Fire for each tests; the different marker shapes correspond to the three different Adjust Gases used to tune the burner. With the burner tuned to Adjust 1 and Adjust 3, it appears that there is some correlation between a change in Wobbe Number and a change in the percent High-Fire to Low-Fire. The duration of the High-Fire period decreases with Wobbe Number for these two Adjust Gases. The correlation, is nonexistent or very slight for Adjust 2, and is in the opposite direction.

Controller response

Only one burner of two is firing the Substitute Gases, all of the noticed effects may therefore double in a real furnace operation.

The overall average firing rate in Table 29 increases very nearly in proportion to the Wobbe Number. This is actually a surprise or maybe a coincidence; the cycling time changed and the % High Fire-to-Low Fire also changed, meaning there should not necessarily be a correlation between Wobbe Number and firing rate.

Figure 156 shows the cycling of the burner between low and high fire, and Figure 157 shows the fuel use integrated over a five-cycle period. The purpose of Figure 156 is to show the change in the cycle duration and %High-Fire visually: the high-fire period for Substitute 2 and S2-1385 are both noticeably narrower than the period for Adjust 2. They are in fact nearly the same width, which may be a surprise; Substitute 2 may have been expected to heat more quickly and thus have a shorter % High-Fire than S2-1385.

Figure 157 shows the total fuel use over the 5 cycles of operation. It illustrates that the total fuel consumed diverges, and the higher Wobbe Number fuels appear to correlate with slightly more energy consumption over time.

Emissions

The % O₂ in the exhaust is presented in Figure 9 through Figure 11. Before comparing in detail, notice that for Adjust 1 and Adjust 3 the first set of Substitute Gases is the Substitute 1 family, while for Adjust 2 the first set is the Substitute 2 family. There are

two important observations for these figures. First, the % O₂ in the exhaust decreases as the Wobbe Number increases; this is as expected because there is a higher heat input combusting with an unchanged volume of air. Second, the % O₂ in the exhaust at low fire is lower than the % O₂ in the exhaust at High Fire by about 1% across all fuels and all adjustments.

There are corresponding changes in the CO emissions that indicate incomplete combustion. Figure 12 through Figure 14 show the measured CO, normalized to 3% O₂. The data have a wide spread (partially because it was difficult to determine whether to associate a data point with High Fire or Low Fire) but the average values still exhibit trends. For the 1308 Wobbe Number Adjust Gas, 7 of the trials with Substitute Gas had average CO emissions above 400 ppmv at low fire and 4 had an average that exceeded 400 ppmv at High Fire. For the 1332 Wobbe Number Adjust Gas, 6 trials at Low Fire and 2 at High Fire exceeded 400 ppmv. Finally, for the 1385 Wobbe Number Adjust Gas, 2 Substitute Gases at Low Fire and none at High Fire had an average that exceeded 400 ppmv. 400 ppmv CO is often a regulatory limit. The Substitute Gases that caused the above-400 ppmv CO emissions at Low Fire were, as expected, the highest. At High Fire, the correlation was not as clear; the above-400 ppmv CO emissions at High Fire did also correspond to high Wobbe Numbers, but not necessarily to the highest. This could be more because of poor selection of where to differentiate between High Fire and Low Fire than from the actual data. A line drawn at 400 ppmv on each of the continuous data in Figure 12 through Figure 14 allow for another interpretation of the data.

Figure 18 through Figure 20 show the NO_x emissions. With the burner tuned to Adjust 1, the average ppmv NO_x emissions vary by less than 7% at High Fire but by up to 67% at Low fire. The High Fire / Low Fire splits for Adjust 2 are 9% / 62%, and for Adjust 3 are 3% / 40%. At Low Fire there appears to be a downward trend in average NO_x emissions as the Wobbe Number of the Substitute Gas increases. At High Fire, there does not appear to be a definite trend.

Particle emissions are summarized in Figure 21 through Figure 23. The data, like the other emissions data, are scattered and do not appear to show a trend with respect to Wobbe Number. Air that was sent through the Radiant Tube before sampling had fewer particles than the exhaust. The maximum average particle count for any Substitute gas in Adjust 3 was 1.5×10^4 . With the burner tuned to Adjust 2, that number was 1.2×10^5 , and with Adjust 3 and last 2.7×10^5 with Adjust 1.

Ignition Test Analysis

Ignition

Figure 170 through Figure 172 show that the Radiant Tube Burner ignited for all Substitute Gases. There are some outlying points on the temperature rise that appear to be anomalies of the data collection system, and not physical jumps in temperature.

Tube temperature distribution

Figure 173 through Figure 175 show the exhaust temperature and furnace temperatures again, as in the previous section, but also include the tube temperature at seven discrete locations. They appear, qualitatively, to match each other in height and curvature. A closer look, both by superimposing the temperature trace with respect to time in Figure 176 and by superimposing the tube temperature profiles in Figure 177 show that there appears to be no qualitative difference between the temperature rise or tube temperature distribution for the gases tested; the temperature spread is about 6%. There is no understandable correlation between the ordering of the temperatures from highest to lowest.

Conclusions

Conclusions are listed in the same sections below as appear in the Results and Analysis sections.

Continuous Test Conclusions

Firing Rate

Firing rate should be proportional to the Wobbe Number, all other things held equal, so it should be expected that the Wobbe Number and the firing rate fit a line for a single firing rate. Variations can be from small fluctuations in upstream fuel or air pressure or from a change in ambient temperature.

One explanation why the duration of the High-Fire period decreases with Wobbe Number for Adjust 1 and Adjust 3 but appears to be flat or decrease for Adjust 2 is that the High-Fire for Adjust 2 was set at about 120,000-150,000 Btu/hr compared with the 220,000-250,000 Btu/hr for the other two adjust gases. This means that the heating was more intense for the latter two, and any effect of the heating on time would be amplified.

Controller Response

A reason why Substitute 2 has a longer high-fire period than S2-1385 could be incomplete combustion. Figure 159 shows 0% O₂ when firing Substitute 2 and 0.1% O₂ when firing S2-1385. Figure 162 corroborates that there is incomplete combustion when firing Substitute 2: the CO emissions exceed 5000 ppmv. Incomplete combustion implies incomplete release of the chemical energy, meaning some energy leaves the stack and is not transferred to the product. It makes sense in this context that Substitute 2 has a longer high-fire period than S2-1385 even though Substitute 2 has a higher Wobbe Number. Incomplete combustion also makes it reasonable that fuel consumption is higher for higher Wobbe Numbers.

These observations merit a side comment: the reason it was surprising to see greater fuel use with a higher Wobbe Number is because it was expected that there would always be enough air for complete combustion. Then a higher Wobbe Number (up until there are excessive CO emissions) means a higher efficiency because there is less excess air to heat. If the initial air-to-fuel ratio had been high enough to avoid incomplete combustion, a decrease in fuel usage might have been observed with increasing Wobbe Number. "High enough" appears, from observation during these tests, to be right around 3% O₂. This allows for a 1.5% decrease in exhaust %O₂ with 1.5% remaining; enough to just keep above the high CO emissions.

Emissions

The emissions data in Figure 9 through Figure 20 are consistent across the %O₂, ppmv CO and ppmv NO_x. At Low Fire, there is incomplete combustion with the higher Wobbe Number fuels: when the %O₂ in the exhaust passes below about 1.5%, the CO increases past 400 ppmv. It is reasonable that the NO_x emissions did not trend appreciably at high

fire, because burner design and excess air likely mitigated the peak flame temperature. At very low exhaust % O₂, NO_x emissions decreases, as would be expected for fuel-rich flames.

The ultrafine particle data in Figure 21 through Figure 23 are scattered and difficult to interpret, although more particles were counted at higher Wobbe Numbers on burners that were tuned to the lower-Wobbe Number Adjust Gases. The highest estimated emissions, 273,000 counts per cubic centimeter, was recorded for Substitute 2 with the burner tuned to Adjust 1. For perspective, a report by D. Westerdahl¹ indicates that industrial burner emissions are usually below 100,000 counts per cubic centimeter. According to that report, vehicles can produce up to ten times as many counts. The number of counts read could have been artificially large; sampling was not kept isokinetic but was pulled at a constant speed. That speed was as much as three times the speed of the surrounding fluid.

Ignition Test Conclusions

Ignition

The ignition data and operator observation both agree that there was no trouble during ignition tests.

Tube Temperature Distribution

Indistinguishable tube temperature profiles and a nearly indistinguishable heat-up rate were not anticipated. Either the ignition test duration should have been longer, to observe values as they settled out, or there are no major differences in the tube temperature or its distribution when firing the selected Substitute Gases. The 6% difference shown in Figure 176 and Figure 177 is above measurement error for the thermocouples, and could have meaning, but none could be readily inferred.

¹ Westerdahl D. 2003. "Operation of an Advanced Mobile Air Monitoring Platform in Los Angeles: Ultrafine PM and Associated Gaseous Pollutants in Urban Air." California Air Resources Board, Chairman's Air Pollution Seminar Series, August 19, 2003.

Photographs

Laboratory Set-Up

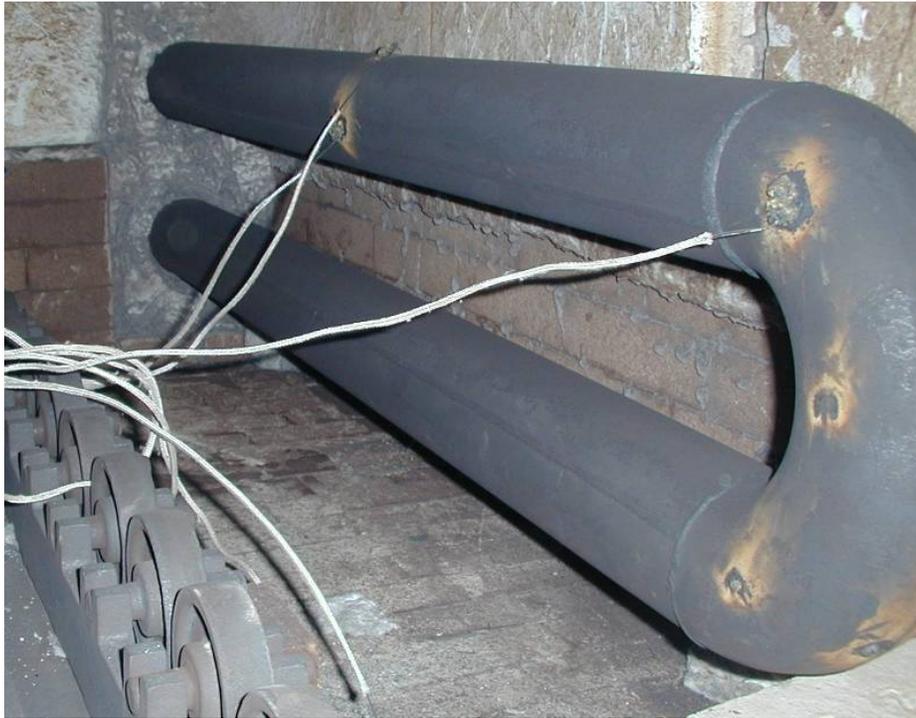


Figure 177. Radiant Tube in the Heat-Treat Furnace

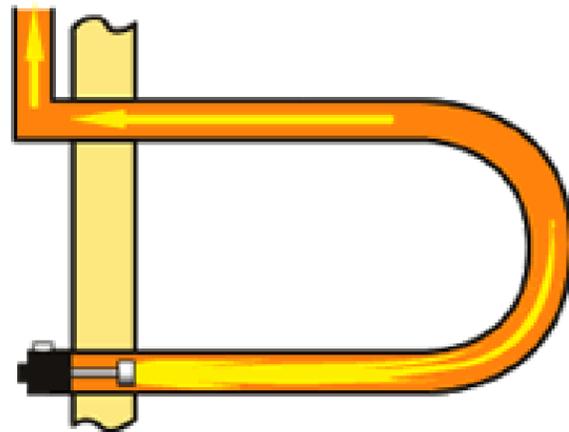
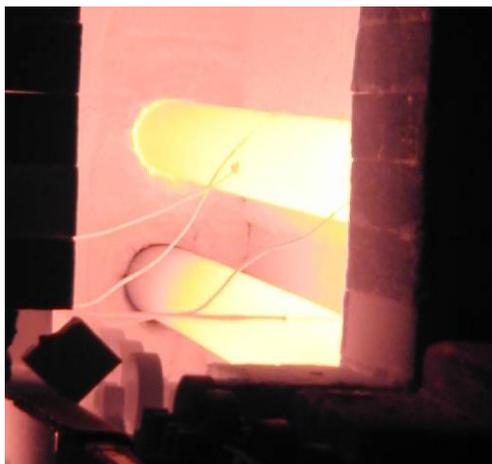


Figure 178. Radiant Tube with Burner Firing, and Sketch



Figure 179. Two Views of the Blending Station with Constituent Gases



Figure 180. Rosemount (left) and Horiba (right) Gas Analyzers



Figure 181. Gas Chromatograph Case (left) and Electrostatic Classifier with Scanning Mobility Particle Sizer (right)

**NATURAL GAS IN CALIFORNIA: ENVIRONMENTAL IMPACTS
AND DEVICE PERFORMANCE**

**Industrial Burner Evaluations:
Boiler Interchangeability Test Report**

Prepared by

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(GTI Project No. 20352)

For

California Energy Commission

Contract No. CEC-500-05-026

**Commission Project Manager
Marla Mueller**

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Objective

The purpose of the boiler interchangeability tests is to assess the performance of a low NO_x burner and industrial boiler when fired with different natural gas compositions. The burner's and boiler's performance when firing selected Adjust Gases was compared with its performance when firing selected Substitute Gases with and without different levels of nitrogen ballasting.

Approach

The tests used a laboratory setup intended to mimic industrial operating conditions. The burner was first tuned to operate with an "adjust" gas composition.

Operating/switching tests and ignition tests were then performed. During these tests several "substitute" gas compositions were fired in sequence on the burner. These tests were then repeated with the other two "adjust" gases as a basis.

Operating tests were performed in two modes, constant firing rate and constant steam pressure. Constant firing rate tests were performed with the PID loop in boiler's PLC control system set to manual mode with a fixed 60% output. This value was chosen so that the firing rate did not exceed 90% of the fuel delivery system's (blending station's) capacity. The system's response in terms of emissions, steam pressure, and temperature was recorded.

Constant steam pressure tests were performed with the PID loop in boiler's PLC control system set to automatic mode with a setpoint of 70 psig steam pressure. This required tuning of the PID loop so that the swings in firing rate to maintain the desired steam pressure did not exceed 100% of the fuel delivery system's capacity. The system's response in terms of emissions, and the controller's response in terms of firing rate were recorded.

Ignition tests were performed with the boiler cycling between an "on" point of 47.5 psig steam pressure and an "off" point of 50 psig steam pressure, with the PID loop output limited to a maximum of 60% during the "on" portion of the cycle. The cycle time varied between about 6 minutes and 15 minutes, depending on whether or not the boiler was taking in fresh (cold) water.

For all test sequences, the boiler was first warmed up on house gas, with the firing rate manually ramped up to 60% and the steam valves adjusted for about 70 psig steam pressure. The fuel was then switched to an "adjust" gas, and the burner was tuned for low NO_x performance by adjusting the pressure regulator on the boiler's fuel train so that less than 9 ppm of NO_x was measured in the exhaust when corrected to 3% O₂.

It was not an objective of these interchangeability tests to gauge the emissions performance of the boiler throughout the firing rate range of the boiler. As with the

previous burners that had been tested, the tests with the boiler were meant to gauge the performance of the boiler with different fuels under similar operating conditions.

Table 9 shows the specific performance measurements.

Table 29. Performance Metrics for the Boiler

BASIC PERFORMANCE METRICS
Gaseous Pollutant Emissions
Turnaround and Exhaust Temperature
System or Controller Response upon Switching:
Steam Pressure or Firing Rate

Test Apparatus

The boiler used for this test was an 80 hp Cleaver Brooks two-pass firetube steam boiler rated for 150 psig. The boiler was fitted with a Cleaver Brooks low NO_x burner, HawkICS integrated control system (PLC), and parallel positioning system for fuel flow, air flow, and FGR flow. The burner used a spark-ignited raw gas pilot. A pressure transmitter for steam was included with the boiler. One thermocouple was added to the turnaround point between the two passes of the boiler, and another thermocouple was added to the exhaust of the boiler. Also added to the exhaust of the boiler was a stainless steel sampling probe, which was connected through a filtering and drying train to a set of continuous emissions analyzers for THC, NO_x, CO₂, CO, and O₂. It and the rest of the experimental setup are shown in Figure 37 through Figure 225.

A custom-built blending station was used to provide simulated natural gas compositions to the boiler at 5 psig. The blending station allowed for one of two main streams, house gas and cleaned gas, to be selected, to which metered amounts of ethane, propane, butane, and nitrogen could be added. The house gas was the normal natural gas delivered to GTI. The cleaned gas was this natural gas processed through a set of three regenerative scrubbing towers that removed carbon dioxide from the gas. The cleaned gas was the basis for all the "adjust" and "substitute" gases. House gas was used only for warming up the boiler.

Mass flow meters were used to measure the house gas and cleaned gas flows. Motorized ball valves were used to select one of the two main streams. Mass flow controllers were used to add ethane, propane, butane, and nitrogen to the main stream. Ethane was supplied from a bank of 4 gas cylinders, propane and butane were each supplied from the gaseous outlet of liquid cylinders, and nitrogen was supplied from GTI's header, which is fed by a liquid tank. All gases were regulated down to about 15

psig before or upon entering the blending station except butane, which is delivered at its saturation vapor pressure of about 14 psig. The selected main stream is further regulated down to about 5 psig before the other gases are blended in. A pressure transmitter and thermocouple were used to monitor the mixed gas pressure and temperature.

The steam pressure transmitter, turnaround and exhaust thermocouples, continuous emissions analyzers, mass flow meters and controllers, and motorized ball valves were connected to a data acquisition and control system. Instruments used to perform this test are listed in Table 3.

Table 30. Summary of Test Instruments

Instrument	Parameter	Range	Accuracy
National Instruments Field Point Modules	Data logging and control	4-20 mA, 0-5 V, 0-10 V, ± 100 mV, on/off (relay)	16 bit input current; 12 bit input voltage; 12 bit output current; 16 bit temperature
LabView software	Data logging	—	—
Custom software	Control	—	—
Laptop computer	Data logging and control	—	—
Setra Systems 256	Steam pressure	0 to 150 psig	0.13% of full scale
Type K thermocouple	Turnaround temperature	2502°F	—
Type K thermocouple	Exhaust temperature	2502°F	—
Rosemount Analytical 400A	THC concentration	0-1000 ppm, Span 800 ppm	1% full scale
Thermo Environmental 42C High Level	NO concentration, NOx concentration	0-200 ppm, Span 198 ppm	0.5 ppm
Rosemount Analytical 880A	CO ₂ concentration	0-20%, Span 18.0%	1% full scale
Rosemount Analytical Xstream	CO concentration; O ₂ concentration	0-1000 ppm, Span 924 ppm; 0-25%, Span 8.05%	1% full scale
Brooks Instruments 5863S	House gas flow rate	2066 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5863S	Cleaned gas flow rate	1826 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5853S	Ethane gas flow rate	224 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5851S	Propane gas flow rate	68.5 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5851S	Butane gas flow rate	31.4 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5851S	Nitrogen gas flow rate	141 SCFH	0.7% of rate plus 0.2% of full scale
Inline Ball Valve with Electric Actuator	Main stream selection	—	—
Wika S-10	Mixed gas pressure	0-100 psig	0.25% of span
Type T thermocouple	Mixed gas temperature	752°F	—

The measured flow rates of the fuel gases supplied from the custom blending station to the burner were recorded using National Instruments Field Point Modules and a LabView program running on a laptop computer. The fuel gas compositions were commanded through a separate, custom program on the same laptop computer. The custom program used the measured flow rate of the main stream to determine the flow rates of the added gases. A table of ratios of each added gas to main stream for each "adjust" and "substitute" gas was created for the custom program.

Test Gases

The test gases were selected to match compositions distributed in California, and international compositions that may be imported into California. The compositions distributed in California are designated "adjust gases" for the purpose of tuning the burner for optimum performance on each of them. The remaining gases are designated "substitute gases" for the purpose of comparing performance with the substitute gases to performance with the adjust gases. Table 4 summarizes the gas compositions. Adjust 1 is representative of natural gas in the Sacramento area, Adjust 2 is an average value for the state of California, and Adjust 3 is representative of some areas in California with higher Btu content due to local natural gas production. The two substitute gases, Sub 1 and Sub 2, were selected from a set of potential LNG compositions available to California; Sub 1 has a relatively low Wobbe Number (1408) compared with the other LNG compositions, and Sub 2 has a relatively high Wobbe Number (1425). Because it is possible that these "substitute" gases will be conditioned with nitrogen prior to distribution in California, additional compositions with nitrogen added to make the Wobbe Number match those of the selected "adjust" gases.

Table 31. Summary of Adjust and Substitute Gases

Name	Gas Composition, mol %							HHV	Wobbe
	C1	C2	C3	C4	C5+	N2	CO2		
Adjust 1	93.2	2.52	0.41	0.14	0.093	2.691	0.920	1010	1309
Adjust 2	94.5	2.55	0.42	0.14	0.094	1.361	0.931	1024	1332
Adjust 3	90.61	2.45	3.41	1.25	0.094	1.305	0.893	1094	1374
Sub 1	92.4	4.9	1.9	0.79	0.0	0.0	0.0	1099	1408
@1385	91.3	4.8	1.9	0.79	0.0	1.2	0.0	1086	1387
@1375	90.7	4.8	1.9	0.79	0.0	1.9	0.0	1080	1375
@1332	88.3	4.8	1.8	0.79	0.0	4.4	0.0	1053	1331
@1308	87.8	4.6	1.8	0.70	0.0	5.5	0.0	1036	1308
Sub 2	89.4	7.1	2.5	1.04	0.0	0.0	0.0	1131	1426
@1385	87.5	7.0	2.4	1.00	0.0	2.1	0.0	1106	1387
@1375	86.9	6.9	2.4	1.00	0.0	2.7	0.0	1098	1376
@1332	84.5	6.7	2.4	1.00	0.0	5.4	0.0	1070	1330
@1308	83.6	6.6	2.3	1.00	0.0	6.5	0.0	1057	1310

For small-scale testing (up to about 40,000 Btu/h), it is practical to purchase cylinders with these exact compositions, with only nitrogen being blended in as needed. For medium-scale testing (up to about 200,000 Btu/h), it is practical to create these compositions from cylinders of pure gases using a blending station. For large-scale testing (over 1,000,000 Btu/h), the amount of pure methane needed requires a tube trailer, but none were available from GTI's gas supplier during the time of the test campaign. The "adjust" gases could be simulated (same heating value and Wobbe index) by blending in ethane, propane and butane from cylinders, and nitrogen from a liquid tank into GTI's house gas. However, the pure "substitute" gases and conditioned (nitrogen-diluted) "substitute" gases with higher Wobbe indexes could not be simulated this way because of the amount of inerts (CO₂ and N₂) in the house gas.

For another project, GTI assembled a CO₂ stripper which utilized three columns (towers) to remove the CO₂ from the house gas. The first tower performed the function of absorbing the CO₂ from the desired amount of house gas and an additional amount of house gas. The desired amount of cleaned gas went onto the burner being tested, while the additional amount went through the second tower, a heater, and the third tower before being vented or flared. The third tower performed the function of desorbing the CO₂ from the absorbent using the heated gas, while the second tower was being cooled

by the cleaned gas. The towers rotated their function every 3 hours, so the process was regenerative.

The cleaned gas with the heavy molecular weight CO₂ removed was then used a basis for simulating the "adjust" gases and the conditioned "substitute" gases. The pure "substitute" gases were still not quite reached, so the points of maximum heating value and Wobbe index, along the same lines as the conditioned "substitute" gases, were used in their place. The final compositions are shown in Table 12.

Table 32. Summary of Test Gases

Name	Gas Composition, mol %					HHV	Wobbe
	Cleaned Gas	Ethane	Propane	Butane	Nitrogen		
Adj1TC	95.90%	0.00%	0.89%	0.00%	3.21%	1010.0	1309.0
Adj2TC	97.10%	0.00%	0.95%	0.00%	1.95%	1024.0	1332.0
Adj3TC	90.71%	4.66%	1.97%	0.81%	1.84%	1094.0	1374.0
Sub1TCM	94.67%	3.34%	1.41%	0.58%	0.00%	1089.4	1392.8
Sub1TC-Hi	94.28%	3.33%	1.41%	0.58%	0.40%	1085.0	1385.5
Sub1TC-A3	93.68%	3.30%	1.40%	0.58%	1.04%	1078.0	1374.1
Sub1TC-A2	91.29%	3.22%	1.36%	0.56%	3.57%	1050.4	1329.2
Sub1TC-A1	90.23%	3.18%	1.35%	0.56%	4.68%	1038.3	1309.7
Sub2TCM	91.83%	5.12%	2.16%	0.89%	0.00%	1121.1	1410.5
Sub2TC-Hi	90.66%	5.05%	2.13%	0.88%	1.27%	1106.8	1387.7
Sub2TC-A3	90.10%	5.02%	2.12%	0.88%	1.88%	1100.0	1377.0
Sub2TC-A2	87.60%	4.88%	2.06%	0.85%	4.60%	1069.3	1329.2
Sub2TC-A1	86.58%	4.82%	2.04%	0.84%	5.71%	1056.9	1309.9

Test Schedule

The performance tests with constant firing rate were performed first for all three "adjust" gases. These were followed by performance tests with constant steam pressure. The ignition tests were performed last. Table 13 shows the schedule of test sequences.

Table 33. Test Schedule

Type	Constant Firing Rate			Constant Steam Pressure			Ignition		
Basis	Adj2TC	Adj1TC	Adj3TC	Adj3TC	Adj2TC	Adj1TC	Adj1TC	Adj2TC	Adj3TC
Subs	Sub1TC-A1	Sub1TC-A1	Sub1TC-A1	Sub1TC-A1	Sub1TC-A1	Sub1TC-A1	Sub1TC-A1	Sub1TC-A1	Sub1TC-A1
	Sub1TC-A2	Sub1TC-A2	Sub1TC-A2	Sub1TC-A2	Sub1TC-A2	Sub1TC-A2	Sub1TC-A2	Sub1TC-A2	Sub1TC-A2
	Sub1TC-A3	Sub1TC-A3	Sub1TC-A3	Sub1TC-A3	Sub1TC-A3	Sub1TC-A3	Sub1TC-A3	Sub1TC-A3	Sub1TC-A3
	Sub1TC-Hi	Sub1TC-Hi	Sub1TC-Hi	Sub1TC-Hi	Sub1TC-Hi	Sub1TC-Hi	Sub1TC-Hi	Sub1TC-Hi	Sub1TC-Hi
	Sub1TCM	Sub1TCM	Sub1TCM	Sub1TCM	Sub1TCM	Sub1TCM	Sub1TCM	Sub1TCM	Sub1TCM
	Sub2TC-A1	Sub2TC-A1	Sub2TC-A1	Sub2TC-A1	Sub2TC-A1	Sub2TC-A1	Sub2TC-A1	Sub2TC-A1	Sub2TC-A1
	Sub2TC-A2	Sub2TC-A2	Sub2TC-A2	Sub2TC-A2	Sub2TC-A2	Sub2TC-A2	Sub2TC-A2	Sub2TC-A2	Sub2TC-A2
	Sub2TC-A3	Sub2TC-A3	Sub2TC-A3	Sub2TC-A3	Sub2TC-A3	Sub2TC-A3	Sub2TC-A3	Sub2TC-A3	Sub2TC-A3
	Sub2TC-Hi	Sub2TC-Hi	Sub2TC-Hi	Sub2TC-Hi	Sub2TC-Hi	Sub2TC-Hi	Sub2TC-Hi	Sub2TC-Hi	Sub2TC-Hi
	Sub2TCM	Sub2TCM	Sub2TCM	Sub2TCM	Sub2TCM	Sub2TCM	Sub2TCM	Sub2TCM	Sub2TCM

The first test sequence, with Adj2TC, was performed with the tuning developed during the burner's recent recommissioning, which used house gas with nearly the same exact heating value and Wobbe index as Adj2TC. The recommissioning process was an extensive tuning process that involved setting the fuel flow, air flow, and FGR flow with the parallel positioning system for eight points along a firing rate curve to achieve low NOx performance as the firing rate ramps up. For interchangeability tests, since most of the tests were conducted near a fixed firing rate, tuning was achieved by only adjusting the fuel flow rate, and that was attained by adjusting the fuel delivery pressure to the burner. This involved adjusting the fuel pressure regulator, avoided reprogramming the parallel positioning system, and allowed each sequence of tests (each column in Table 13) to be performed during a single day. The initial adjustments to the fuel delivery pressure from one "adjust" gas to the next were based on achieving the same heat release in the boiler for the same firing rate output from the boiler's PID loop. This was followed by a smaller adjustment to ensure low NOx performance. Where the same "adjust" gas was used on consecutive days, the burner was not necessarily retuned.

Activities Performed

Setup

Preliminary tests with the boiler were conducted to determine an ideal firing rate (60%) which was within the ranges of the mass flow meters, and achievable steam pressure (70 psig) at that firing rate, the functionality of the blending station (by switching between the different "adjust" gases), the functionality of the CO₂ scrubber, and the functionality of the continuous emissions analyzers.

Continuous Tests – Constant Firing Rate

The boiler was first warmed up on house gas, at low fire until the water temperature reached 200 °F. The firing rate was ramped up with the PID loop in boiler's PLC control system set to manual mode. At about 25 psig steam pressure, the steam valves were partially opened. As the firing rate was further ramped up, the steam valves were opened further. When 60% firing rate was achieved, the steam valves were further adjusted until about 70 psig steam pressure was reached.

The fuel was then switched to Adj2TC, the continuous emissions analyzers were calibrated, and the burner was observed to have low NO_x performance (less than 9 ppm of NO_x was measured in the exhaust when corrected to 3% O₂). The steam valves were adjusted for near constant steam pressure. Twenty minutes of readings were collected by the data acquisition system at 5 second intervals.

The fuel was next switched to Sub1TC-A1, and another 20 minutes of readings were collected. This was repeated for Sub1TC-A2, Sub1TC-A3, Sub1TC-Hi, and Sub1TCM. The continuous emissions analyzers were then recalibrated.

The fuel was subsequently switched to Sub2TC-A1, and another 20 minutes of readings were collected. This was repeated for Sub2TC-A2, Sub2TC-A3, Sub2TC-Hi, and finally Sub2TCM. The calibrations of the continuous emissions analyzers were then checked.

The above sequence of tests were repeated on the next day with two changes. The first change was that Adj1TC was used instead of Adj2TC. The second change was that the fuel pressure regulator on the boiler was adjusted upward for Adj1TC to achieve the same heat input into the boiler as Adj2TC. Low NO_x performance was observed and testing proceeded.

This sequence of tests were repeated on the third day with two changes. The first change was that Adj3TC was used instead of Adj1TC. The second change was that the fuel pressure regulator on the boiler was first adjusted downward for Adj3TC to achieve the same heat input into the boiler as Adj1TC. Low NO_x performance was not observed so the fuel pressure was reduced a little more. Low NO_x performance was then observed and testing proceeded.

For all of the above sequences with constant firing rate, the response of the boiler's performance in terms of steam pressure was recorded with the emissions data at 5 second intervals.

Continuous Tests – Constant Steam Pressure

The boiler was first warmed up on house gas, at low fire until the water temperature reached 200 °F. The firing rate was ramped up with the PID loop in boiler's PLC control system set to manual mode. At about 25 psig steam pressure, the steam valves were partially opened. As the firing rate was further ramped up, the steam valves were opened further. When 60% firing rate was achieved, the steam valves were further adjusted until about 70 psig steam pressure was reached.

The fuel was then switched to Adj3TC, the continuous emissions analyzers were calibrated, and the burner was observed to have borderline low NO_x performance (exactly 9 ppm of NO_x was measured in the exhaust when corrected to 3% O₂).

The fuel pressure regulator on the boiler was first adjusted slightly downward and NO_x dropped below 9 ppm.

The steam valves were adjusted for near constant steam pressure at about 70 psig. The PID loop in boiler's PLC control system was switched to automatic mode with a setpoint of 70 psig steam pressure.

The fuel flow to the boiler began to oscillate with a 5 minute period and an increasing amplitude, indicating unstable control. The peaks of the oscillations exceeded the range of the clean gas mass flow meter. This mode of operation had not been attempted before during use at GTI; the boiler has always run under manual control. The proportional band of the PID loop was then adjusted to dampen the oscillations so that the peaks of the oscillations were still within the range of the clean gas mass flow meter. Twenty minutes of readings were collected by the data acquisition system at 5 second intervals.

The fuel was next switched to Sub1TC-A1, and another 20 minutes of readings were collected. This was repeated for Sub1TC-A2, Sub1TC-A3, Sub1TC-Hi, and Sub1TCM. The continuous emissions analyzers were then recalibrated.

The fuel was subsequently switched to Sub2TC-A1, and another 20 minutes of readings were collected. This was repeated for Sub2TC-A2, Sub2TC-A3, Sub2TC-Hi, and finally Sub2TCM. The calibrations of the continuous emissions analyzers were then checked.

The above sequence of tests was repeated on the next day with two changes. The first change was that Adj2TC was used instead of Adj3TC. The second change was that the fuel pressure regulator on the boiler was first adjusted upward for Adj2TC to achieve the same heat input into the boiler as Adj3TC, and then adjusted slightly downward to achieve low NO_x performance. Testing then proceeded.

This sequence of tests were repeated on the following day with two changes. The first change was that Adj1TC was used instead of Adj2TC. The second change was that the fuel pressure regulator on the boiler was first adjusted upward for Adj1TC to achieve the same heat input into the boiler as Adj2TC. Low NO_x performance was not observed so the fuel pressure was reduced a little. Low NO_x performance was then observed and testing proceeded.

For all of the above sequences with constant steam pressure, the response of the boiler's control system in terms of fuel flow rate was recorded with the emissions data at 5 second intervals. In addition, the minimum and maximum output of the PID loop was manually recorded for one oscillation cycle of the fuel flow rate.

Ignition Tests

For the continuous tests, ignition had not been a concern because the burner was not shut off and restarted between tests. There had been times when the burner failed to light (on house gas) on the first try at the beginning of the day's testing, but it usually lit on the first or second attempt.

To partially automate the process of performing the ignition tests, the boiler's control system was set to cycle the burner on and off at particular values of steam pressure. Normally, in automatic mode, the control system would modulate the firing rate to maintain a set steam pressure. To force the control system to cycle, the steam pressure setpoint was set outside (above) the "on" and "off" points. The steam pressure setpoint was set to 70 psig, while the "on" and "off" points were set to 30 psig and 50 psig, respectively. The maximum firing rate was limited to 60% output by setting another feature of the control system. The steam valves were opened enough so that the steam pressure would settle slightly above 70 psig at 60% firing rate had the burner been not allowed to shut off at 50 psig (i.e., by setting the control system to manual mode). This allowed for tuning of the burner at the usual conditions (60% firing rate).

The automated operation of the burner was such that at below 30 psig steam pressure, the burner would start at low fire (0% output), then the firing rate would be ramped up quickly to 60% output, the steam pressure would rise to 50 psig, the burner would be shut off, and the steam pressure would fall off, eventually reaching 30 psig. The observed cycle time between 30 psig and 50 psig and back to 30 psig, or more practically, between 50 psig and 30 psig and back to 50 psig, was about 20 minutes. Since multiple ignition tests with the same "adjust" or "substitute" gas were planned, this time was deemed too long to allow a single sequence of tests to be completed in one day. Part of the reason for the long cycle time was that the steam pressure would continue to fall off, as much as 8 psig, while the burner was restarting, which includes a purge portion. To shorten the cycle time, the "on" point was raised to 40 psig, then 45 psig, and finally to 47.5 psig. With a 47.5 psig "on" point and a 50 psig "off" point, the cycle time was reduced to about 5-6 minutes as long as the boiler was not taking in any fresh (cold)

water to maintain the water level in the boiler. With the boiler taking in fresh (cold) water, the cycle time was about 12-15 minutes.

The above setup work was done with the burner firing on house gas, and lastly on Adj1TC when the switch to the 47.5 psig "on" point was made. Also, the regulated gas pressure on the boiler was raised slightly to help shorten the cycle times while maintaining low NO_x performance (less than 9 ppm of NO_x was measured in the exhaust when corrected to 3% O₂) when the firing rate was at 60% during the "on" portion of the cycle. A test sequence began at this point.

The test plan was to have a discounted ignition (#0) after switching to a particular gas to allow the pilot line to be filled with that gas, and then to have three consecutive cycles with ignitions (#'s 1-3) on that gas (with both pilot line and main line filled with that gas) before switching to the next gas. The pilot only runs during the ignition process.

On the #2 ignition trial with Adj1TC, the burner would not light. Five additional attempts were made to light the burner. On the first two attempts, the main flame failed to light, while on the last four attempts, the pilot flame failed to lit. Visual observation was that the pilot flame was actually lighting, but the flame safeguard, which controls the purge-pilot ignition-main ignition-run-post purge process, was not seeing the pilot flame via its attached infrared flame sensor. The pilot and flame sensor follow parallel paths through the burner, and the pilot flame must be swirled by the combustion air so that at least a portion of it is visible to the flame sensor. The visual observation was that the pilot flame was not large enough to be reliably seen by the flame sensor.

Reliable ignition with an "adjust" gas is required for any suitable comparison with the "substitute" gases, so the pilot had to be adjusted. The fuel was switched back to house gas, and the pilot gas pressure regulated pressure (independent of the main gas regulated pressure that was used for tuning) was increased by 50%. After a couple of successful ignitions, the fuel was switched again to Adj1TC, and unreliable ignitions again occurred. The pilot gas pressure was raised by another 67%, and successful ignitions were finally achieved.

The test sequence with the "adjust" gas Adj1TC serving as a basis began on the following day. The burner was first started on house gas, the control system was placed in automatic mode, and the boiler was allowed to warm up. At 30 psig steam pressure, the switch was made from house gas to Adj1TC. At 50 psig steam pressure the boiler's control system shut off the burner and the steam pressure began dropping. At 47.5 psig steam pressure, the control system restarted the burner, and thus the discounted #0 ignition cycle began. The amplified flame sensor voltage, as displayed by the control system, was manually recorded for the pilot ignition and main ignition. The control system ramped the firing rate up to 60%, the steam pressure increased to 50 psig (after dropping to almost 40 psig during the purging and ignition), the control system shut off the burner, and the steam pressure decreased. At 47.5 psig steam pressure, the control system restarted the burner, beginning the #1 ignition cycle (the first cycle where the

pilot line was completely filled with the appropriate gas before ignition). Again the amplified flame sensor voltages were manually recorded for the pilot ignition and main ignition. The cycle repeated itself two more times (for the #2 and #3 ignitions), with the amplified flame sensor voltages were manually recorded for the ignitions.

After the #3 ignition with Adj1TC, the fuel was switched to Sub1TC-A1. Four ignition cycles (the discounted #0 and the recorded #'s 1-3) were allowed to be completed, with the amplified flame sensor voltages were manually recorded for the ignitions.

After the #3 ignition with Sub1TC-A1, the fuel was switched to Sub1TC-A2 and the above process of four ignition cycles was performed. This process was then repeated with Sub1TC-A3, Sub1TC-Hi, and Sub1TCM. The continuous emissions analyzers were then recalibrated.

The fuel was subsequently switched to Sub2TC-A1, and the above process of four ignition cycles was performed. This was repeated for Sub2TC-A2, Sub2TC-A3, Sub2TC-Hi, and finally Sub2TCM. The calibrations of the continuous emissions analyzers were then checked.

The above sequence of tests were repeated on the next weekday with two changes. The first change was that Adj2TC was used instead of Adj1TC. The second change was that the fuel pressure regulator on the boiler was first adjusted downward for Adj2TC to achieve the same heat input into the boiler as Adj1TC at 60% firing rate, and low NO_x performance was observed. Testing then proceeded.

The above sequence of tests was repeated on the following day with two changes. The first change was that Adj3TC was used instead of Adj2TC. The second change was that the fuel pressure regulator on the boiler was first adjusted downward for Adj3TC to achieve the same heat input into the boiler as Adj2TC, and then further adjusted downward to achieve low NO_x performance. Testing then proceeded.

Results

Continuous Tests – Constant Firing Rate

The major results from the continuous tests with constant firing rate are the emissions and the steam pressure (the system's response) when the boiler is tuned for low NO_x performance with a particular "adjust" gas, and the fuel is switched to various "substitute" gases. Figure 48 through Figure 200 show the emissions, steam pressure, and boiler temperatures over the 20 minute data collection intervals for each gas.

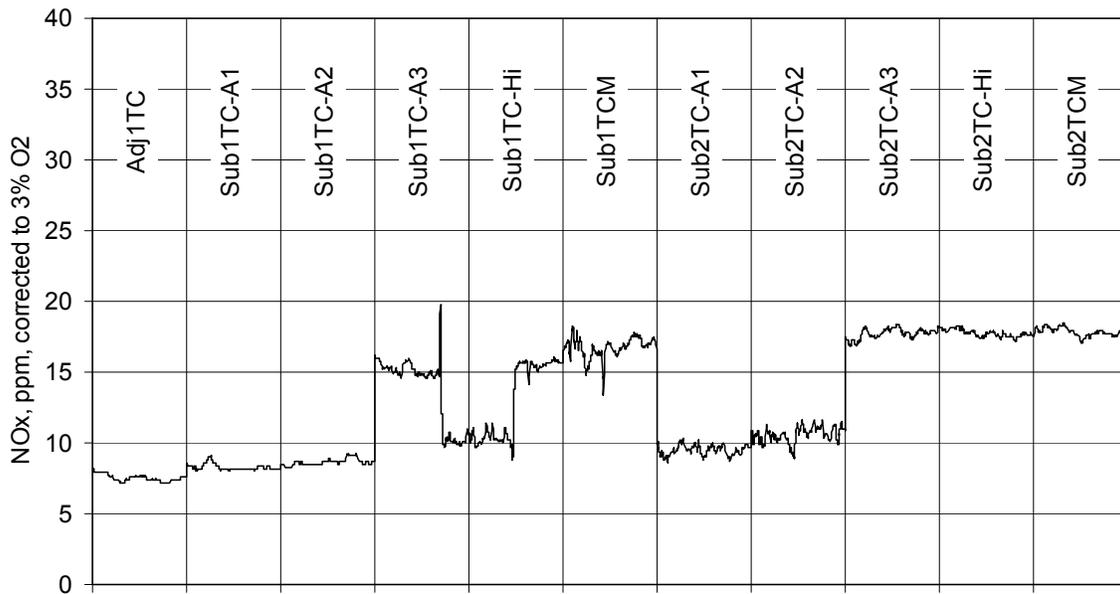


Figure 182. NO_x Emissions for Adjust1 tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

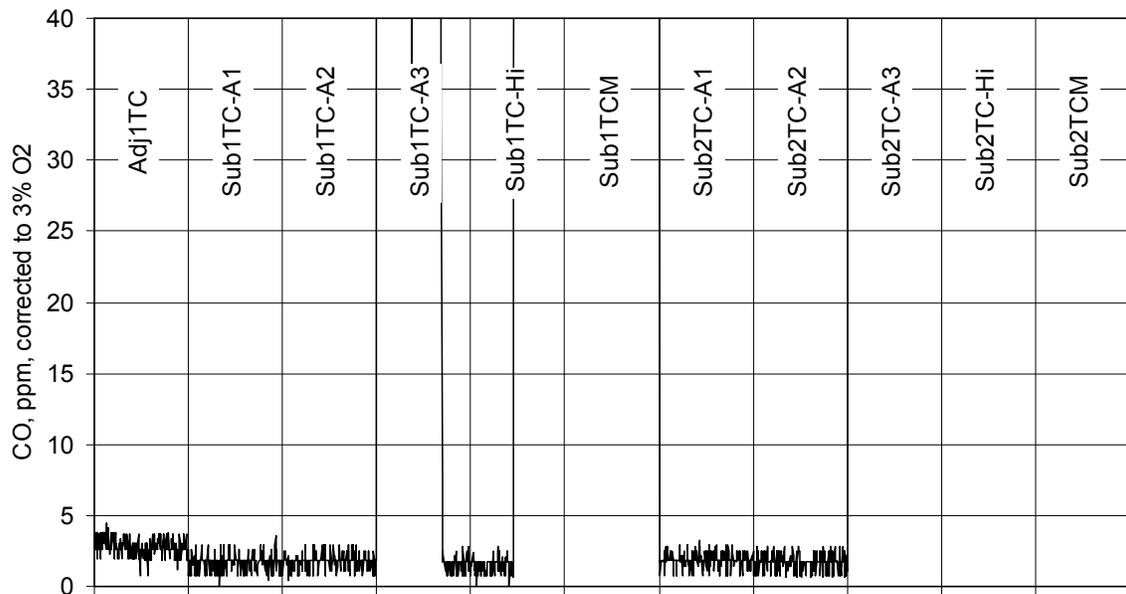
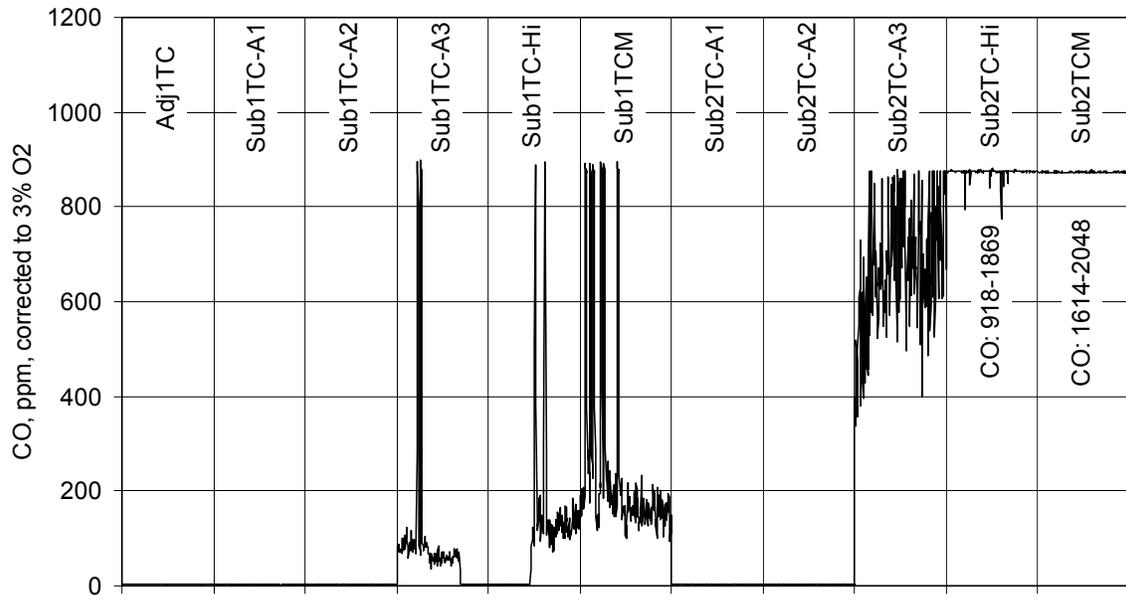


Figure 183. CO Emissions for Adjust1 tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

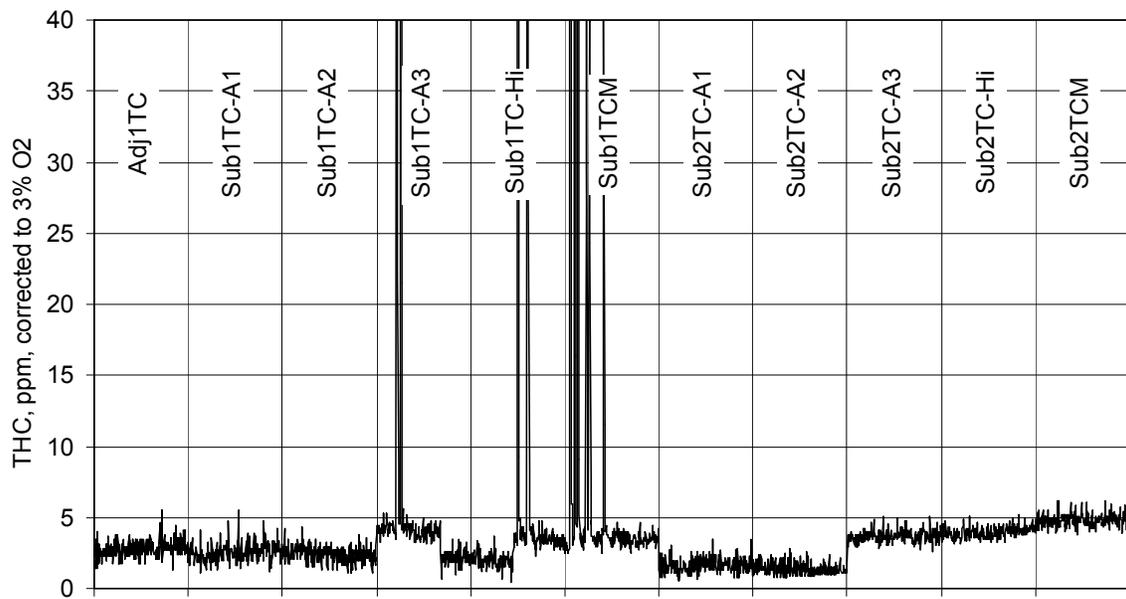
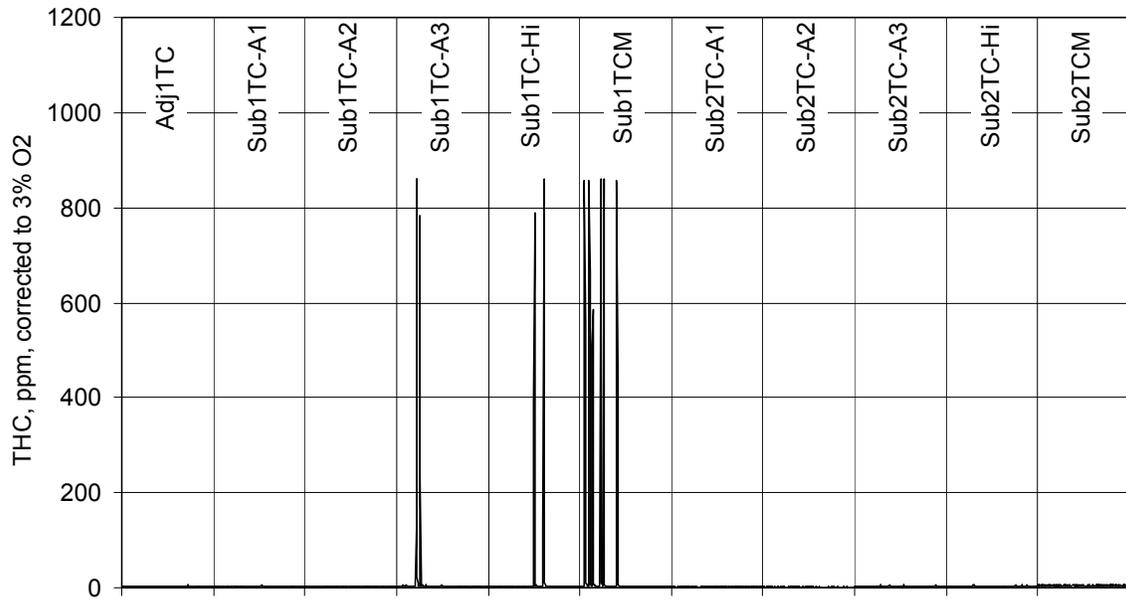


Figure 184. THC Emissions for Adjust1 tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

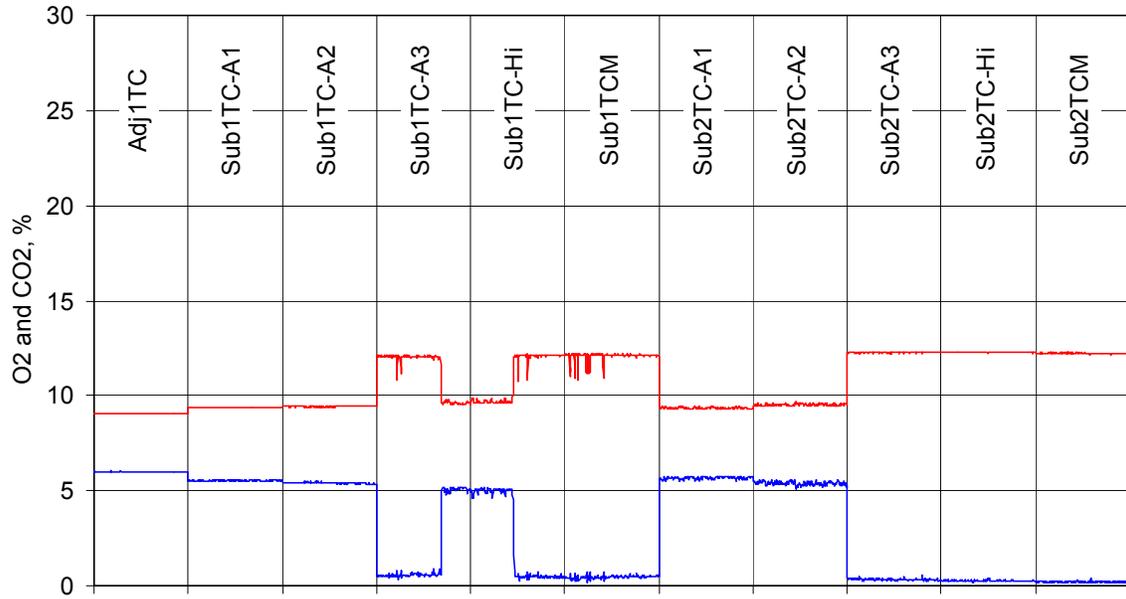


Figure 185. CO₂ and O₂ Emissions for Adjust1 tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

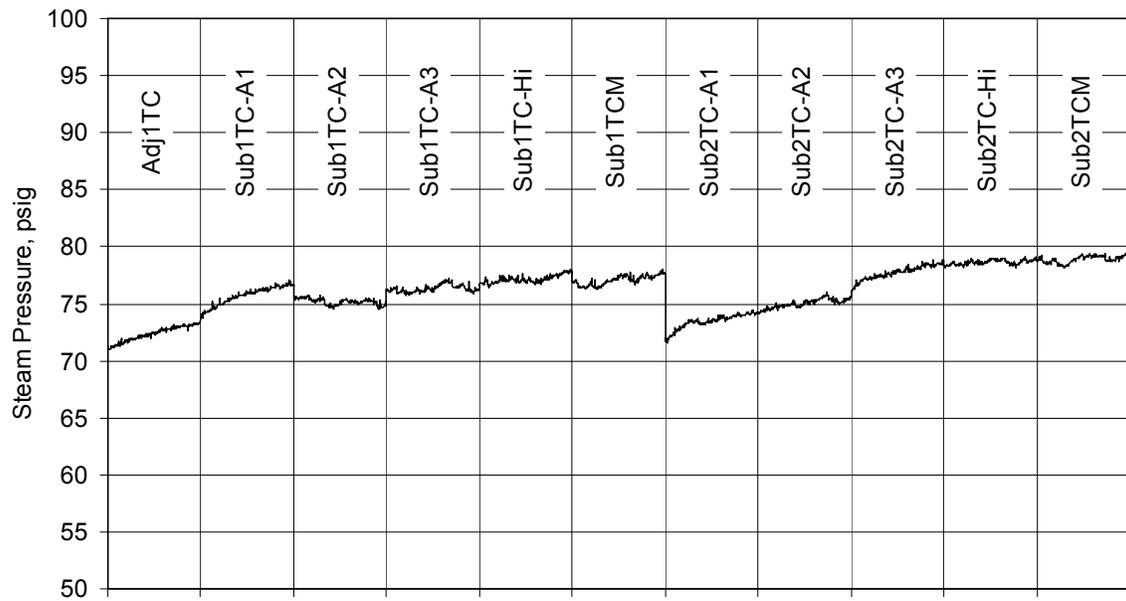


Figure 186. Steam Pressure for Adjust1 tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

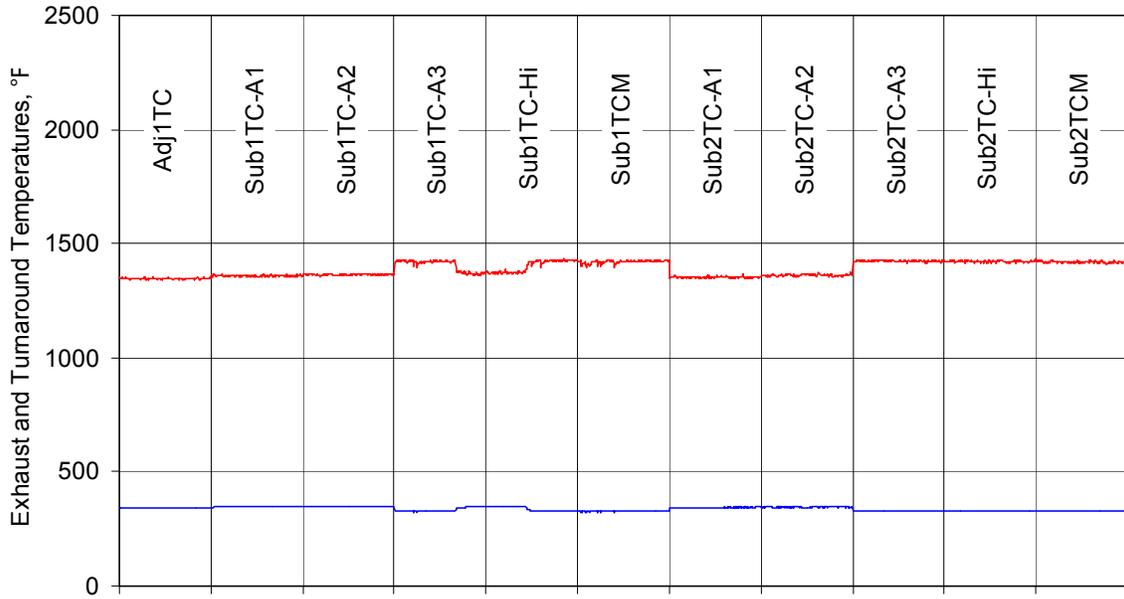


Figure 187. Exhaust and Turnaround Temperature for Adjust1 tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

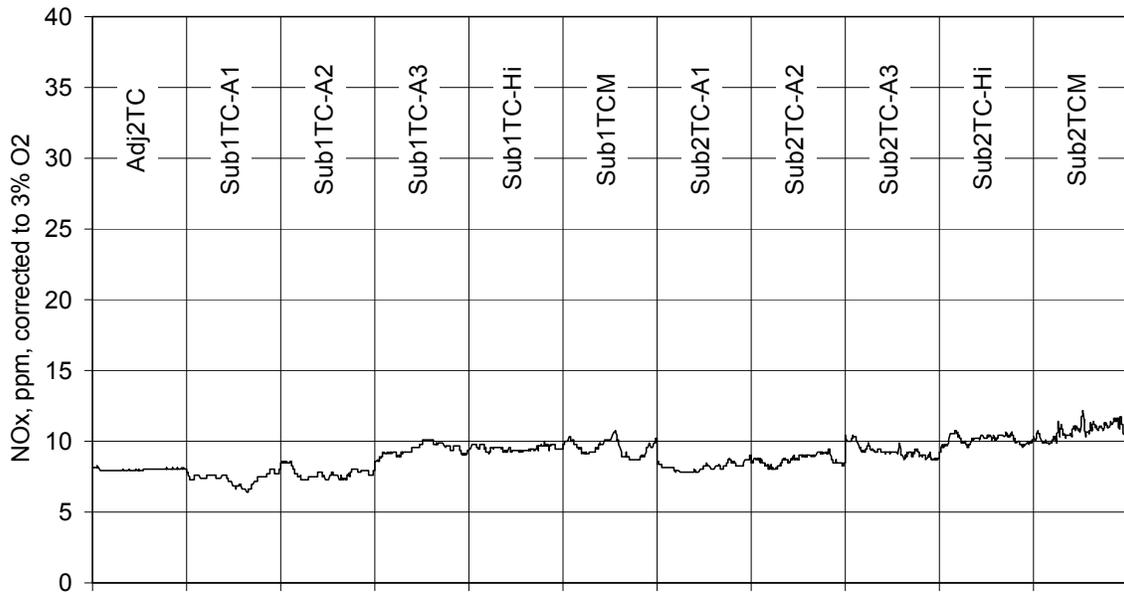


Figure 188. NOx Emissions for Adjust2 tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

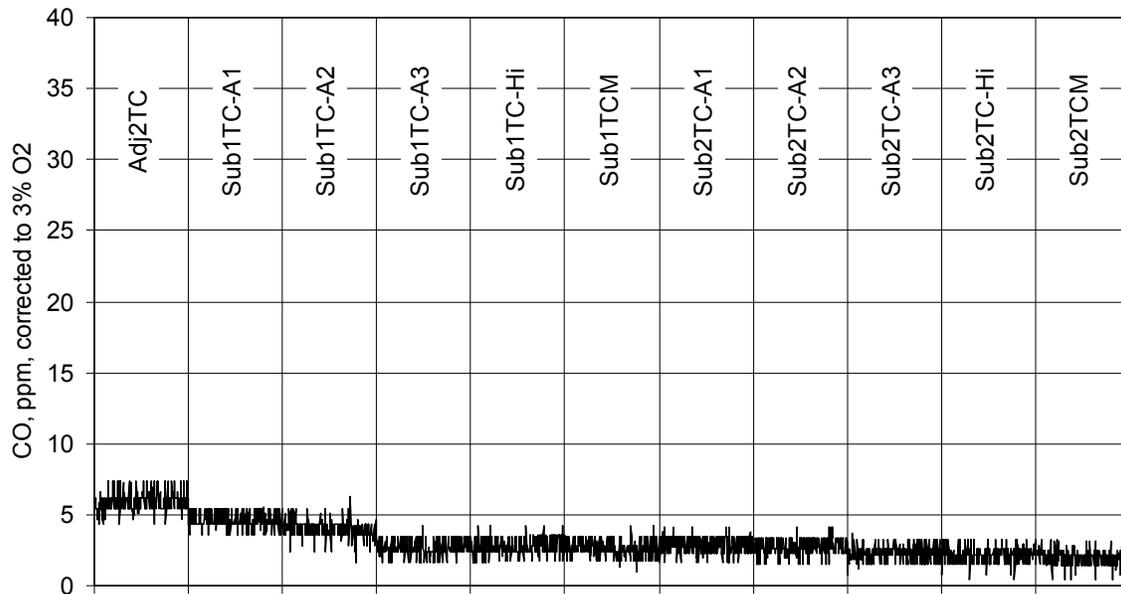


Figure 189. CO Emissions for Adjust2 tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

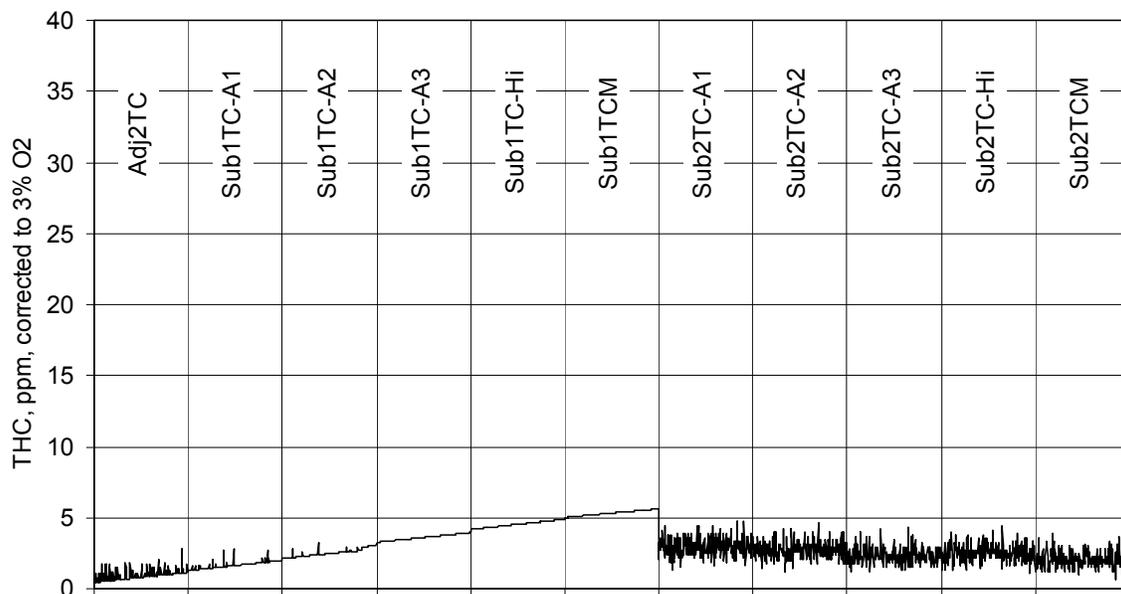


Figure 190. THC Emissions for Adjust2 tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

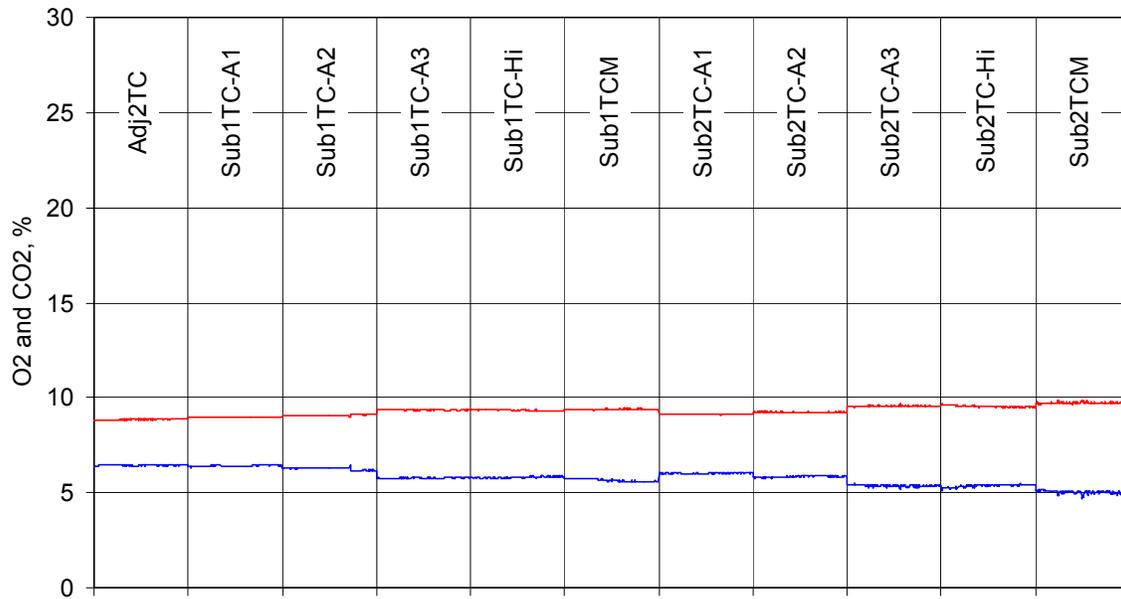


Figure 191. O₂ and CO₂ Emissions for Adjust2 tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

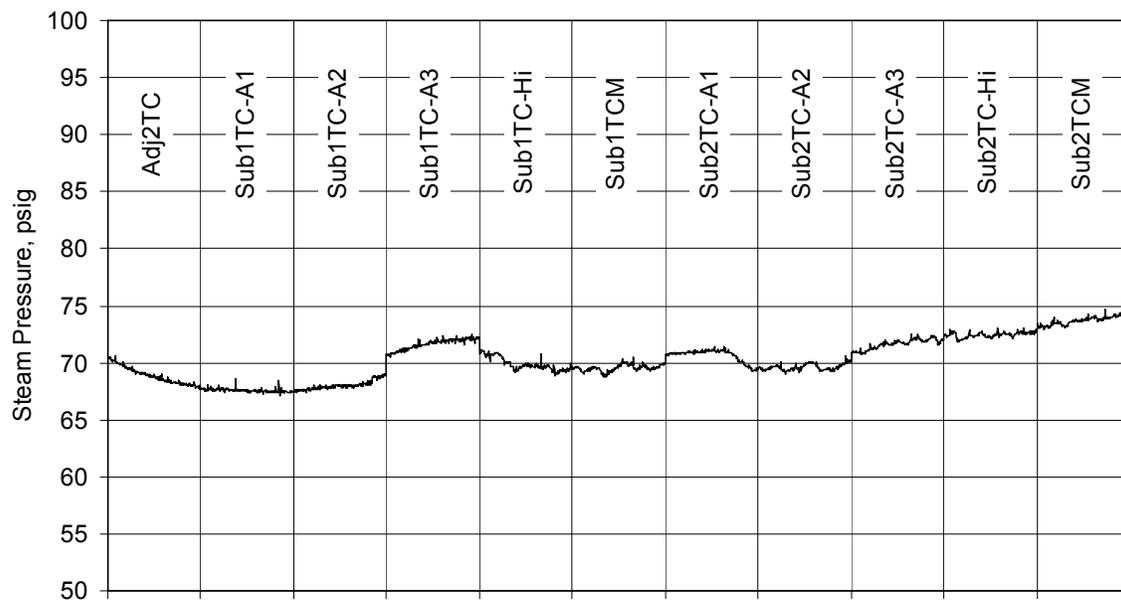


Figure 192. Steam Pressure for Adjust2 tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

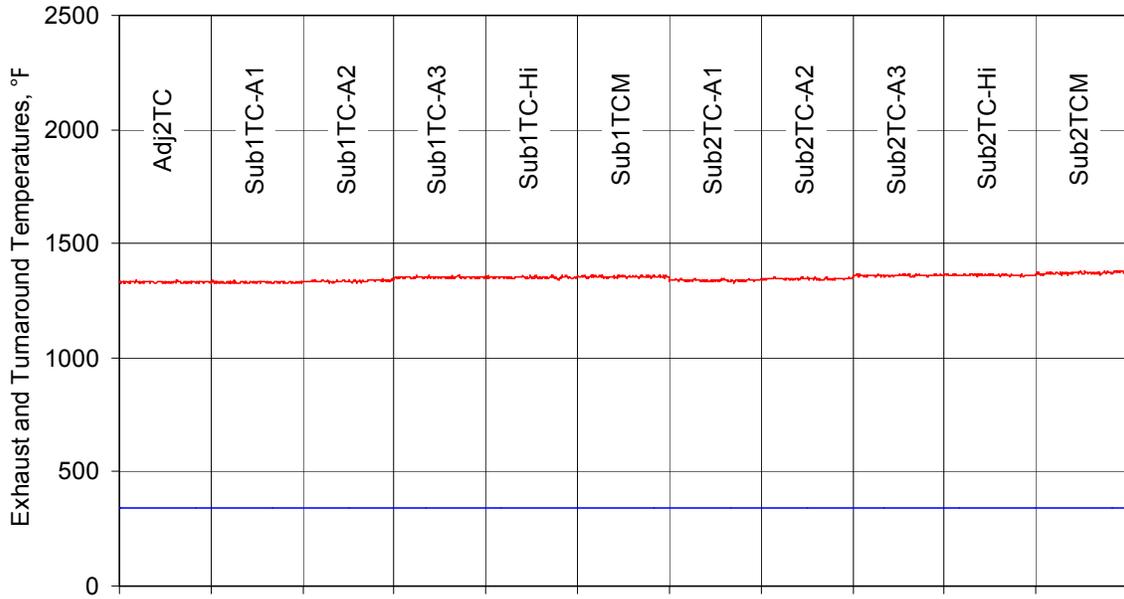


Figure 193. Exhaust and Turnaround Temperature for Adjust2 tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

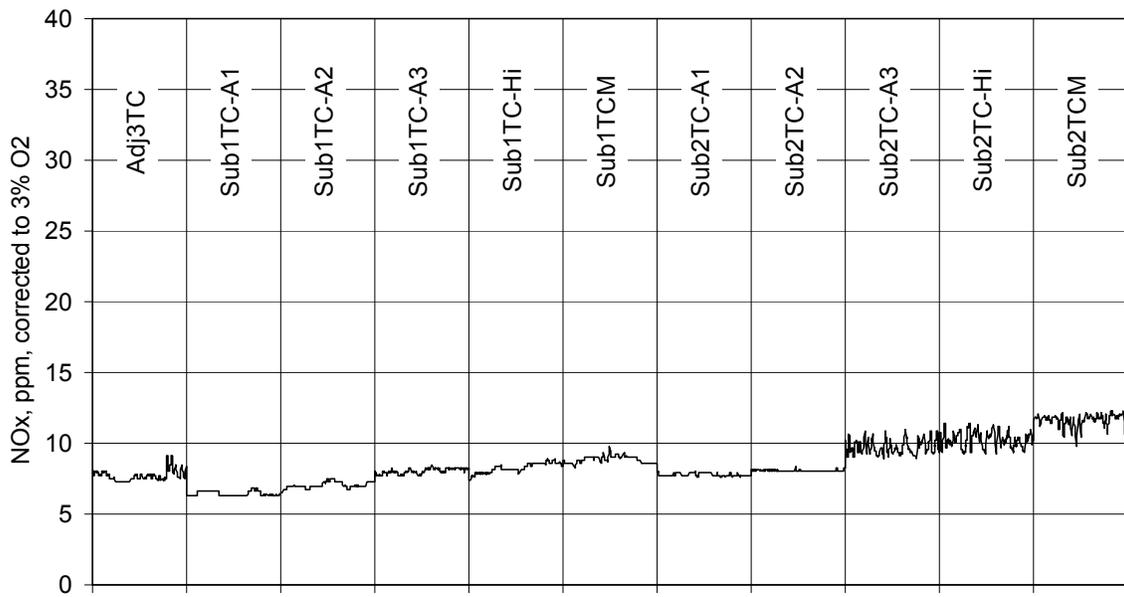


Figure 194. NO_x Emissions for Adjust3 tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

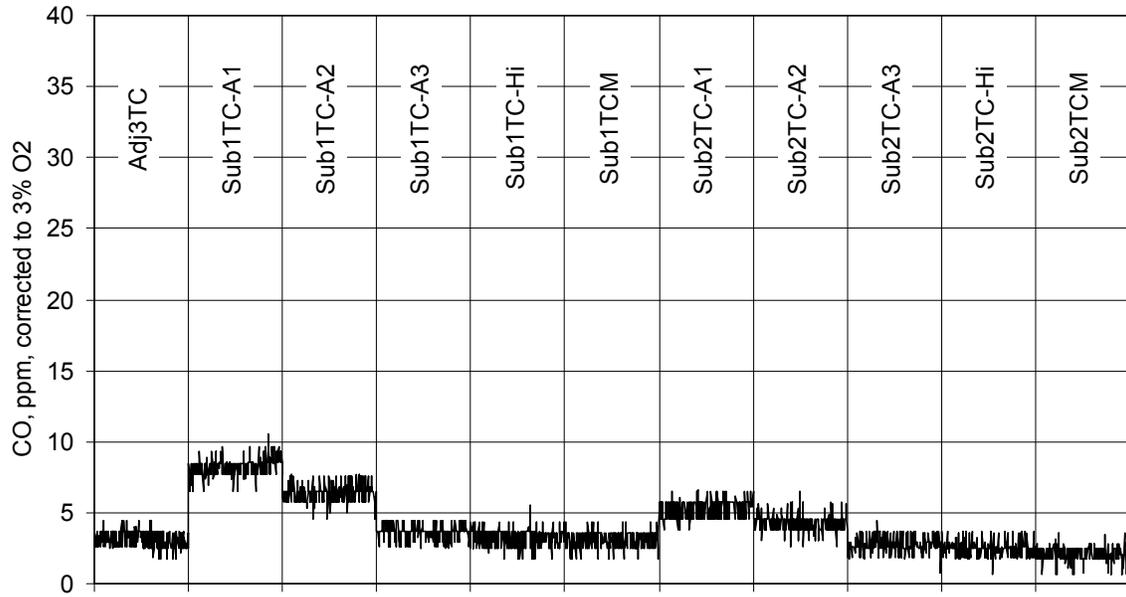


Figure 195. CO Emissions for Adjust3 tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

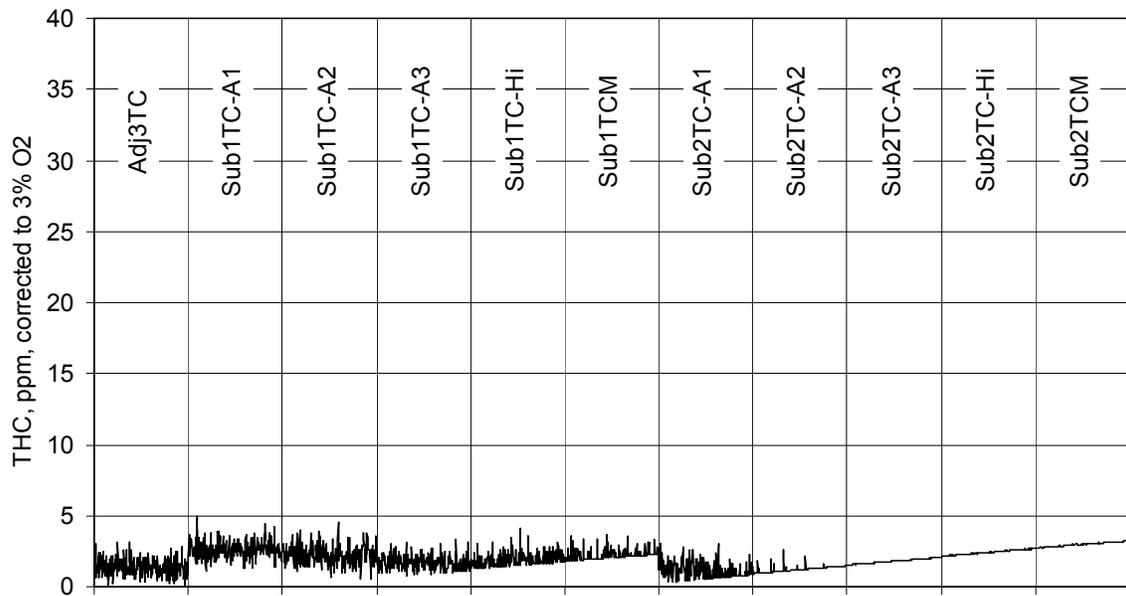


Figure 196. THC Emissions for Adjust3 tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

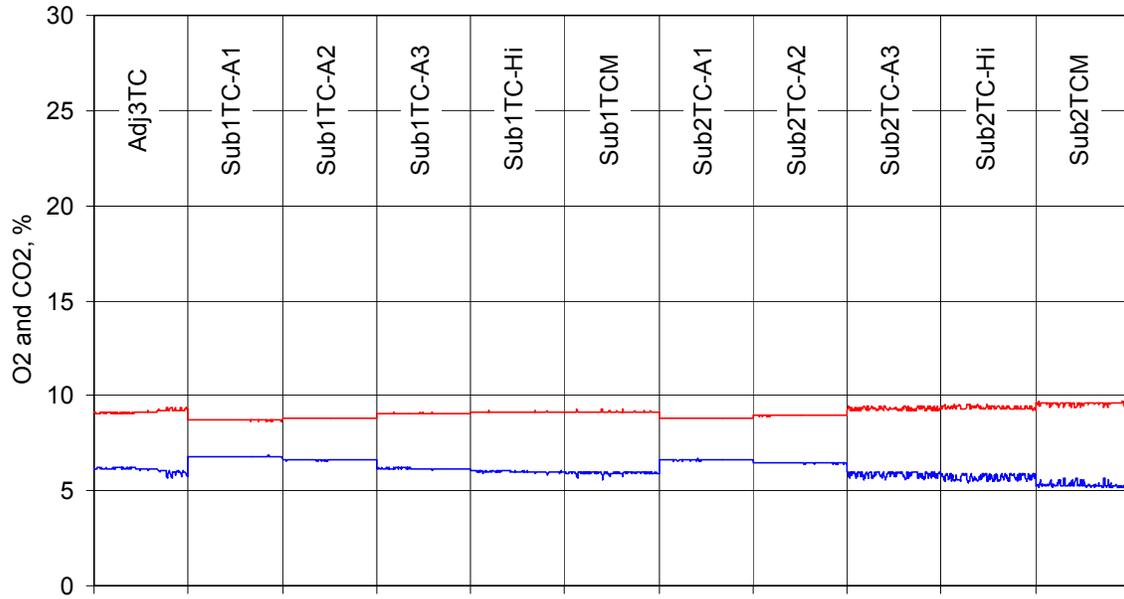


Figure 197. O₂ and CO₂ Emissions for Adjust3 tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

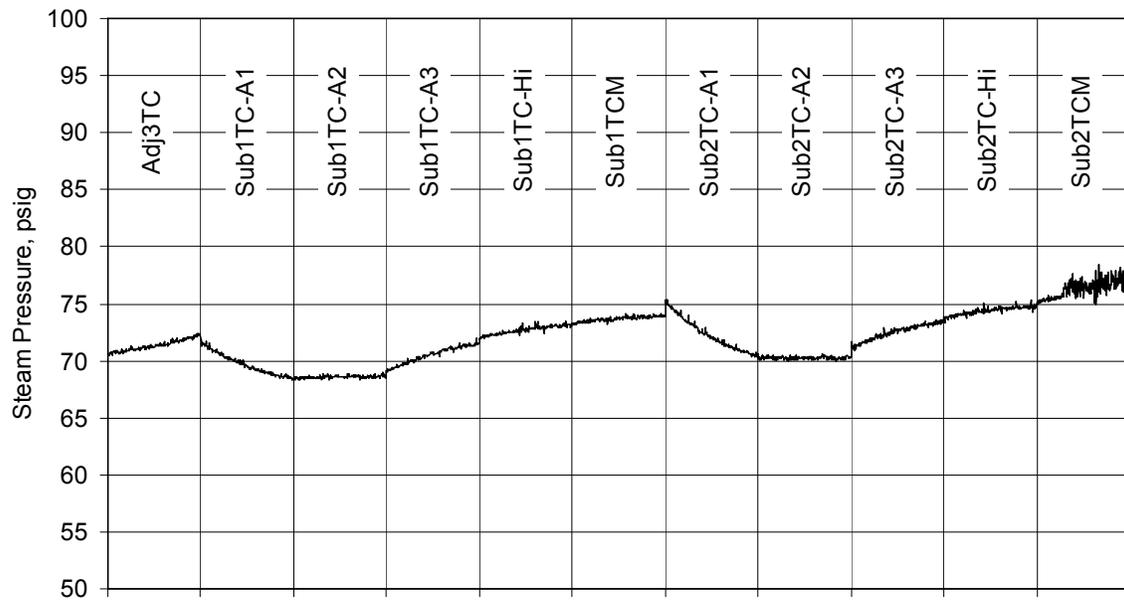


Figure 198. Steam Pressure for Adjust3 tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

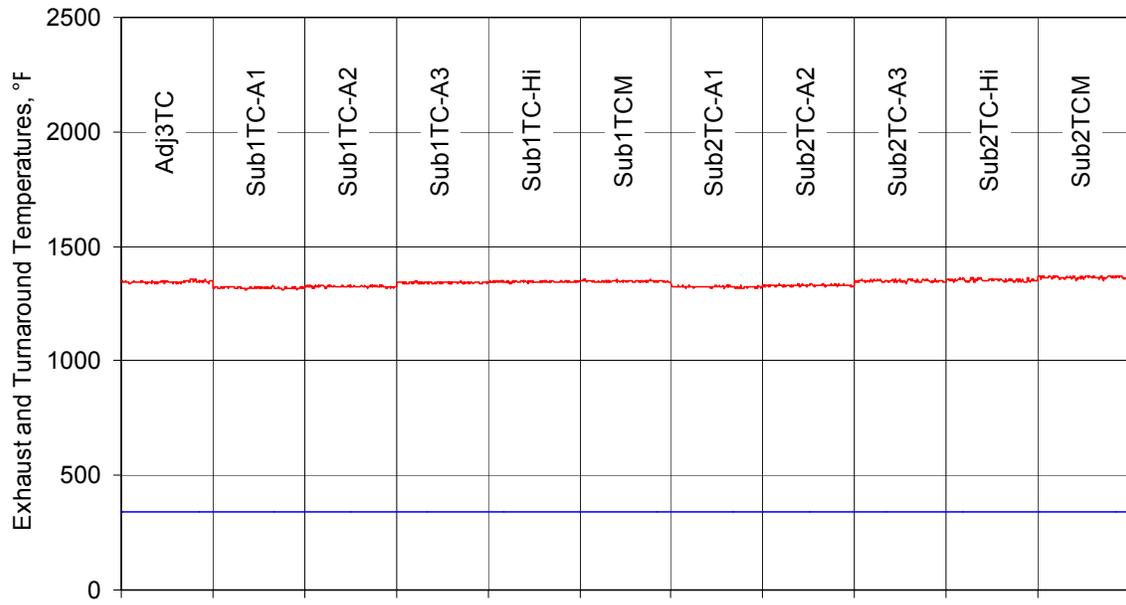


Figure 199. Exhaust and Turnaround Temperature for Adjust3 tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

Continuous Tests – Constant Steam Pressure

The major results from the continuous tests with constant steam pressure are the emissions and the fuel flow rate or heat input (the controller's response) when the boiler is tuned for low NO_x performance with a particular "adjust" gas, and the fuel is switched to various "substitute" gases. Figure 54 through Figure 221 show the emissions, fuel flow rate, heat input, and boiler temperatures over the 20 minute data collection intervals, which was about 4 oscillation cycles of the fuel flow rate.

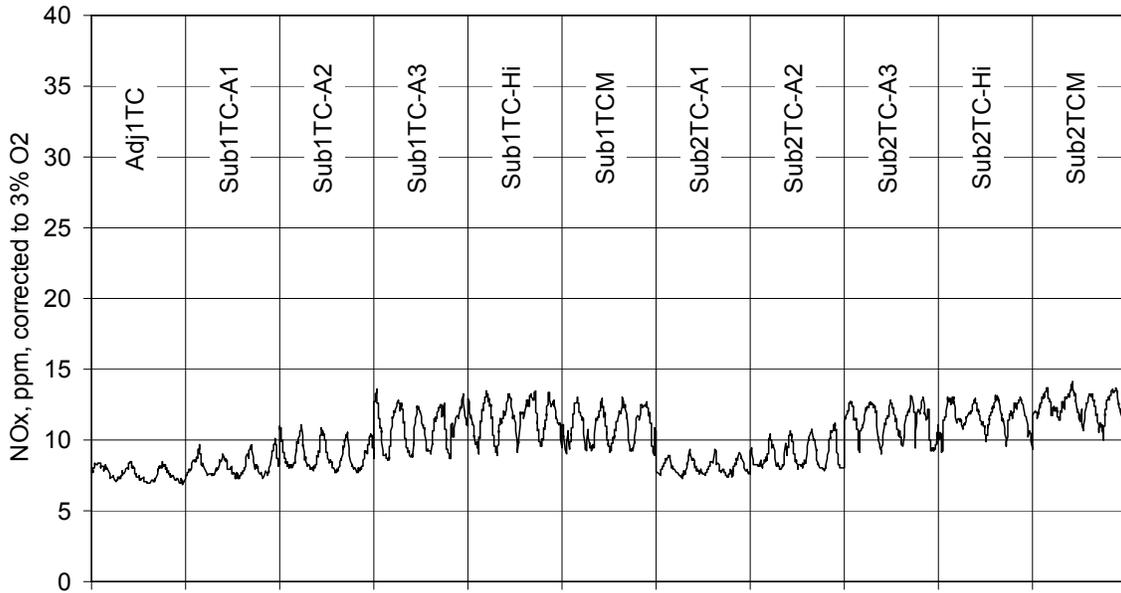


Figure 200. NO_x Emissions for Adjust1 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

(Corrected to 3% O₂)

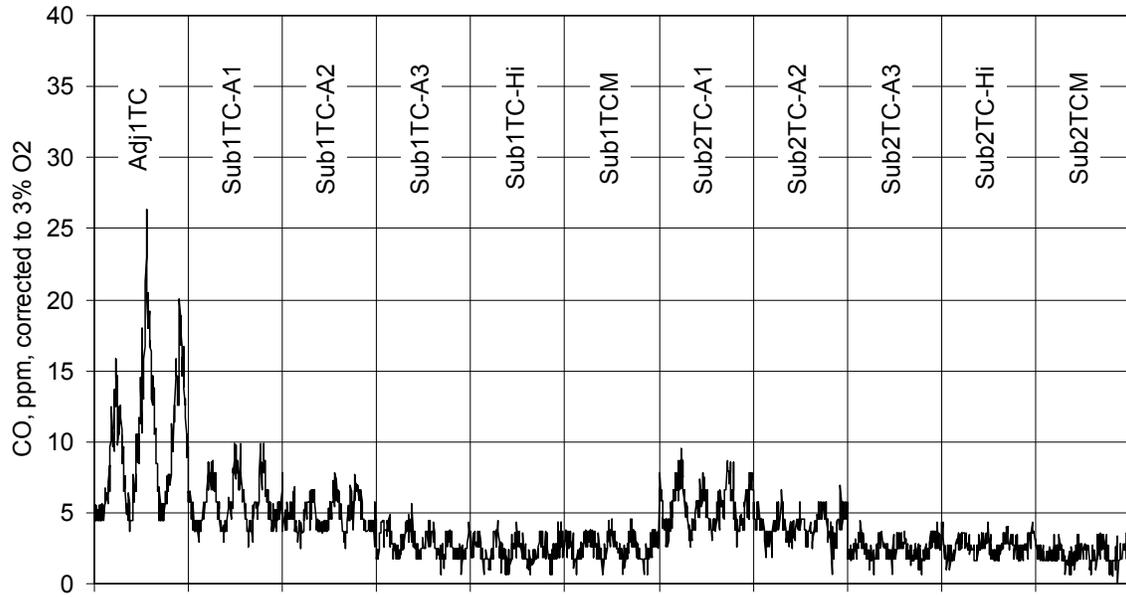


Figure 201. CO Emissions for Adjust1 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

(Corrected to 3% O₂)

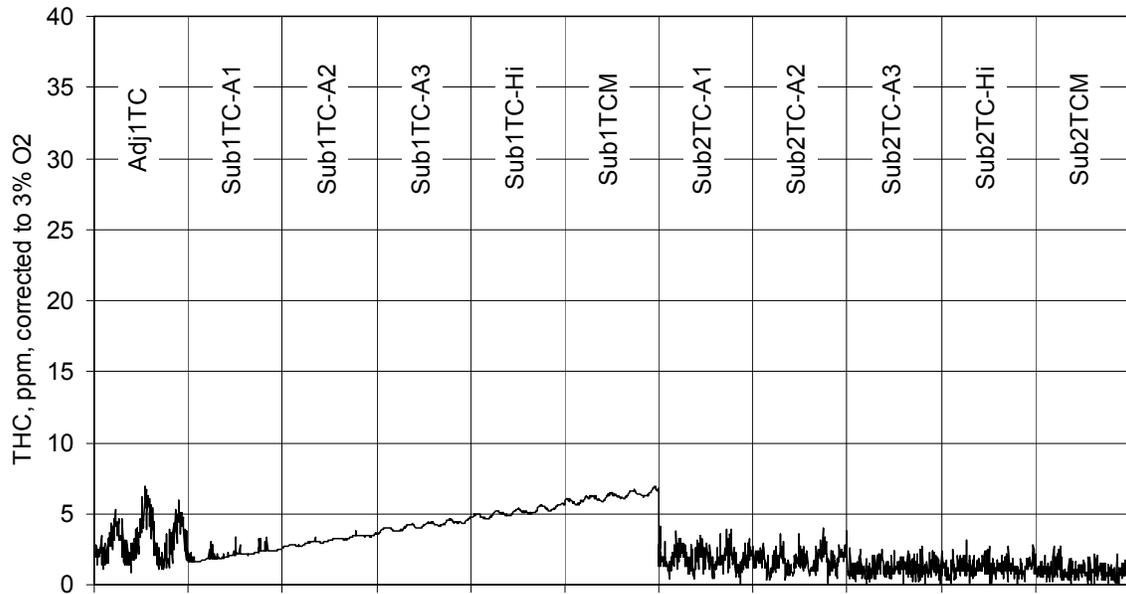


Figure 202. THC Emissions for Adjust1 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

(Corrected to 3% O₂)

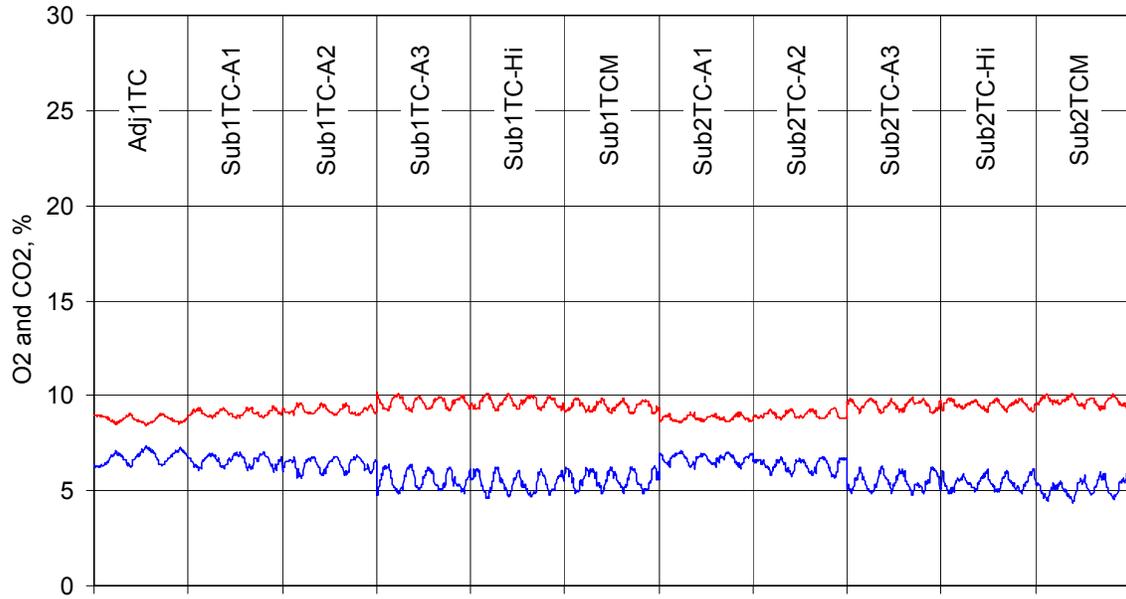


Figure 203. O₂ and CO₂ Emissions for Adjust1 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

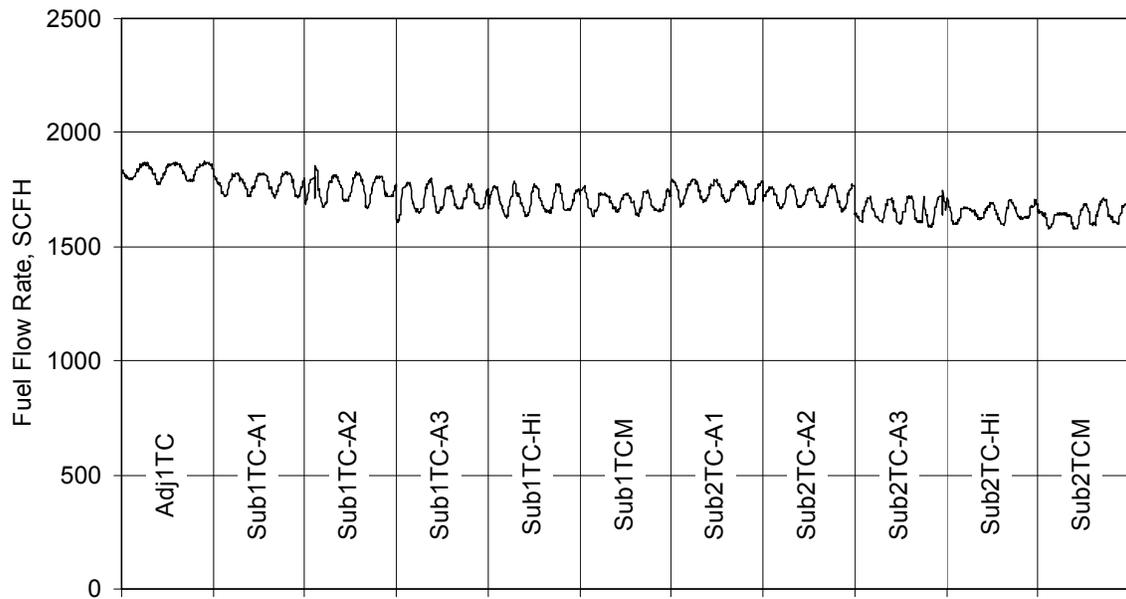


Figure 204. Fuel Flow Rate for Adjust1 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

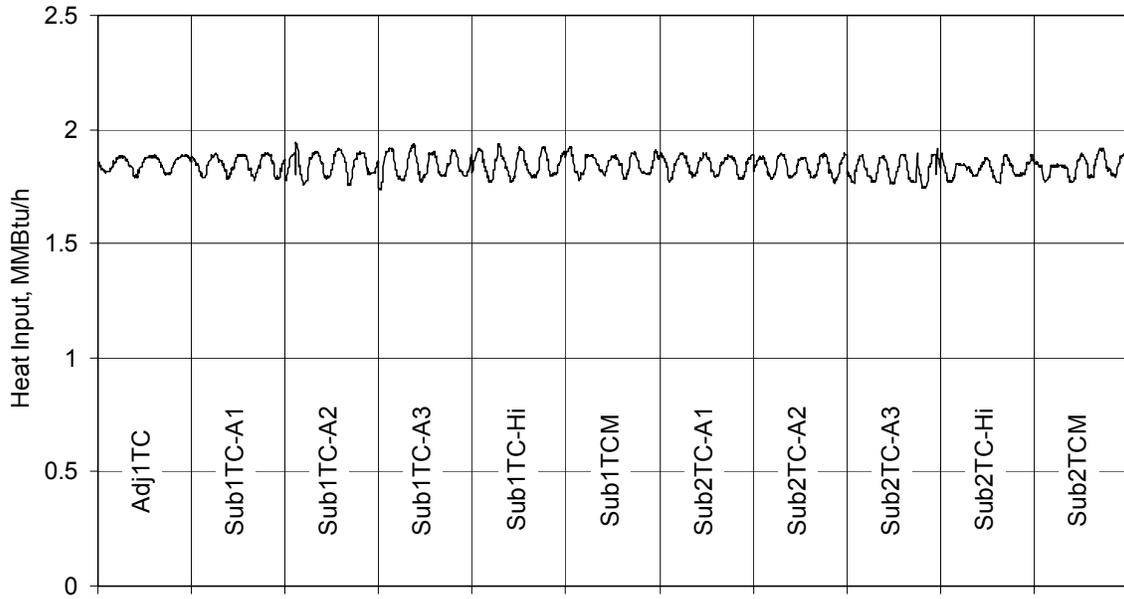


Figure 205. Heat Input for Adjust1 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

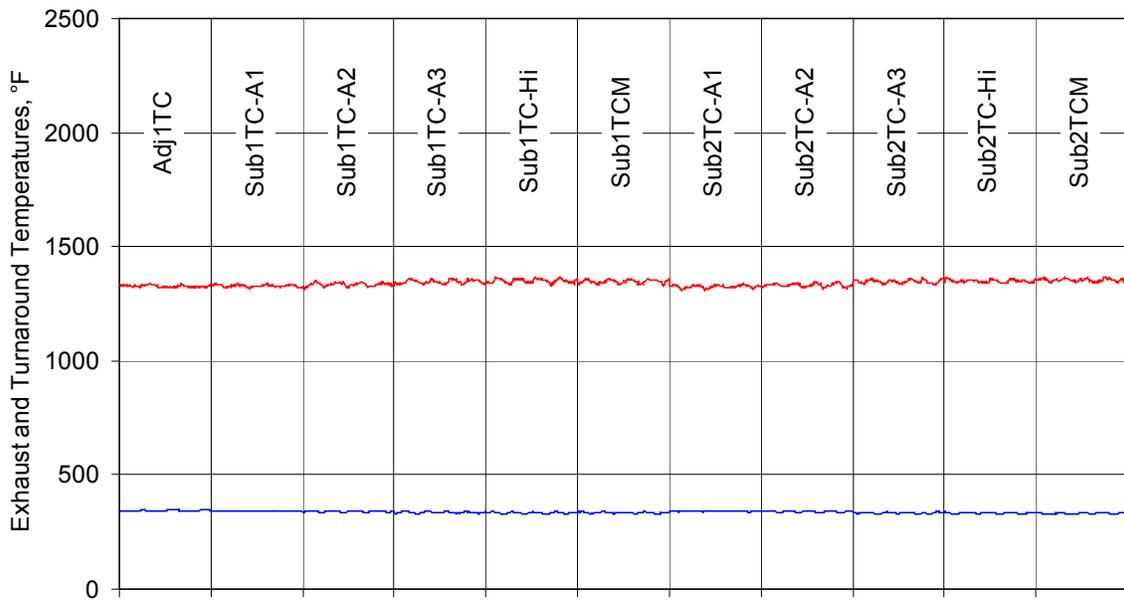


Figure 206. Exhaust and Turnaround Temperature for Adjust1 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

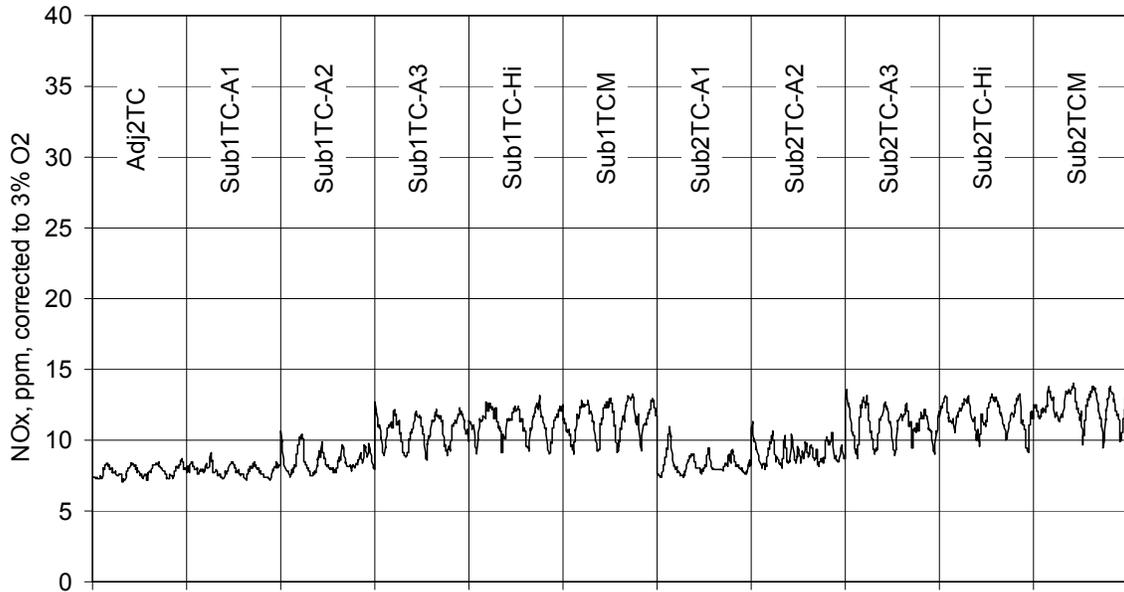


Figure 207. NOx Emissions for Adjust2 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

(Corrected to 3% O₂)

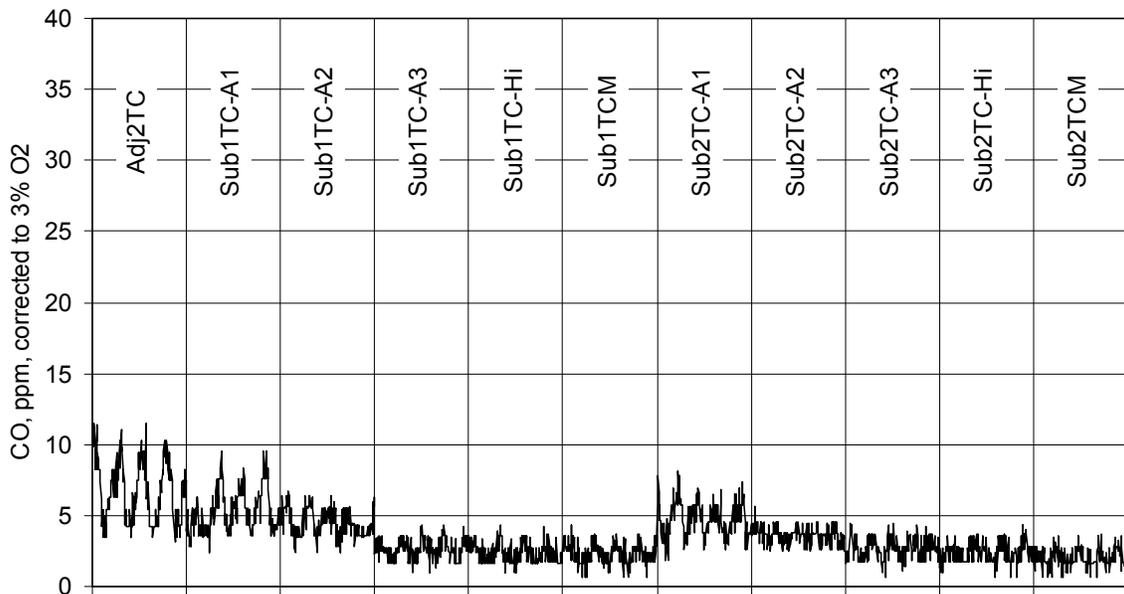


Figure 208. CO Emissions for Adjust2 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

(Corrected to 3% O₂)

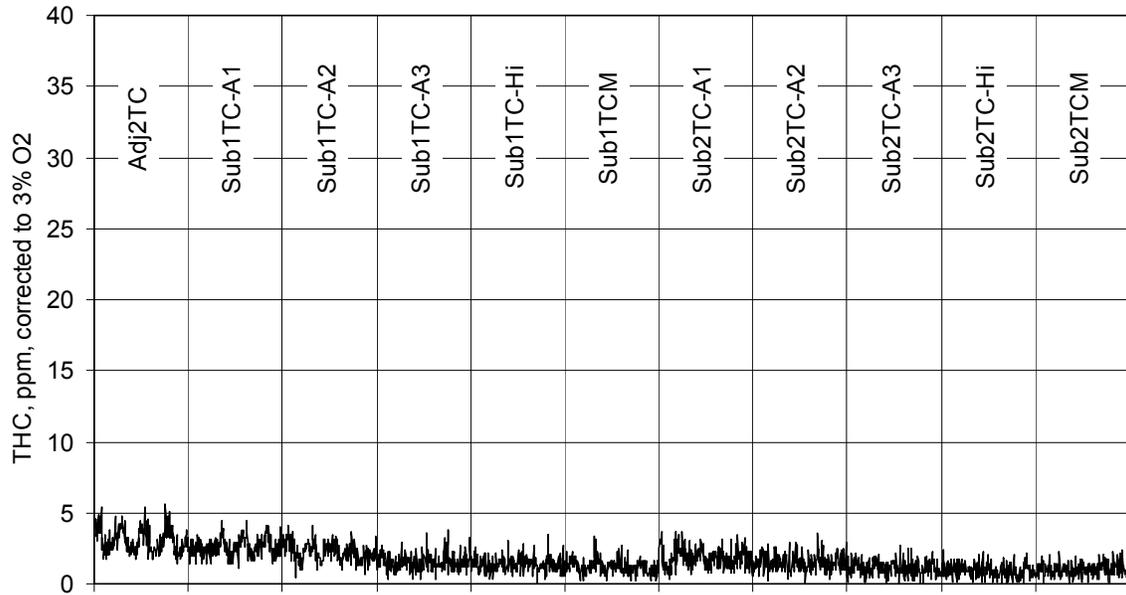


Figure 209. THC Emissions for Adjust2 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

(Corrected to 3% O₂)

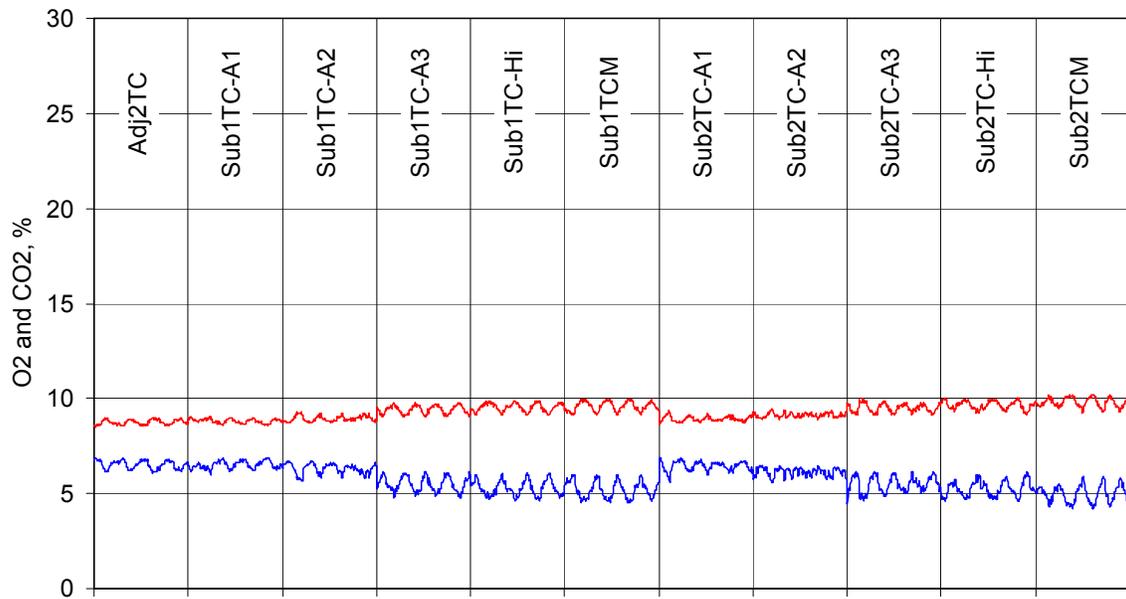


Figure 210. O₂ and CO₂ Emissions for Adjust2 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

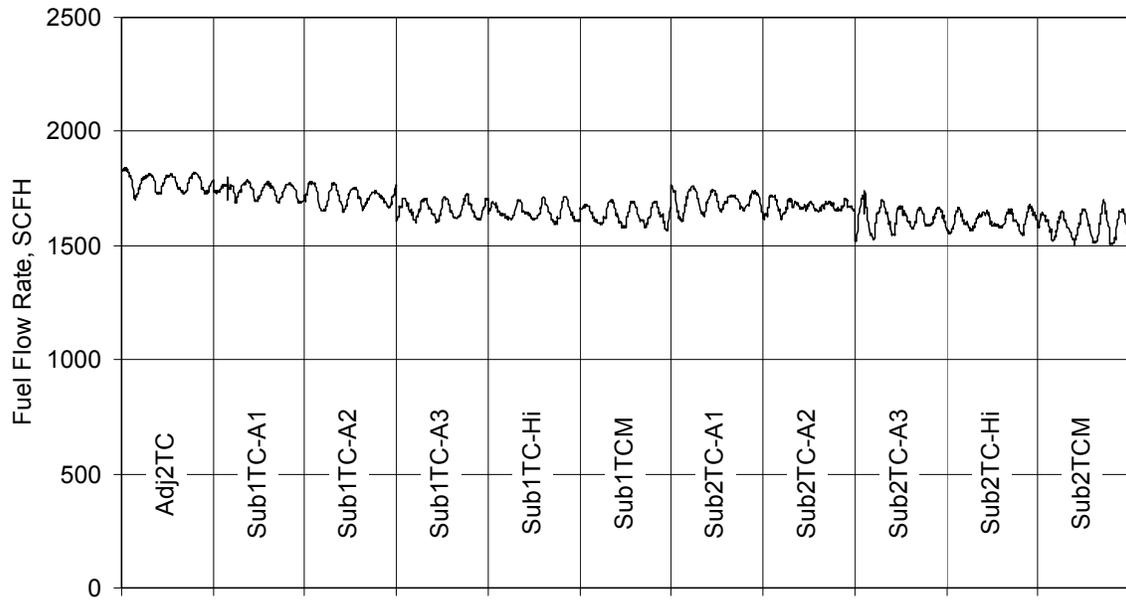


Figure 211. Fuel Flow Rate for Adjust2 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

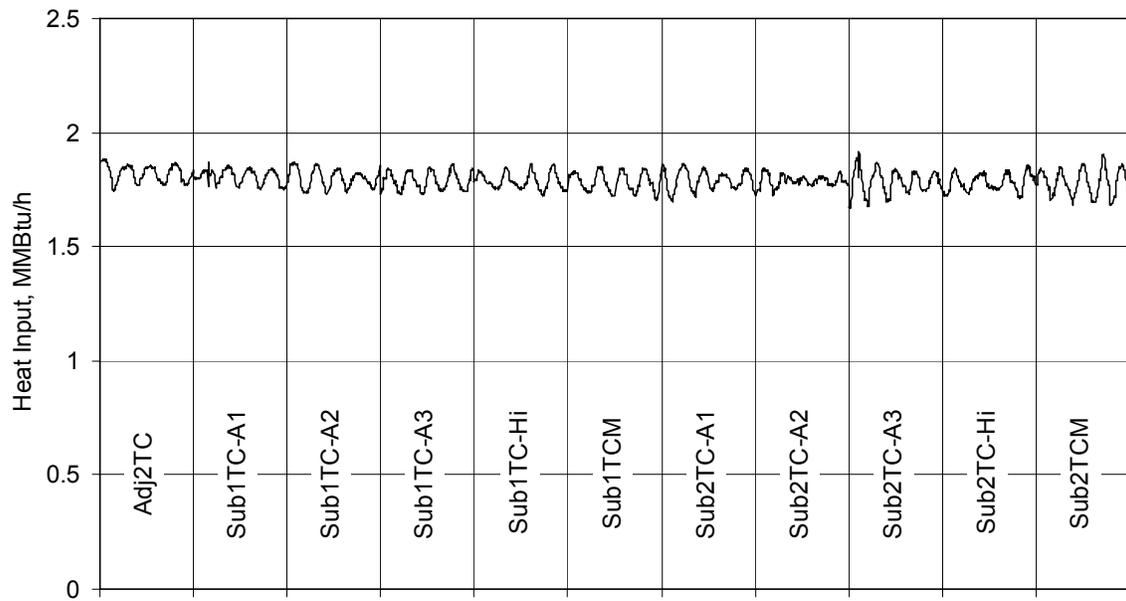


Figure 212. Heat Input for Adjust2 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

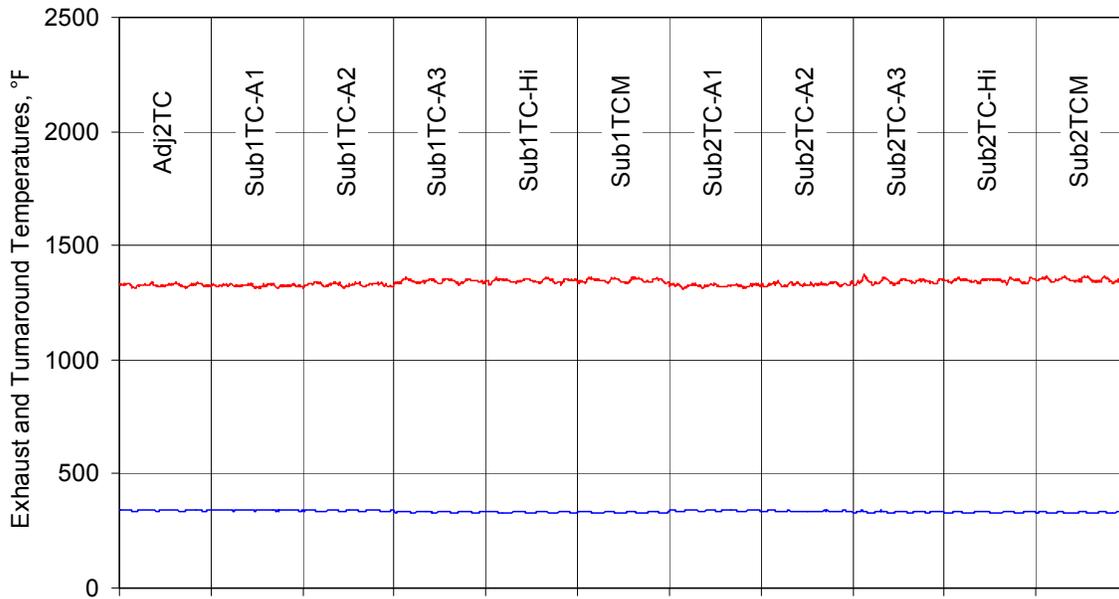


Figure 213. Exhaust and Turnaround Temperature for Adjust2 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

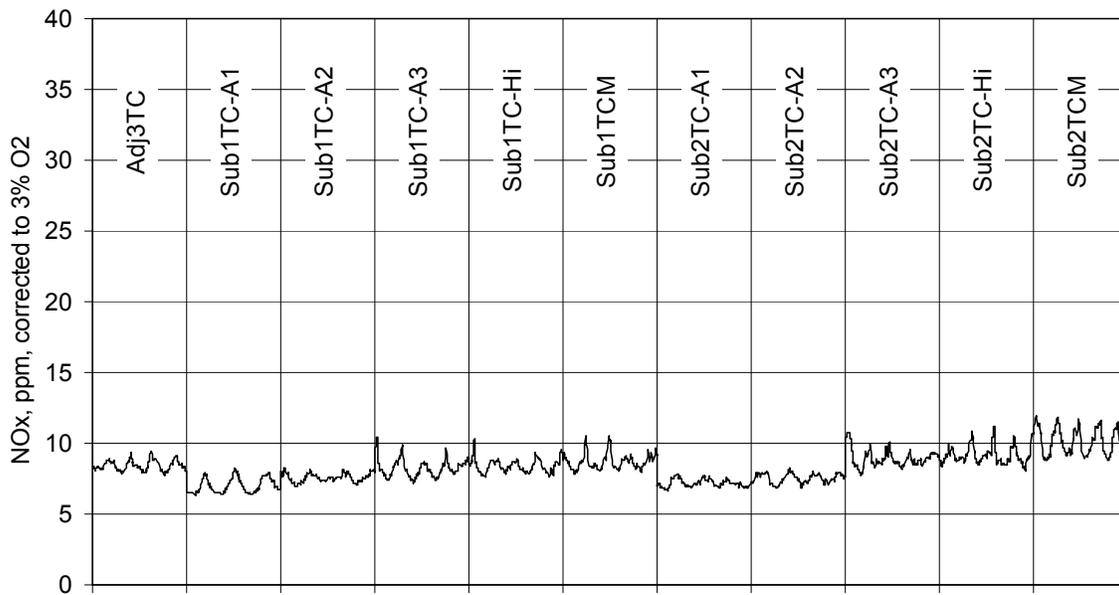


Figure 214. NO_x Emissions for Adjust3 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

(Corrected to 3% O₂)

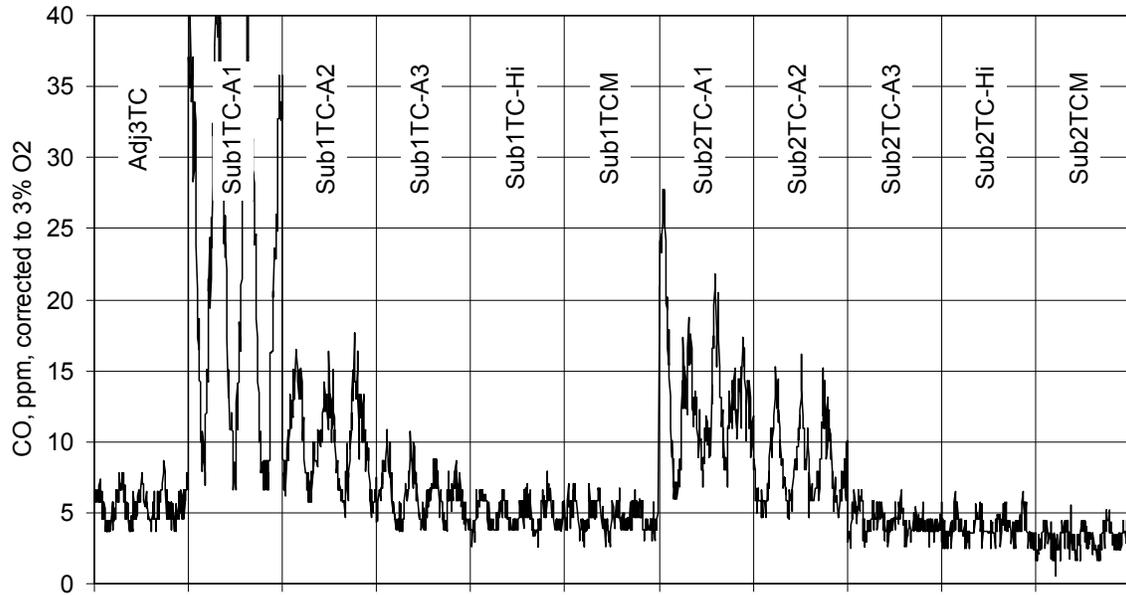


Figure 215. CO Emissions for Adjust3 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

(Corrected to 3% O₂)

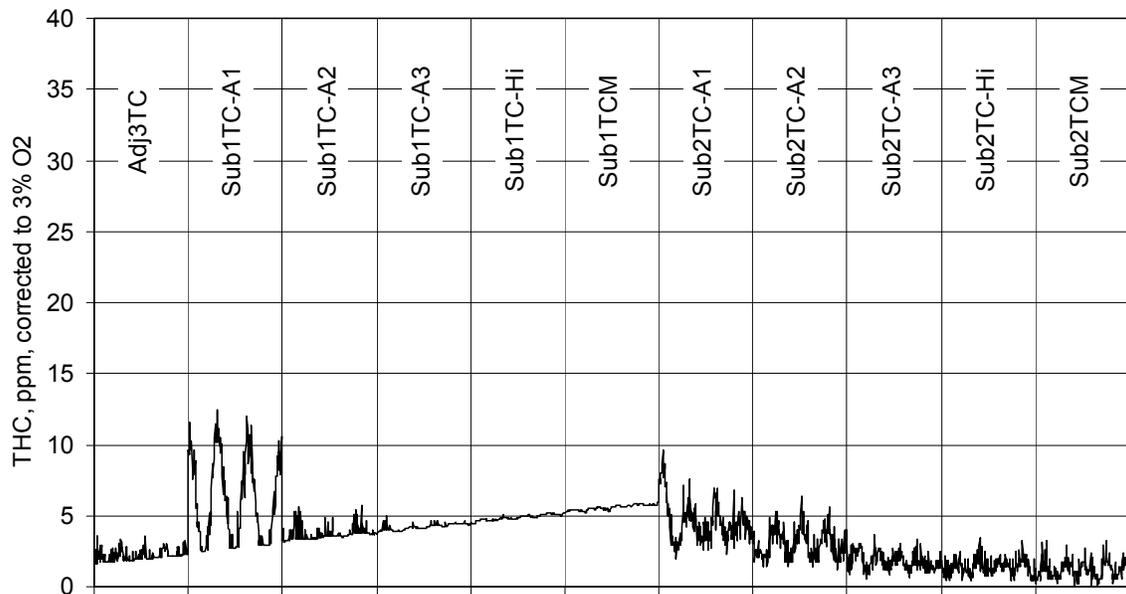


Figure 216. THC Emissions for Adjust3 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

(Corrected to 3% O₂)

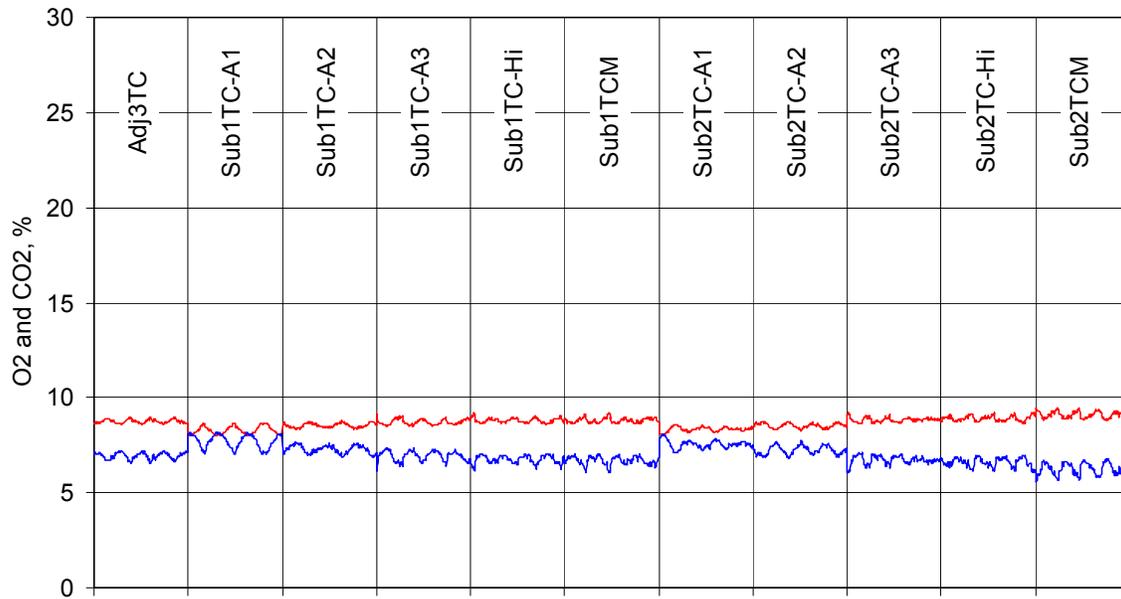


Figure 217. O₂ and CO₂ Emissions for Adjust3 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

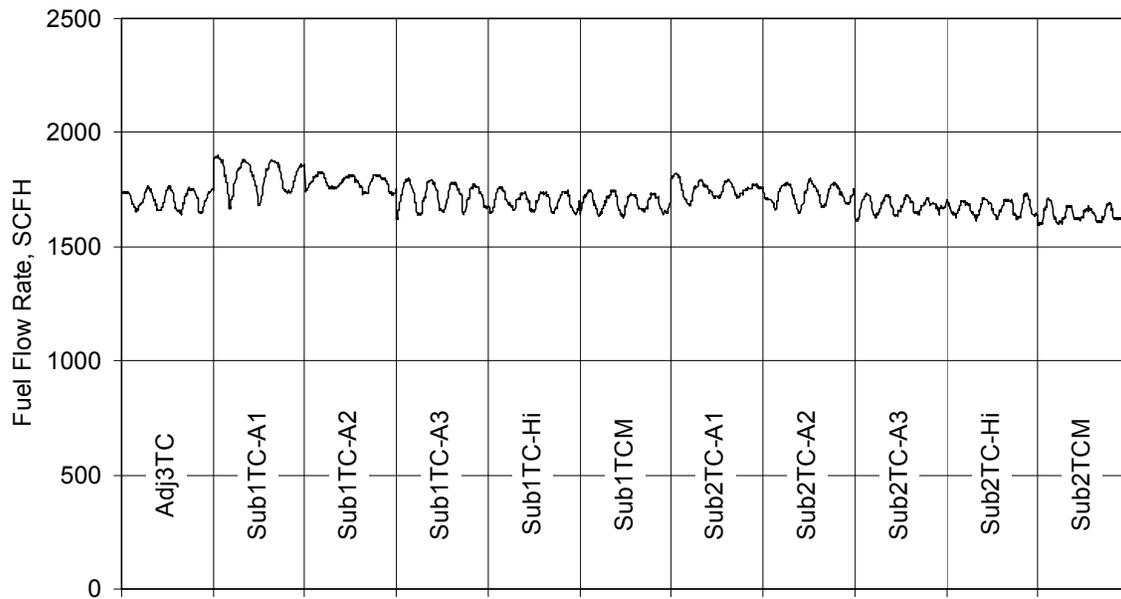


Figure 218. Fuel Flow Rate for Adjust3 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

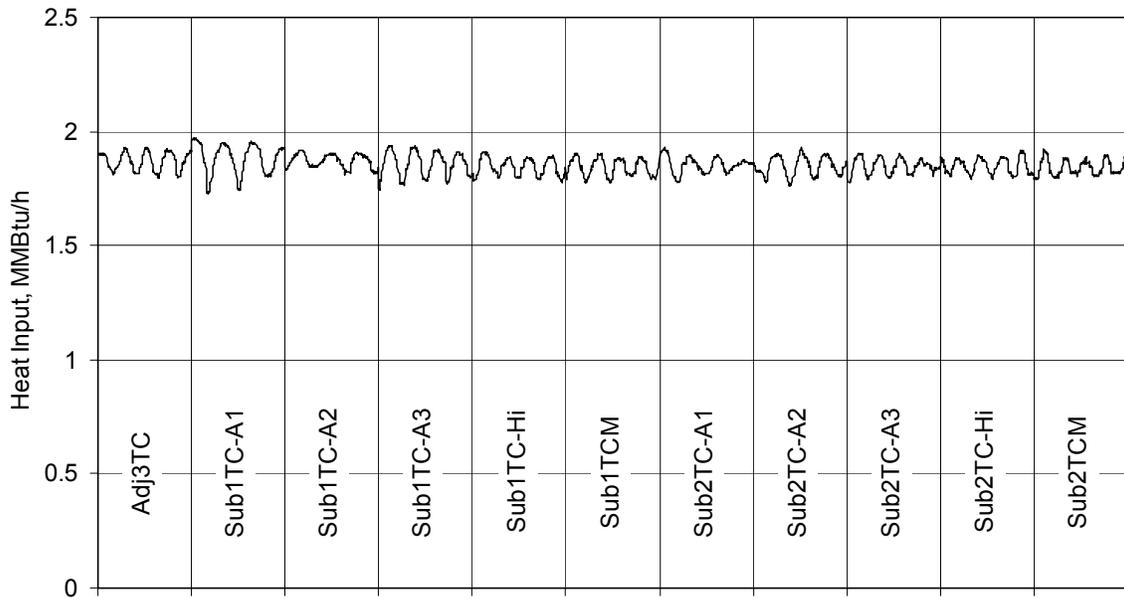


Figure 219. Heat Input for Adjust3 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

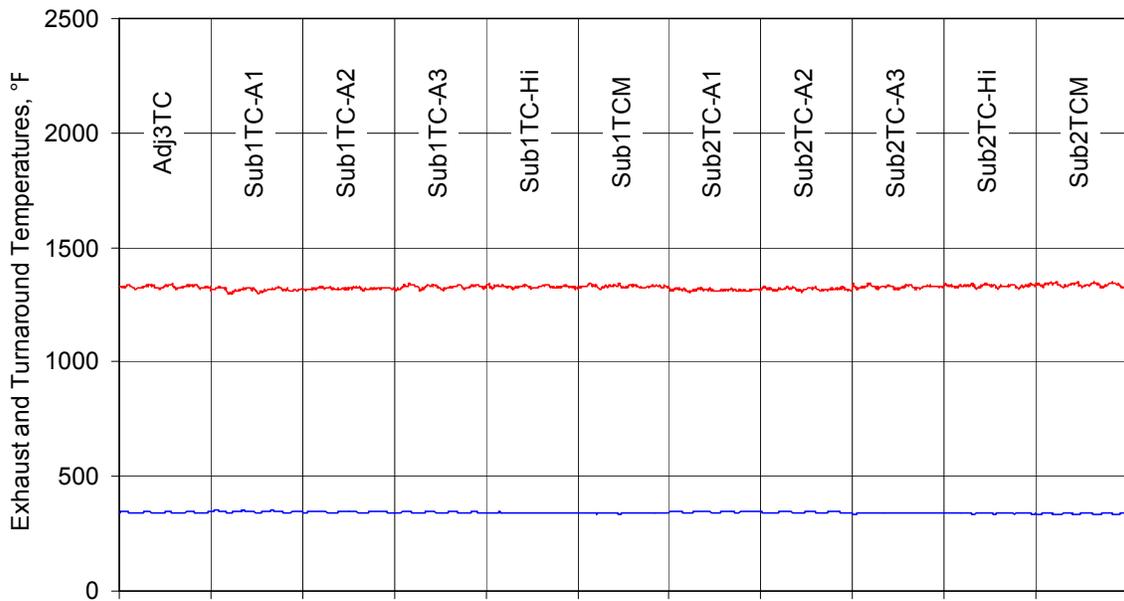


Figure 220. Exhaust and Turnaround Temperature for Adjust3 tuning and All Substitute Gases for Continuous Testing with Constant Steam Pressure

Ignition Tests

The major result from the ignition tests is the reliability of the startup of the burner. Once reliable ignition had been achieved for Adj1TC during the setup process, all subsequent ignitions during the test sequences (132 startups) were successful.

Calculations

All concentrations of emissions were measured on a dry basis. The equations below is the linear correction used to approximately cancel out analyzer drift;

$$X_{corr}(t) = (X_{meas}(t) - Z(t)) \frac{C}{S(t)},$$

where

$$Z(t) = Z_1 + (Z_2 - Z_1) \frac{(t - t_{z1})}{(t_{z2} - t_{z1})},$$

$$S(t) = S_{c1} + (S_{c2} - S_{c1}) \frac{(t - t_{s1})}{(t_{s2} - t_{s1})},$$

$$S_{c1} = S_1 - Z(t_{s1}),$$

$$S_{c2} = S_2 - Z(t_{s2}),$$

where $X_{corr}(t)$ is the corrected emissions value and $X_{meas}(t)$ is the measured value at time t , $Z(t)$ is the zero drift correction, $S(t)$ is the span drift correction, C is the span gas concentration, Z_1 and Z_2 are the instrument readings on zero gas at times T_{z1} and T_{z2} , respectively, S_1 and S_2 are the instrument readings on span gas at times T_{s1} and T_{s2} , respectively, and S_{c1} and S_{c2} are the values of the span readings corrected for zero drift, respectively.

After this correction, emissions were normalized to 3%O₂ using the formula,

$$X_{3\%O_2}(t) = X_{corr}(t) \cdot \left(\frac{21\% - 3\%}{21\% - \%O_{2,corr}(t)} \right),$$

where $X_{3\%O_2}(t)$ is the final value after both the correction for analyzer drift and the normalization to a common 3% oxygen concentration in the dried exhaust.

The Heat Input was calculated from the actual flow rate data, by multiplying the sum of the flow rates of the flowing constituents by the heating value of the "adjust" or "substitute" gas as determined via the ASTM D3588 – 98(03) standard at 70°F.

Analysis and Conclusions

The charts and data are analyzed in the same sections below as appear in the Results section.

Continuous Tests – Firing Rate

For the most part, "substitute" gases with lower Wobbe indexes than the "adjust" gas the boiler was tuned for yielded lower NO_x emissions, maintaining the low NO_x performance, while "substitute" gases with higher Wobbe indexes than the "adjust" gas the boiler was tuned for yielded higher NO_x emissions, usually exceeding 9 ppm when corrected to 3% O₂. Some "substitute" gases caused the boiler to noticeably rumble. This was particularly evident when Adjust1 (Adj1TC) was used as the basis, where heavy rumbling and "coughing" caused additional back pressure in the boiler, causing the air flow to become reduced, sometimes to the point of not having enough air to complete combustion (see Figure 48 through Figure 186). The FGR flow rate, and consequently NO_x emissions, was also affected since the combustion air blower also serves as the FGR fan for this burner.

Two unusual results were observed when Sub1TC-A3 and Sub1TC-Hi were fired with the burner tuned for Adj1TC. When the fuel was switched from Sub1TC-A2 to Sub1TC-A3, rumbling started, and continued for about 15 minutes. The burner then ceased rumbling, and emissions became inline with the trend with Sub1TC-A1 and Sub1TC-A2. When the fuel was switched from Sub1TC-A3 to Sub1TC-Hi, quiet operation continued for about 10 minutes and then rumbling started. The burner rumbled continuously with Sub1TCM, Sub2TC-A3, Sub2TC-Hi, and Sub2TCM.

The steam pressure and temperatures tend to follow the Wobbe index. This was not unexpected since the heat input to the boiler is directly tied to Wobbe index. Rumbling affected the temperatures but not the steam pressure. When not rumbling, CO emissions tended to trend oppositely with Wobbe index.

The smooth upwardly sloping line in some of the THC data (Figure 191 and Figure 197) was due to analyzer zero drift. The drift caused the analyzer to display negative values, which were recorded as a constant zero by the data acquisition system. The actual readings are somewhat below the graphed values during this time.

Continuous Tests – Constant Steam Pressure

NO_x emissions followed the same trend with Wobbe index as with the constant firing rate tests (higher NO_x for higher firing Wobbe gases). Also NO_x emissions tend to be higher when the firing rate was lower during each cycle. CO emissions and THC emissions trended together and they trended oppositely to NO_x emissions for each gas. CO emissions and THC emissions were overall lower for higher Wobbe gases for each sequence.

The fuel flow rate tended to inversely follow the Wobbe index. This was not unexpected since the heat input to the boiler is directly tied to Wobbe index. The average heat input was almost identical for all gases for each sequence.

Ignition Tests

Since all 132 startups (11 gases times 4 ignitions times 3 tuning bases) were successful, comparisons are not possible. With proper setup, the raw gas pilot does not appear to be affected by the fuel used. Manually recorded readings of the amplified flame sensor voltage, as displayed by the control system, did not show any trends. These readings were only updated about once every 3 seconds, and thus are not of sufficient quantity to fully analyze.

Selected Photographs

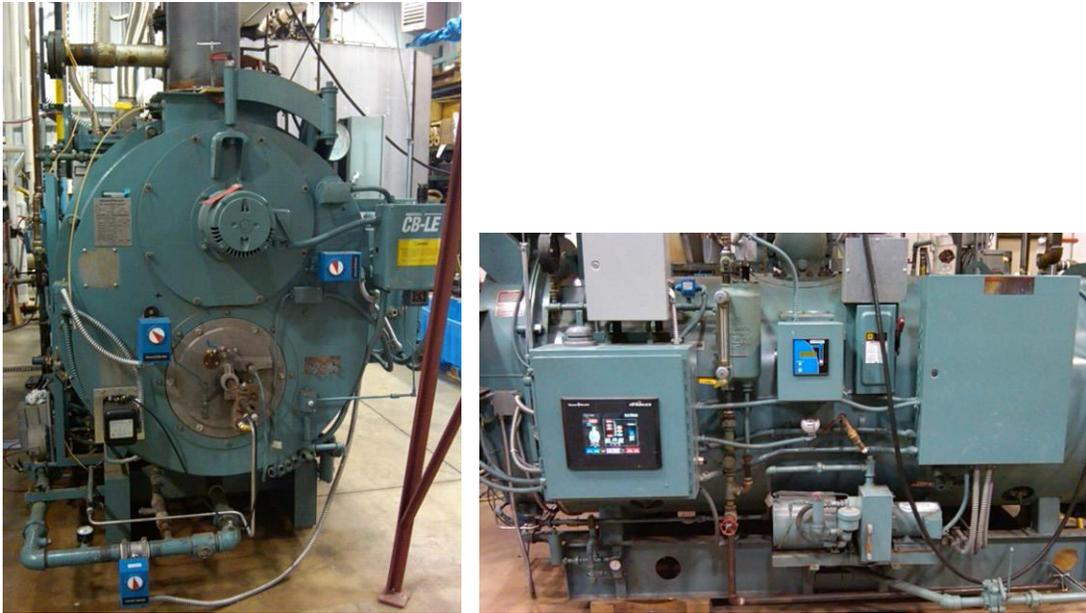


Figure 221. Cleaver Brooks Low NOx Boiler



Figure 222. CO₂ Scrubber



Figure 223. Blending Station with Constituent Gases



Figure 224. Continuous Emissions Analyzers with Span Gases

**NATURAL GAS IN CALIFORNIA: ENVIRONMENTAL IMPACTS
AND DEVICE PERFORMANCE**

**Industrial Burner Evaluations:
Packaged Boiler Burner Test Report**

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For

California Energy Commission

Contract No. CEC-500-05-026

**Commission Project Manager
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April 2011

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Objective

The purpose of the boiler burner interchangeability tests is to assess the performance of a packaged burner (burner with attached blower and controls), used in boilers and other furnaces, when fired with different natural gas compositions. The burner's performance when firing selected Adjust Gases was compared with its performance when firing selected Substitute Gases with and without different levels of nitrogen ballasting.

Approach

The tests used a laboratory setup intended to mimic boiler operating conditions. Operating/Switching tests and Ignition tests were then performed. During these tests, the burner was first tuned to operate with an "adjust" gas composition, then several "substitute" gas compositions were fired in sequence on the burner. These tests were then repeated with the other two "adjust" gases as a basis.

Operating tests were performed in two modes, constant firing rate and constant exhaust temperature. Both tests used a fuel control valve and the packaged burner's air damper to maintain the fuel flow rate proportional to the air flow rate. Constant firing rate tests were performed with the air damper and fuel control valve set manually, yielding an exhaust temperature of about 1335°F at a firing rate of about 65% or 890,000 Btu/hr. Constant temperature tests were performed with a PID-loop temperature controller manipulating the air damper and fuel control valve to maintain the exhaust temperature at about 1300°F.

Ignition tests were performed from the same start conditions of an approximately 130°F exhaust temperature to the same end conditions of an approximately 1000°F exhaust temperature at a firing rate of 32% or 435,000 Btu/hr, a low firing rate as recommended by the burner manufacturer.

For all test sequences, the chamber was first warmed up on house gas. The fuel was then switched to an "adjust" gas, and the burner was tuned so the exhaust gases contained as little O₂ as possible without the burner rattling or rumbling or sputtering. The actual O₂ level depended on which "adjust" gas was being used. Table 9 shows the specific performance measurements.

Table 34. Performance Metrics for the Packaged Boiler Burner

BASIC PERFORMANCE METRICS
Gaseous Pollutant Emissions
Exhaust and Chamber Temperatures
System or Controller Response upon Switching

Test Apparatus

The packaged boiler burner used for this test was a Type C model C1-G-12 by Power Flame, Incorporated rated for 1,360,000 Btu/hr. The burner was ignited using a spark-ignited pilot and its flame was sensed using a UV sensor. The burner assembly is shown in Figure 37.

The test burner fired into a water-cooled cylindrical chamber (simulating a firetube boiler) with thermocouples to measure the temperature of the exhaust gases and the chamber. The exhaust thermocouple was used for temperature control. The exhaust temperature of the test setup would be equivalent to the temperature between the firing tube and the convective pass of a firetube boiler. The overall view of the test rig is shown in Figure 67. Water was flowed in three water-cooled sections and the front and back of the chamber. The water flow rate was measured by a magnetic flow meter. The inlet water temperature was measured with a thermocouple before the stream was split to the various cooling sections. The outlet water temperature was measured by a thermocouples placed well after the water streams flowing out of the various cooling sections were merged back together.

A manometer was used to measure the pressure inside the chamber. Added to the exhaust duct was a stainless steel sampling probe, which was connected through a filtering and drying train to a set of continuous emissions analyzers for THC, NO_x, CO₂, CO, and O₂. These are shown in Figure 68.

The air for the burner was supplied using the packaged burner's attached blower. The air was throttled using the packaged burner's built-in damper.

A custom-built blending station was used to provide simulated natural gas compositions to the fuel control valve at 0.9 psig. The blending station allowed for one of two main streams, house gas and cleaned gas, to be selected, to which metered amounts of ethane, propane, butane, and nitrogen could be added. The house gas was the normal natural gas delivered to GTI, and was the basis for all the "adjust" gases. The cleaned gas was the basis for the "substitute" gases. House gas without additions was used for warming up the burner.

Mass flow meters were used to measure the house gas and cleaned gas flows. Motorized ball valves were used to select one of the two main streams. Mass flow controllers were used to add ethane, propane, butane, and nitrogen to the main stream.

Ethane was supplied from a bank of 5 gas cylinders, propane and butane were each supplied from the gaseous outlet of liquid cylinders, and nitrogen was supplied from GTI's header, which is fed by a liquid tank. All gases were regulated down to about 15 psig before or upon entering the blending station except butane, which is delivered unregulated at its saturation vapor pressure of about 14 psig. The selected main stream is further regulated down to about 5 psig before the other gases are blended in. A pressure transmitter, thermocouple, and mass flow meter were used to monitor the mixed gas pressure, temperature, and flow rate. The blending station with constituent gases is shown in Figure 69.

The exhaust, chamber, and water thermocouples, continuous emissions analyzers, mass flow meters and controllers, and motorized ball valves were connected to a data acquisition and control system. Instruments used to perform this test series are listed in Table 3.

Table 35. Summary of Test Instruments

Instrument	Parameter	Range	Accuracy
National Instruments Field Point Modules	Data logging and control	4-20 mA, 0-5 V, 0-10 V, ±100 mV, on/off (relay)	16 bit input current; 12 bit input voltage; 12 bit output current; 16 bit temperature
LabView software	Data logging	—	—
Custom software	Control	—	—
Laptop computer	Data logging and control	—	—
Type K thermocouple	Exhaust temperature	2502°F	—
Type K thermocouple	Chamber temperature	2502°F	—
ABB Mini-Mag 10D1475W	Water flow rates	26.42 gpm	0.5% of rate @ ≥ 7% full scale
Type T thermocouple	Water temperatures	752°F	—
Rosemount Analytical 400A	THC concentration	0-100 ppm, Span 79 ppm	1% full scale
Rosemount Analytical 755R	O ₂ concentration	0-25%, Span 8.0%	0.01% O ₂ or 1% full scale
Thermo Environmental 42C High Level	NO concentration, NO _x concentration	0-100 ppm, Span 197.8 ppm	0.5 ppm
Rosemount Analytical 880A	CO concentration	0-1000 ppm, Span 924 ppm	1% full scale
Rosemount Analytical 880A	CO ₂ concentration	0-20%, Span 18.0%	1% full scale
Brooks Instruments 5863S	House gas flow rate	2066 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5863S	Cleaned gas flow rate	1826 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5853S	Ethane gas flow rate	224 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5851S	Propane gas flow rate	68.5 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5851S	Butane gas flow rate	31.4 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5851S	Nitrogen gas flow rate	141 SCFH	0.7% of rate plus 0.2% of full scale
Sierra Instruments 780S	Fuel flow rate	1738 SCFH	1% of rate plus 0.5% of full scale
Wika S-10	Mixed gas pressure	0-200 psig	0.25% of span
Type T thermocouple	Mixed gas temperature	752°F	—

The measured flow rates of the fuel gases supplied from the custom blending station and measured flow rate of fuel to the burner were recorded using National Instruments Field Point Modules and a LabView program running on a laptop computer. The fuel gas compositions were commanded through a separate, custom program on the same laptop computer. The custom program used the measured flow rate of the main stream to determine the flow rates of the added gases. A table of ratios of each added gas to the main stream for each "adjust" and "substitute" gas was created for the custom program.

The temperature of the exhaust gas was controlled with a Fuji Electric PXZ4 1/16 DIN PID-loop temperature controller driving a motor on the air throttle valve of the burner. In parallel, a valve on the gas line on the burner was operated. The burner came packaged with a gas valve mechanically linked to the air throttle valve. After much effort to try to tune the burner by adjusting this linkage and by adjusting a pressure regulator in the gas line, no satisfactory setup could be achieved to allow tuned operation of the burner for more than a small range of firing rates. A motorized control valve was installed in the gas line at the outlet of the blending station. This valve was driven by the blending station control program based on the output of the temperature controller. Tuning of the burner was thus achieved by altering the relationship (ratio) between the signal from the temperature controller and the signal to the control valve.

Test Gases

Test gases were selected to match compositions distributed in California, and international compositions that may be imported into California. The compositions distributed in California are designated "adjust gases" for the purpose of tuning the burner for optimum performance on each of them. The remaining gases are designated "substitute gases" for the purpose of comparing the performance with substitute gases to the performance with the adjust gases. Table 4 summarizes the gas compositions. Adjust 1 represents natural gas in the Sacramento area, Adjust 2 is an average value for the state of California, and Adjust 3 is representative of some areas in California with higher Btu content due to local natural gas production. The two substitute gases, Sub 1 and Sub 2, were selected from a set of potential LNG compositions available to California; Sub 1 has a relatively low Wobbe Number (1408) compared with other LNG compositions, and Sub 2 has a relatively high Wobbe Number (1425). Because it is possible that these "substitute" gases will be conditioned with nitrogen prior to distribution in California, additional compositions with nitrogen are added to make the Wobbe Number match those of the selected "adjust" gases.

Table 36. Summary of Adjust and Substitute Gases

Name	Gas Composition, mol %							HHV	Wobbe
	C1	C2	C3	C4	C5+	N2	CO2		
Adjust 1	93.2	2.52	0.41	0.14	0.093	2.691	0.920	1010	1309
Adjust 2	94.5	2.55	0.42	0.14	0.094	1.361	0.931	1024	1332
Adjust 3	90.61	2.45	3.41	1.25	0.094	1.305	0.893	1094	1374
Sub 1	92.4	4.9	1.9	0.79	0.0	0.0	0.0	1099	1408
@1385	91.3	4.8	1.9	0.79	0.0	1.2	0.0	1086	1387
@1375	90.7	4.8	1.9	0.79	0.0	1.9	0.0	1080	1375
@1332	88.3	4.8	1.8	0.79	0.0	4.4	0.0	1053	1331
@1308	87.8	4.6	1.8	0.70	0.0	5.5	0.0	1036	1308
Sub 2	89.4	7.1	2.5	1.04	0.0	0.0	0.0	1131	1426
@1385	87.5	7.0	2.4	1.00	0.0	2.1	0.0	1106	1387
@1375	86.9	6.9	2.4	1.00	0.0	2.7	0.0	1098	1376
@1332	84.5	6.7	2.4	1.00	0.0	5.4	0.0	1070	1330
@1308	83.6	6.6	2.3	1.00	0.0	6.5	0.0	1057	1310

For small-scale testing (up to about 40,000 Btu/h), it is practical to purchase cylinders with these exact compositions, with only nitrogen being blended in as needed. For medium-scale testing (up to about 200,000 Btu/h), it is practical to create these compositions from cylinders of pure gases using a blending station. For large-scale testing (over 1,000,000 Btu/h), the amount of pure methane needed requires a tube trailer, but none were available from GTI's gas supplier during the time of the test campaign. The "adjust" gases could be simulated (same heating value and Wobbe index) by blending in ethane, propane and butane from cylinders, and nitrogen from a liquid tank into GTI's house gas. However, the pure "substitute" gases and conditioned (nitrogen-diluted) "substitute" gases with higher Wobbe indexes could not be simulated this way because of the amount of inerts (CO₂ and N₂) in the house gas.

For another project, GTI assembled a CO₂ stripper which utilized three columns (towers) to remove the CO₂ from the house gas. The first tower performed the function of absorbing the CO₂ from the desired amount of house gas and an additional amount of house gas. The desired amount of cleaned gas went onto the burner being tested, while the additional amount went through the second tower, a heater, and the third tower before being vented or flared. The third tower performed the function of desorbing the CO₂ from the absorbent using the heated gas, while the second tower was being cooled

by the cleaned gas. The towers rotated their function every 3 hours, so the process was regenerative.

The cleaned gas with the heavy molecular weight CO₂ removed was then used a basis for simulating the "adjust" gases and the conditioned "substitute" gases. The pure "substitute" gases were still not quite reached, so the points of maximum heating value and Wobbe index, along the same lines as the conditioned "substitute" gases, were used in their place. The final compositions are shown in Table 12.

Table 37. Summary of Test Gases

Name	Gas Composition, mol %						HHV	Wobbe
	House Gas	Cleaned Gas	Ethane	Propane	Butane	Nitrogen		
Adj1Q	97.28%	0.00%	0.00%	0.84%	0.00%	1.89%	1010.0	1309.0
Adj2Q	98.49%	0.00%	0.00%	0.90%	0.00%	0.61%	1024.0	1332.0
Adj3Q	92.02%	0.00%	4.62%	1.95%	0.81%	0.59%	1094.0	1374.0
Sub1QM	0.00%	93.62%	3.99%	1.69%	0.70%	0.00%	1090.3	1394.3
Sub1Q-Hi	0.00%	93.17%	3.97%	1.68%	0.69%	0.49%	1085.0	1385.5
Sub1Q-A3	0.00%	92.57%	3.95%	1.67%	0.69%	1.12%	1078.0	1374.1
Sub1Q-A2	0.00%	90.20%	3.85%	1.63%	0.67%	3.65%	1050.4	1329.2
Sub1Q-A1	0.00%	89.16%	3.80%	1.61%	0.66%	4.76%	1038.3	1309.7
Sub2QM	0.00%	90.82%	5.75%	2.43%	1.00%	0.00%	1122.0	1411.9
Sub2Q-Hi	0.00%	89.58%	5.67%	2.40%	0.99%	1.36%	1106.8	1387.7
Sub2Q-A3	0.00%	89.03%	5.64%	2.38%	0.98%	1.96%	1100.0	1377.0
Sub2Q-A2	0.00%	86.56%	5.48%	2.32%	0.96%	4.68%	1069.3	1329.2
Sub2Q-A1	0.00%	85.56%	5.42%	2.29%	0.95%	5.79%	1056.9	1309.9

Figure 42 illustrates the fuel heating values and Wobbe indexes used for the packaged boiler burner testing.

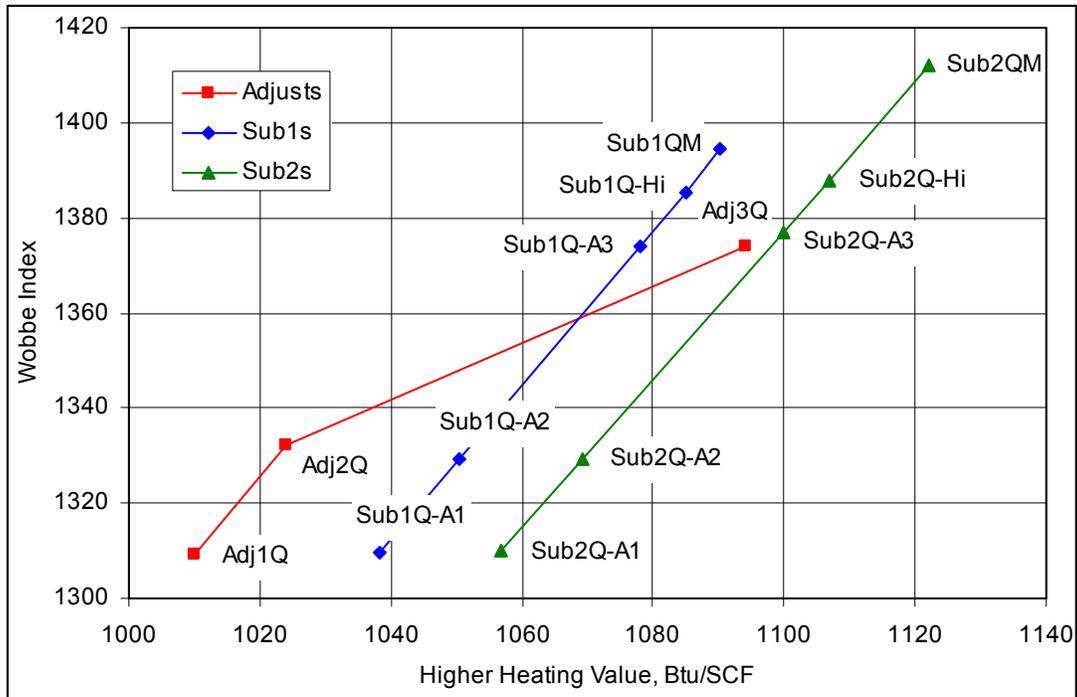


Figure 225. Wobbe Indexes and Heating Values for Packaged Boiler Burner Tests

Test Schedule

The performance tests with constant firing rate were performed first for all three "adjust" gases. These were followed by performance tests with constant exhaust temperature. The ignition tests were performed last. Table 13 shows the schedule of test sequences.

The ignition tests were performed separately from the performance tests, because otherwise heat-up and cool-down time would be prohibitive. Figure 45 illustrates the overall setup, testing, and analysis schedule. Table 13 shows the schedule of test sequences. Each sequence of tests (each column in Table 13) was performed during a single day, with the exception that the ignition tests for the first two "adjust" gases were both performed on the same day.

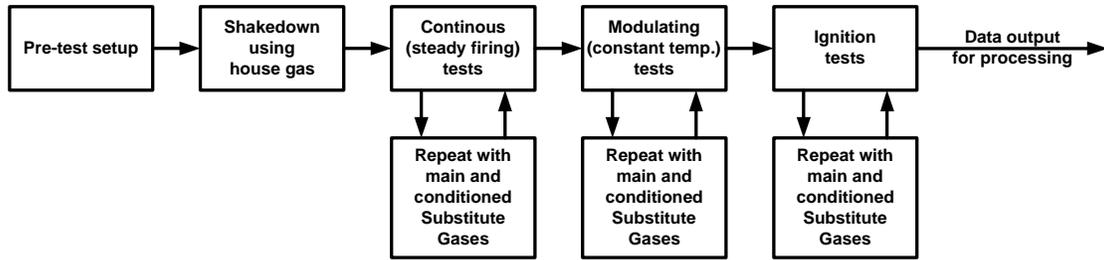


Figure 226. Test Schedule for the Packaged Boiler Burner

Table 38. Test Schedule

Type	Constant Firing Rate			Constant Exhaust Temperature			Ignition		
Basis	Adj2Q	Adj1Q	Adj3Q	Adj2Q	Adj1Q	Adj3Q	Adj2Q	Adj1Q	Adj3Q
Subs	Sub1Q	Sub1Q	Sub1Q	Sub1Q	Sub1Q	Sub1Q	Sub1Q	Sub1Q	Sub1Q
	Sub1Q-Hi	Sub1Q-Hi	Sub1Q-Hi	Sub1Q-Hi	Sub1Q-Hi	Sub1Q-Hi	Sub1Q-Hi	Sub1Q-Hi	Sub1Q-Hi
	Sub1Q-A3	Sub1Q-A3	Sub1Q-A3	Sub1Q-A3	Sub1Q-A3	Sub1Q-A3	Sub1Q-A3	Sub1Q-A3	Sub1Q-A3
	Sub1Q-A2	Sub1Q-A2	Sub1Q-A2	Sub1Q-A2	Sub1Q-A2	Sub1Q-A2	Sub1Q-A2	Sub1Q-A2	Sub1Q-A2
	Sub1Q-A1	Sub1Q-A1	Sub1Q-A1	Sub1Q-A1	Sub1Q-A1	Sub1Q-A1	Sub1Q-A1	Sub1Q-A1	Sub1Q-A1
	Sub2Q	Sub2Q	Sub2Q	Sub2Q	Sub2Q	Sub2Q	Sub2Q	Sub2Q	Sub2Q
	Sub2Q-Hi	Sub2Q-Hi	Sub2Q-Hi	Sub2Q-Hi	Sub2Q-Hi	Sub2Q-Hi	Sub2Q-Hi	Sub2Q-Hi	Sub2Q-Hi
	Sub2Q-A3	Sub2Q-A3	Sub2Q-A3	Sub2Q-A3	Sub2Q-A3	Sub2Q-A3	Sub2Q-A3	Sub2Q-A3	Sub2Q-A3
	Sub2Q-A2	Sub2Q-A2	Sub2Q-A2	Sub2Q-A2	Sub2Q-A2	Sub2Q-A2	Sub2Q-A2	Sub2Q-A2	Sub2Q-A2
	Sub2Q-A1	Sub2Q-A1	Sub2Q-A1	Sub2Q-A1	Sub2Q-A1	Sub2Q-A1	Sub2Q-A1	Sub2Q-A1	Sub2Q-A1

Activities Performed

Setup

Preliminary tests with the typical manufacturer-recommended burner setup were conducted to verify ignition of the burner on house gas and to determine typical chamber temperatures at various firing rates on house gas and cleaned gas, fuel flow rate, the functionality of the blending station (by switching between the different gases), the functionality of the continuous emissions analyzers, and the functionality of the data acquisition system.

Continuous Tests – Constant Firing Rate

The continuous tests with constant firing rate measured how the system responds, i.e., how the exhaust temperature varies, when various "substitute" gases are fired at a fixed rate with the burner tuned for a particular "adjust" gas. These tests are useful for predicting how a system will respond when there is no feedback control.

The test plan was to calibrate the continuous emissions analyzers, fire the burner on house gas, bring the exhaust gases up to an operating temperature of about 1335°F, switch to an "adjust" gas, tune the burner on the "adjust" gas by adjusting the air/fuel ratio, and set the firing rate to around 65% of the burner nominal rated capacity (890,000 Btu/hr) by manually setting the air throttling valve and process controller for the gas control valve. Next was to allow the exhaust temperature to settle and then collect exhaust temperature and emissions data for twenty minutes. The blending station was then switched to one of the "substitute" gases. The emissions were allowed to settle and then exhaust temperature and emissions data were collected for twenty minutes. This series of switching gases and collecting data was repeated with the nine other "substitute" gases. The sampling train for the continuous emission analyzers was purged and the calibration of the continuous emissions analyzers was then checked between the "substitute" gases.

The above process was repeated for the second "adjust" gas and all 10 "substitute" gases, and then repeated again with the third "adjust" gas and all 10 "substitute" gases.

For all of the above sequences with constant firing rate, the response of the system's performance in terms of exhaust temperature was recorded with the emissions data at 5 second intervals.

Continuous Tests – Constant Exhaust Temperature

The continuous tests with constant exhaust temperature measured how the controller responds, i.e., how the firing rate varies, when various "substitute" gases are fired with a system with a fixed operating condition with the burner tuned for a particular "adjust" gas. These tests are useful for predicting how a system will respond when there is feedback control.

The test plan was to calibrate the continuous emissions analyzers, fire the burner on house gas, bring the test chamber up to an operating condition with an exhaust temperature of about 1300°F, switch to an "adjust" gas, tune the burner on the "adjust" gas by adjusting the air/fuel ratio, and connect the temperature controller to the process controller and variable frequency drive installed on the air blower, Next was to allow the firing rate to settle and then collect firing rate and emissions data for twenty minutes. The blending station was then switched to one of the "substitute" gases. The emissions were allowed to settle and then firing rate and emissions data were collected for twenty minutes. This series of switching gases and collecting data was repeated with the nine other "substitute" gases. The sampling trains for the continuous emission analyzers was purged and the calibration of the continuous emissions analyzers was then checked between the "substitute" gases.

The above process was repeated for the second "adjust" gas and all 10 "substitute" gases, and then repeated again with the third "adjust" gas and all 10 "substitute" gases.

For all of the above sequences with constant exhaust temperature, the response of the controller's performance in terms of firing rate was recorded with the emissions data at 5 second intervals.

Ignition Tests

The ignition tests measured whether the burner lights and the rate of heating on various "substitute" gases with the burner tuned for a particular "adjust" gas.

The test plan was to calibrate the continuous emissions analyzers, fire the burner on house gas, bring the test chamber up to an operating temperature of about 1000°F, switch to an "adjust" gas, tune the burner on the "adjust" gas by adjusting the air/fuel ratio, set the firing rate to around 32% of the burner nominal rated capacity (435,000 Btu/hr), shut off the fuel, and allow the chamber to cool to 120°F. Next was to have one (or two) discounted ignition (#0) on the "adjust" gas, allow the exhaust temperature to reach 1000°F, shut off the fuel, and allow the chamber to cool to 120°F. This was followed by three consecutive ignition-warm up-shut off-cool down cycles with recorded ignitions (#'s 1-3) on the "adjust" gas before switching the blending station to one of the "substitute" gases. The switching was done after the third ignition but before the shut off so that the fuel line was filled with the "substitute" gas before the first ignition on that gas. With this "substitute" gas, there were three recorded ignition-warm up-shut off-cool down cycles (#'s 1-3). This series of three cycles was repeated with the nine other "substitute" gases. The calibration of the continuous emissions analyzers was checked periodically between "substitute" gases.

The above process was repeated for the second "adjust" gas and all 10 "substitute" gases, and then repeated again with the third "adjust" gas and all 10 "substitute" gases.

Results

Continuous Tests – Constant Firing Rate

The major results from the continuous tests with constant firing rate are the emissions and the exhaust temperature (the system's response) when the burner is tuned for a particular "adjust" gas, and the fuel is switched to various "substitute" gases. Figure 91 through Figure 102 show the emissions and exhaust temperature data over the 20 minute data collection intervals for each of the three "adjust" gas tunings separately. Figure 103 through Figure 106 show the affect of Wobbe Number on emissions and exhaust temperature data for the three different tunings combined.

Continuous Tests – Constant Exhaust Temperature

The major results from the continuous tests with constant exhaust temperature are the emissions and the fuel flow rate (the controller's response) when the burner is tuned for a particular "adjust" gas, and the fuel is switched to various "substitute" gases. Figure 75 through Figure 86 show the emissions and firing rate data over the 20 minute data collection intervals for each of the three "adjust" gas tunings separately. Figure 47 through Figure 90 show the affect of Wobbe Number on emissions and firing rate data for the three different tunings combined.

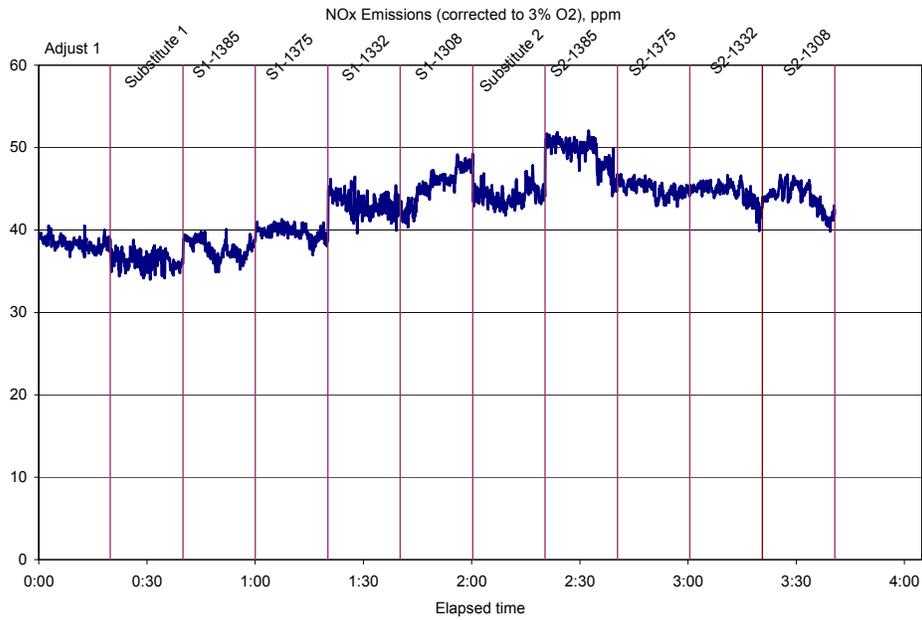


Figure 227. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 1

(Corrected to 3% O₂)

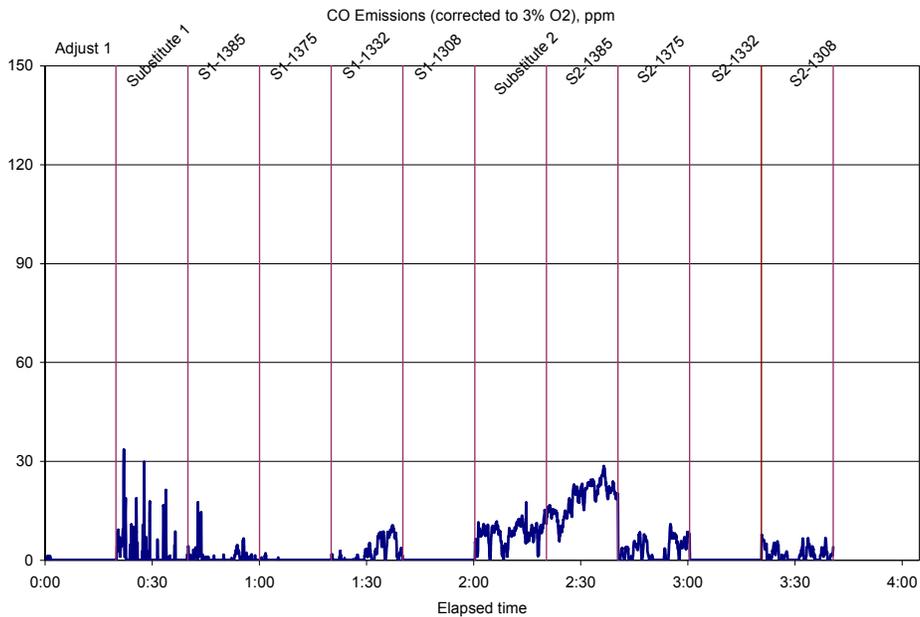


Figure 228. CO Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 1

(Corrected to 3% O₂)

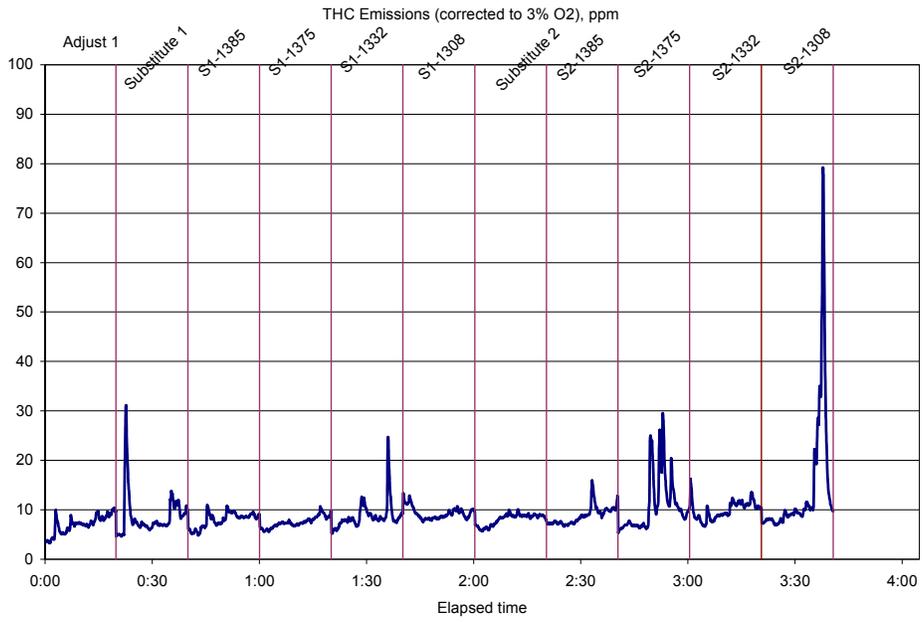


Figure 229. THC Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 1

(Corrected to 3% O₂)

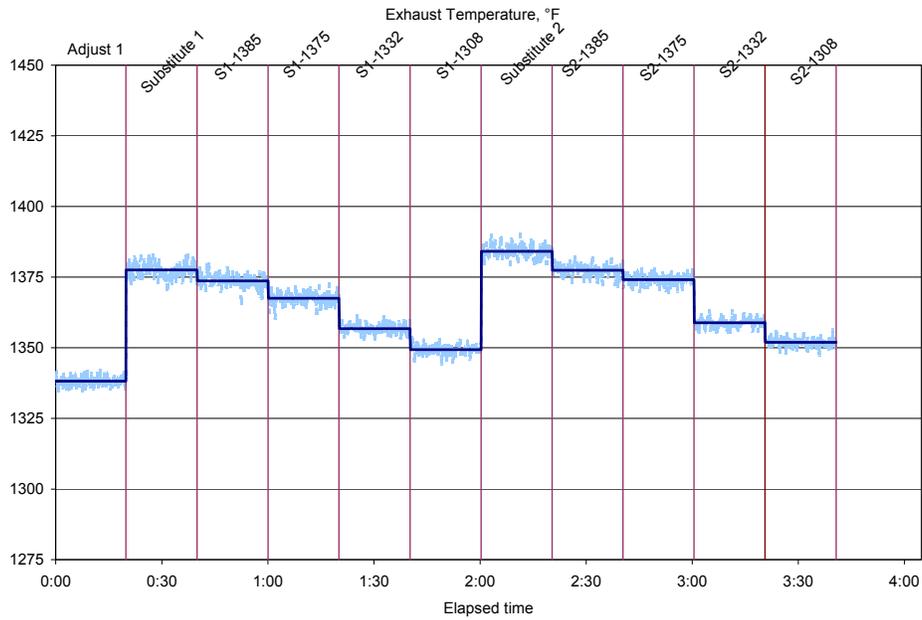


Figure 230. Exhaust Temperature for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 1

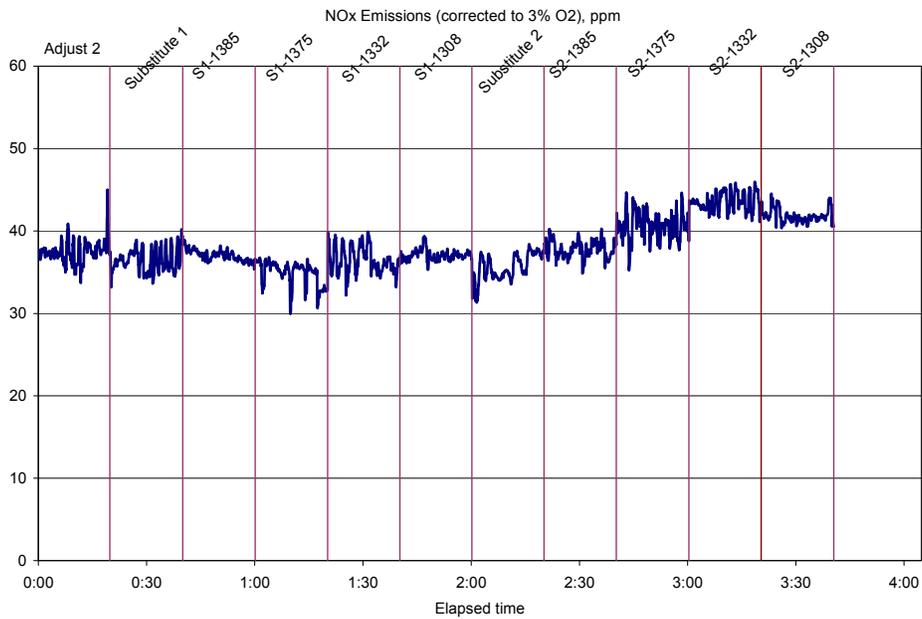


Figure 231. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 2

(Corrected to 3% O₂)

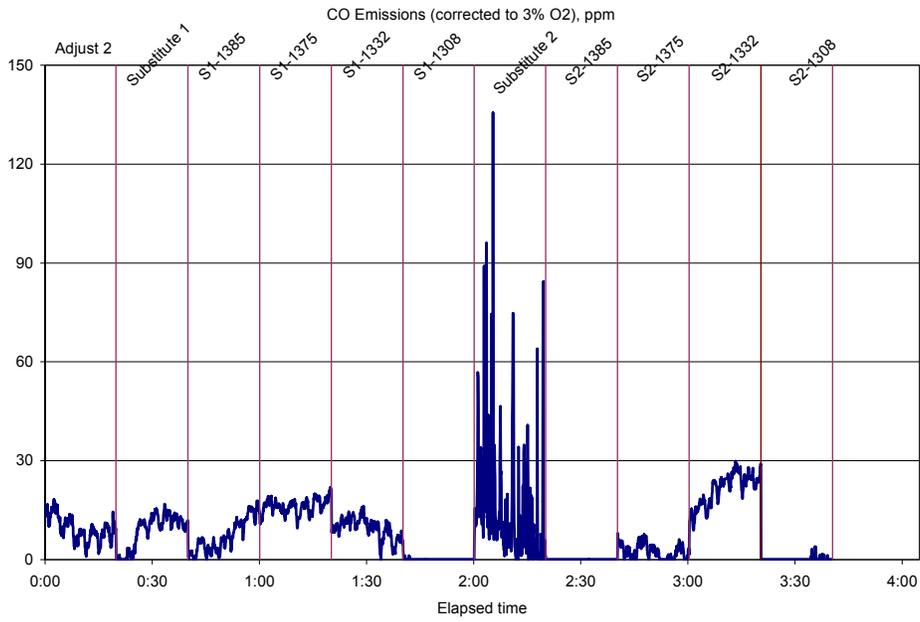


Figure 232. CO Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 2

(Corrected to 3% O₂)

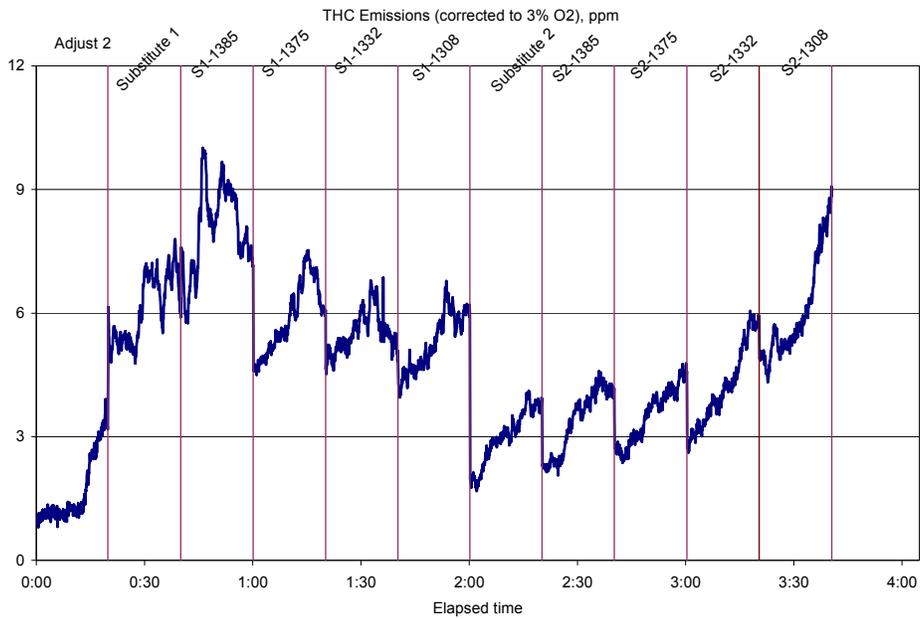


Figure 233. THC Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 2

(Corrected to 3% O₂)

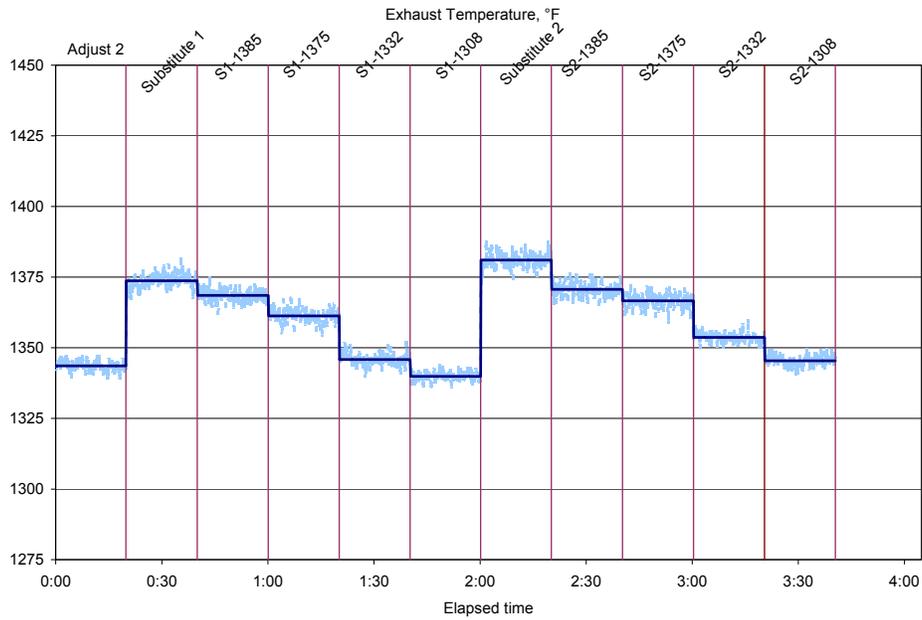


Figure 234. Exhaust Temperature for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 2

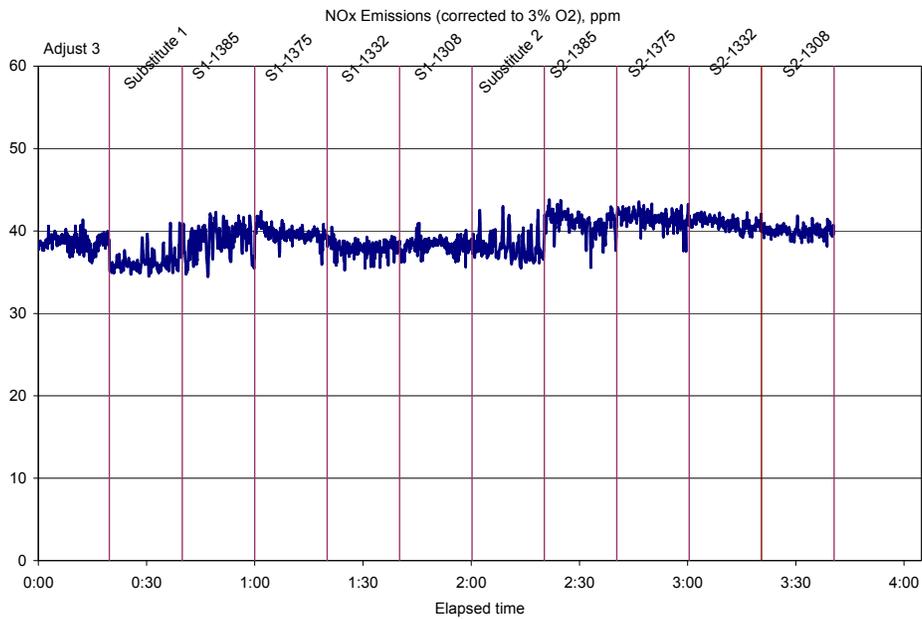


Figure 235. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 3

(Corrected to 3% O₂)

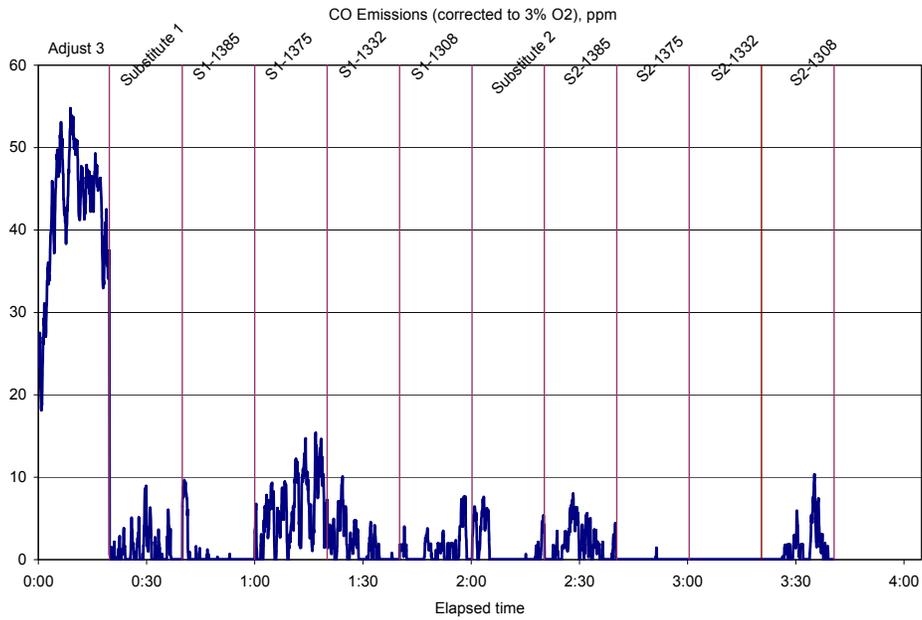


Figure 236. CO Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 3

(Corrected to 3% O₂)

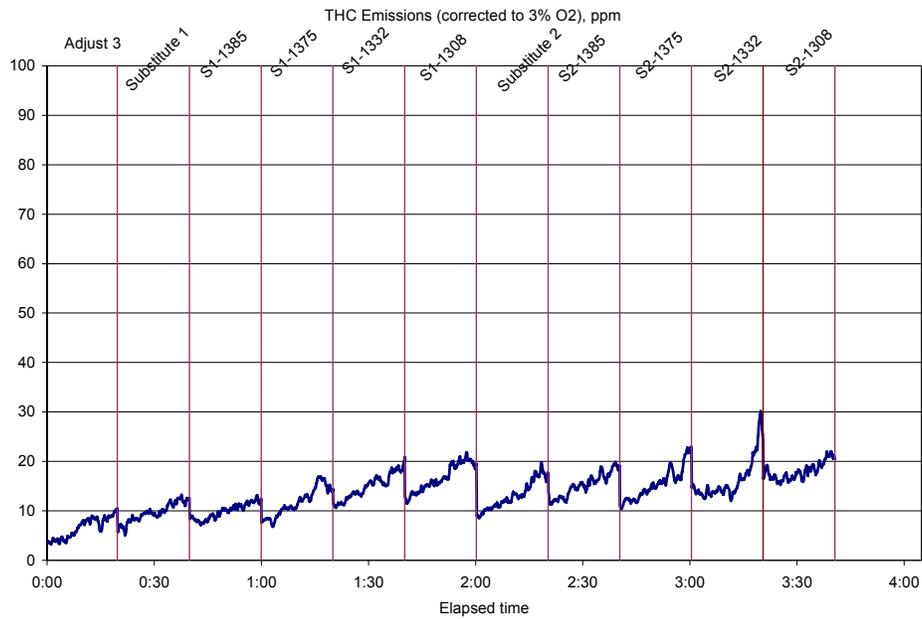


Figure 237. THC Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 3

(Corrected to 3% O₂)

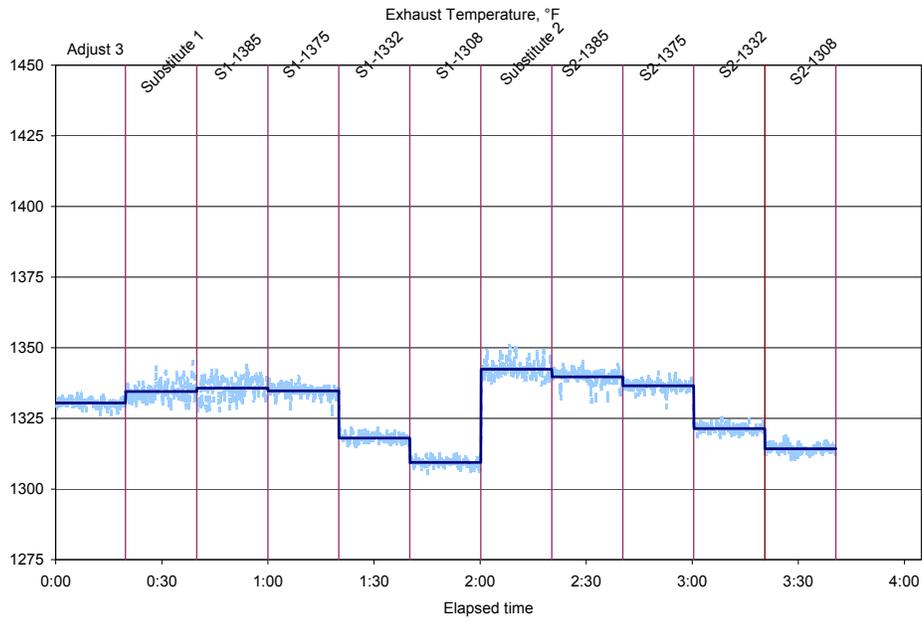


Figure 238. Exhaust Temperature for All Substitute Gases for Continuous Testing with Constant Firing Rate with Burner Tuned for Adjust 3

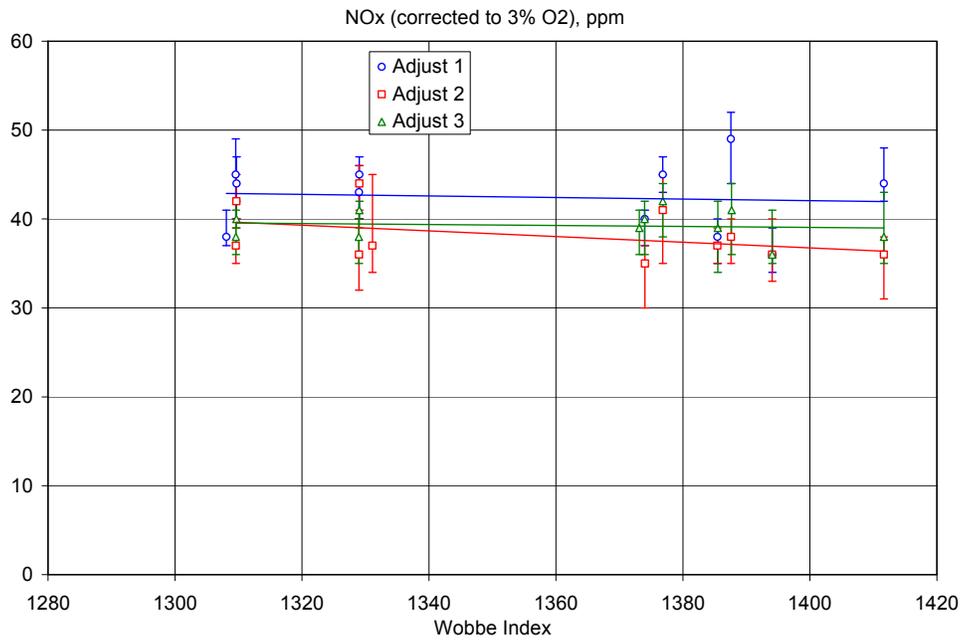


Figure 239. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

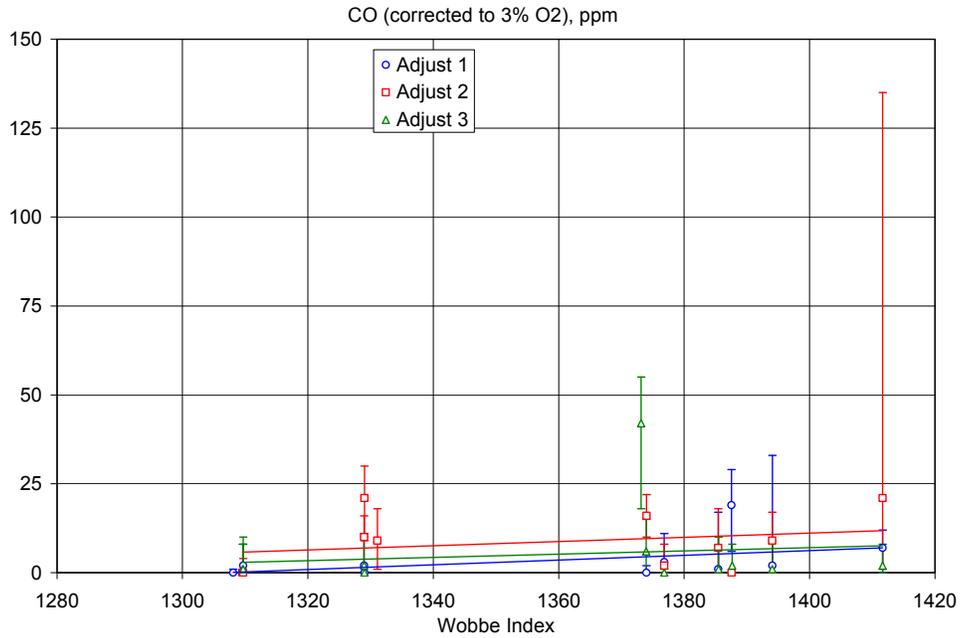


Figure 240. CO Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

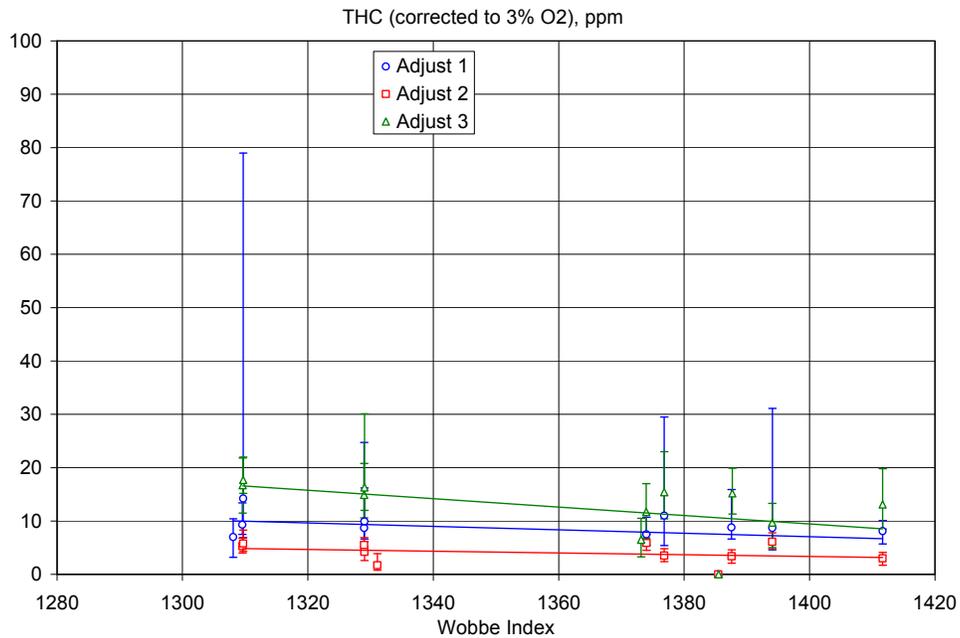


Figure 241. THC Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

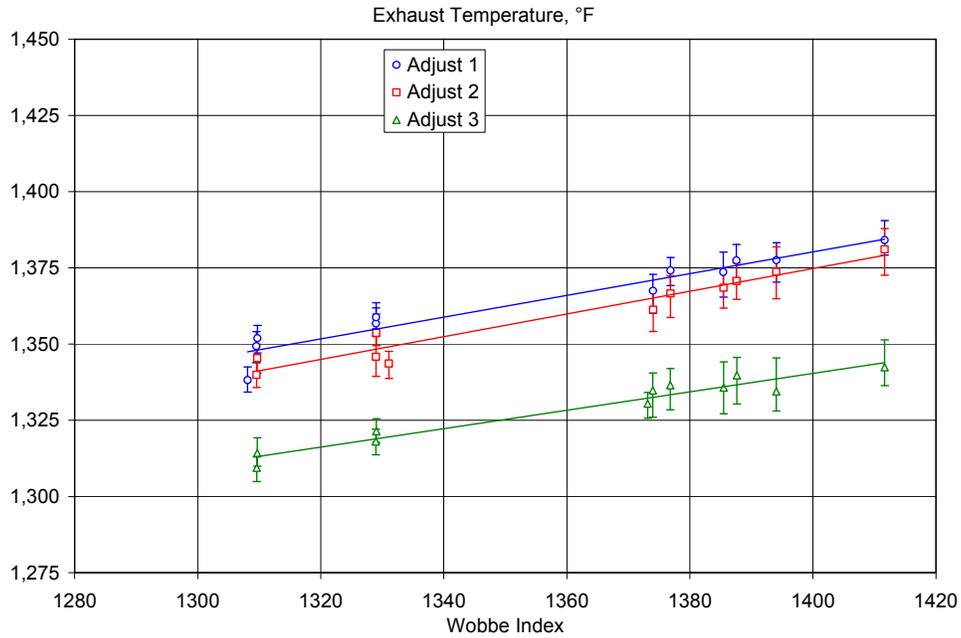


Figure 242. Exhaust Temperature for All Substitute Gases for Continuous Testing with Constant Firing Rate

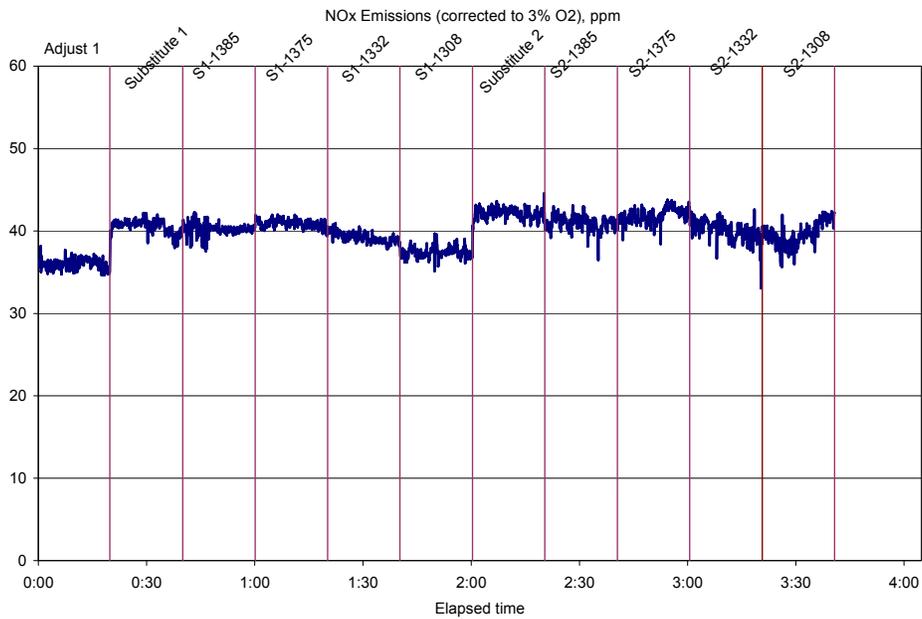


Figure 243. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 1

(Corrected to 3% O₂)

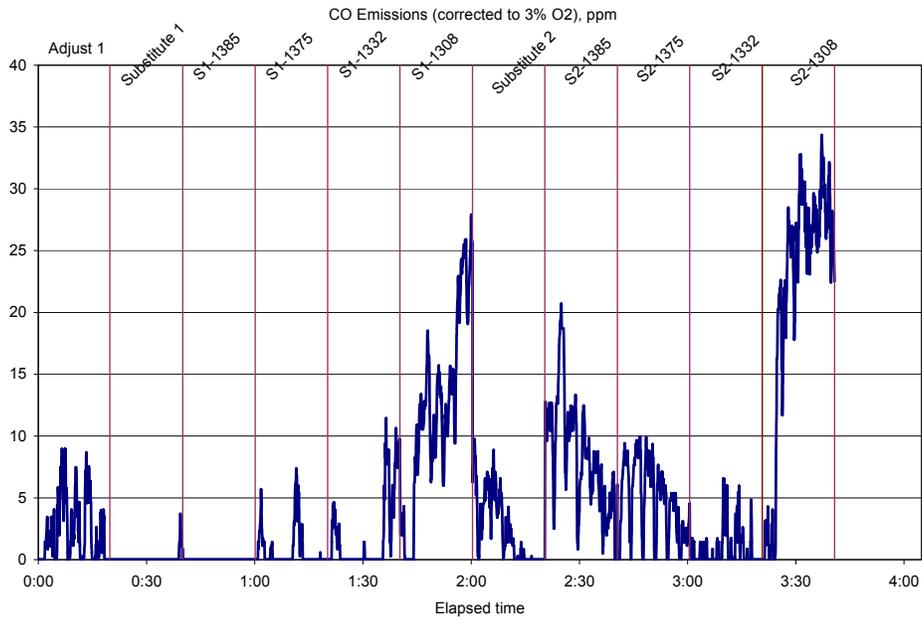


Figure 244. CO Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 1

(Corrected to 3% O₂)

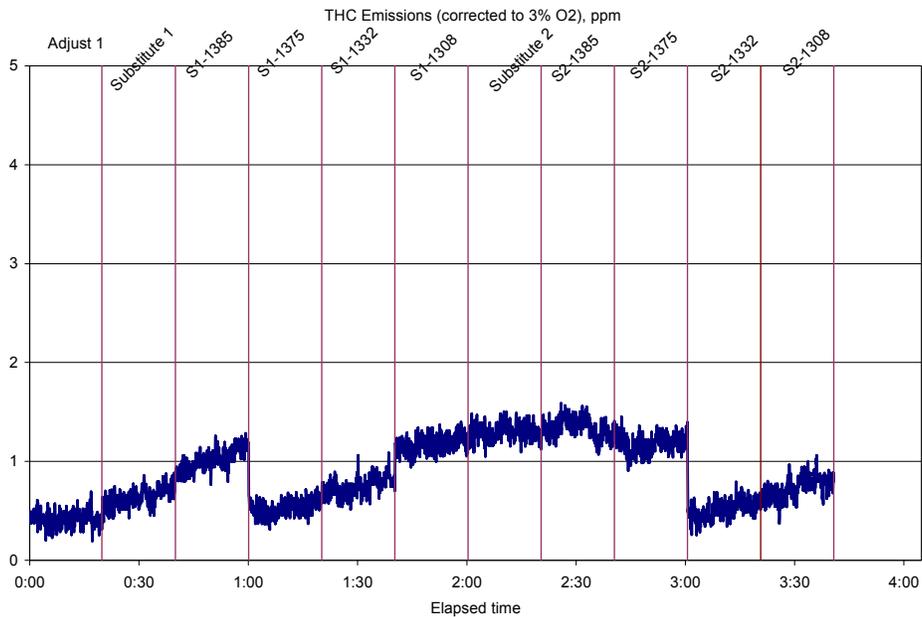


Figure 245. THC Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 1

(Corrected to 3% O₂)

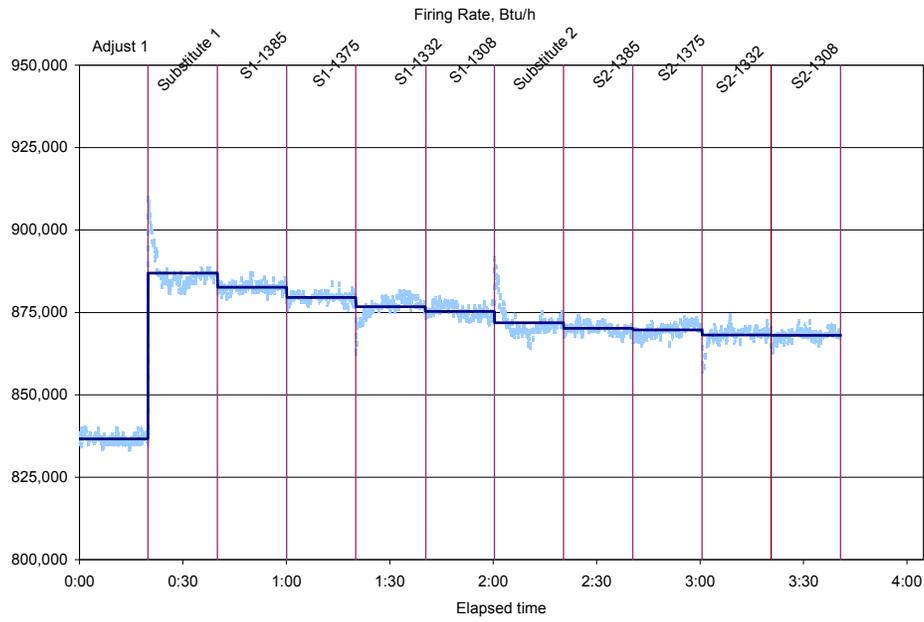


Figure 246. Firing Rate for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 1

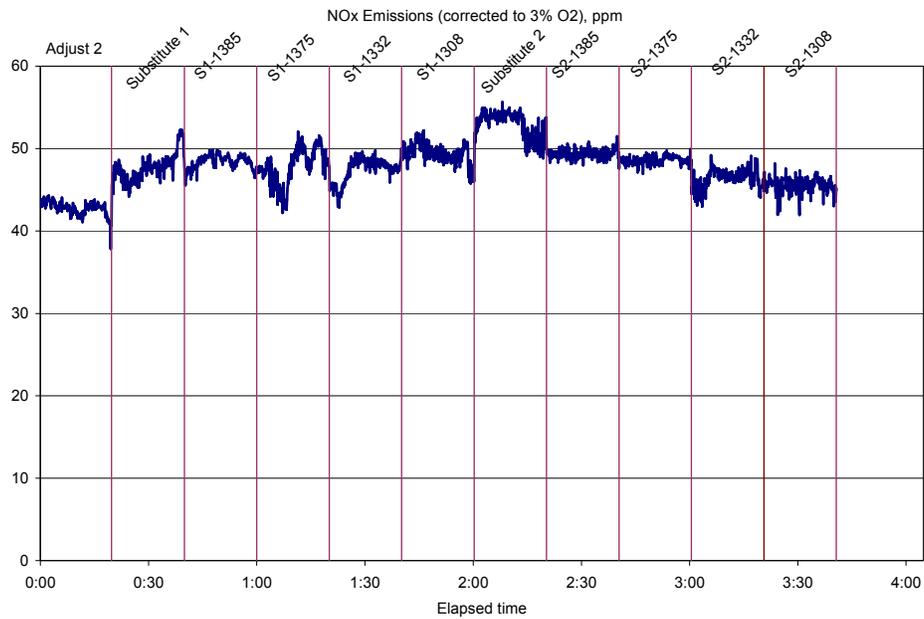


Figure 247. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 2

(Corrected to 3% O₂)

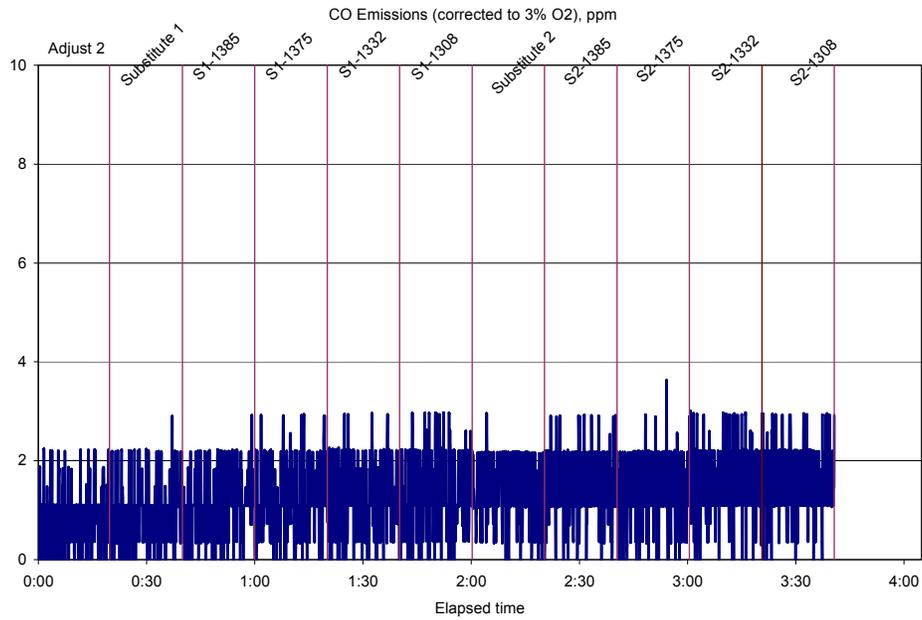


Figure 248. CO Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 2

(Corrected to 3% O₂)

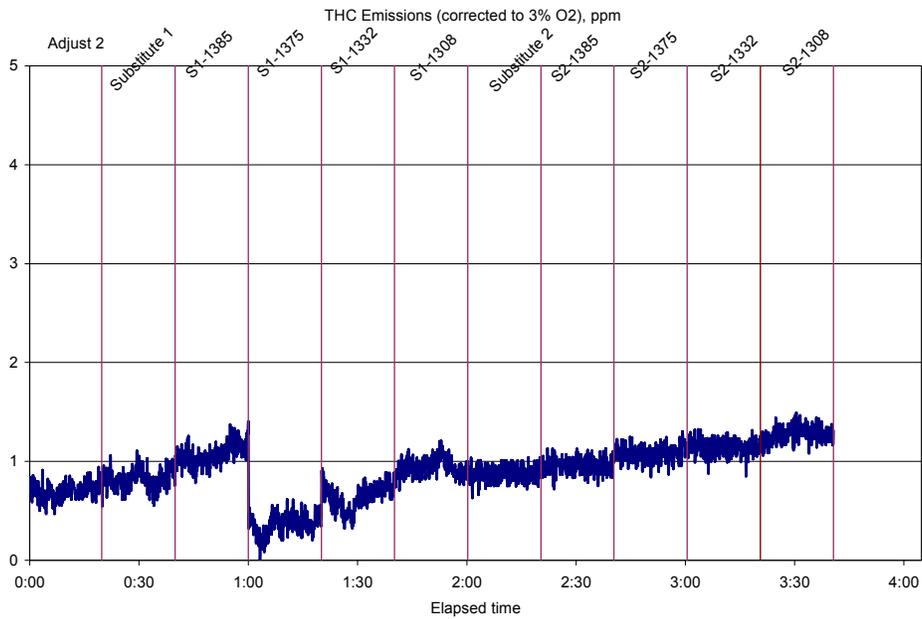


Figure 249. THC Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 2

(Corrected to 3% O₂)

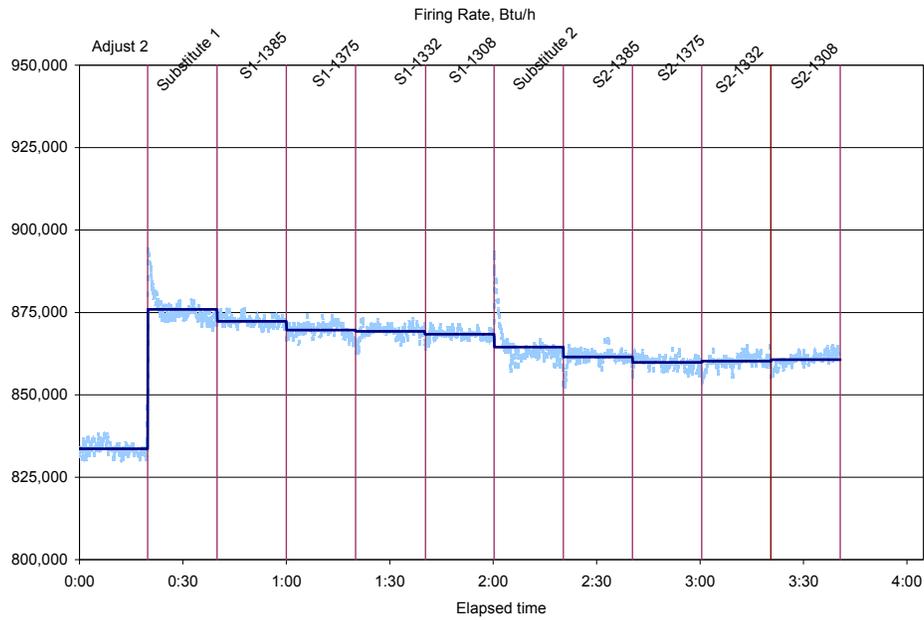


Figure 250. Firing Rate for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 2

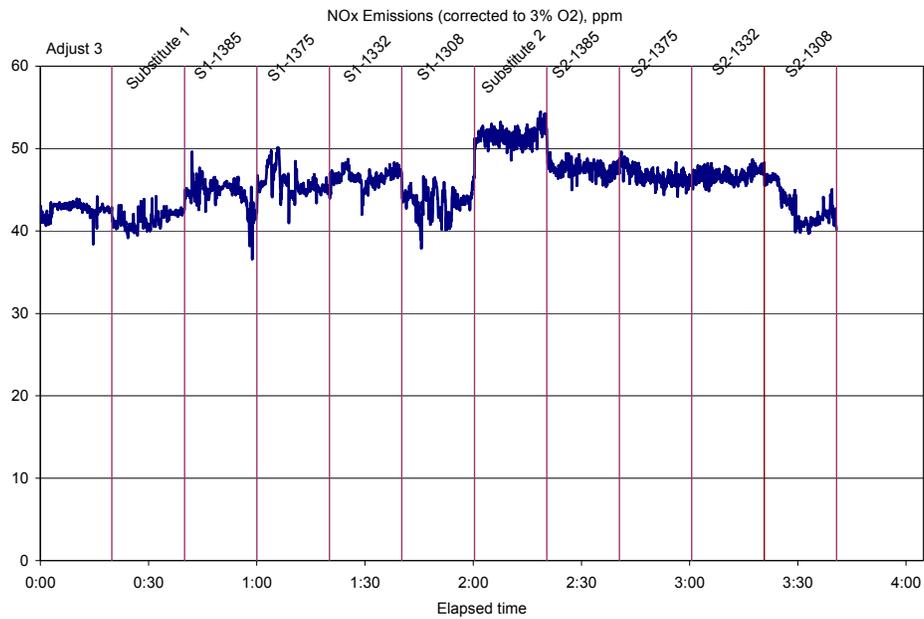


Figure 251. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 3

(Corrected to 3% O₂)

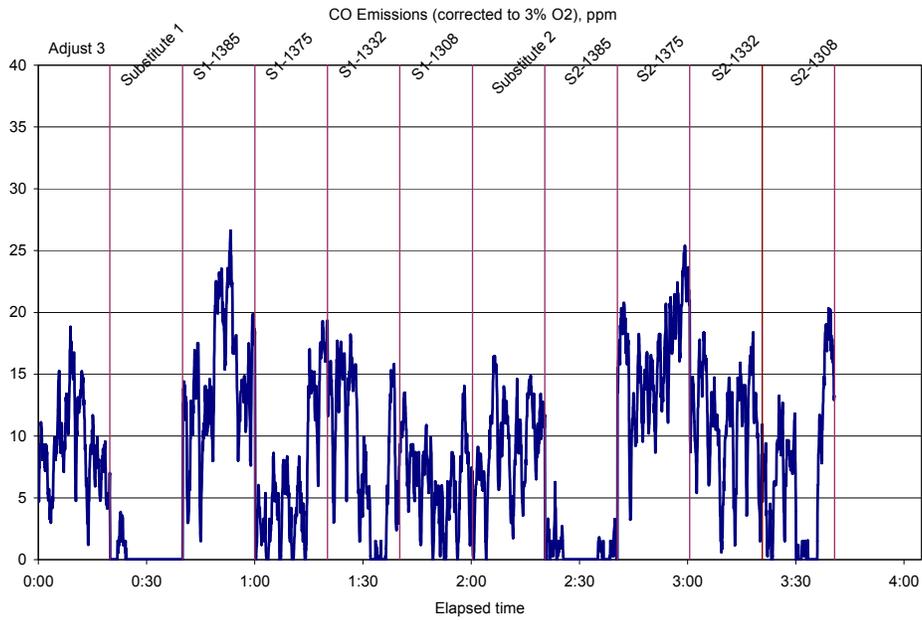


Figure 252. CO Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 3

(Corrected to 3% O₂)

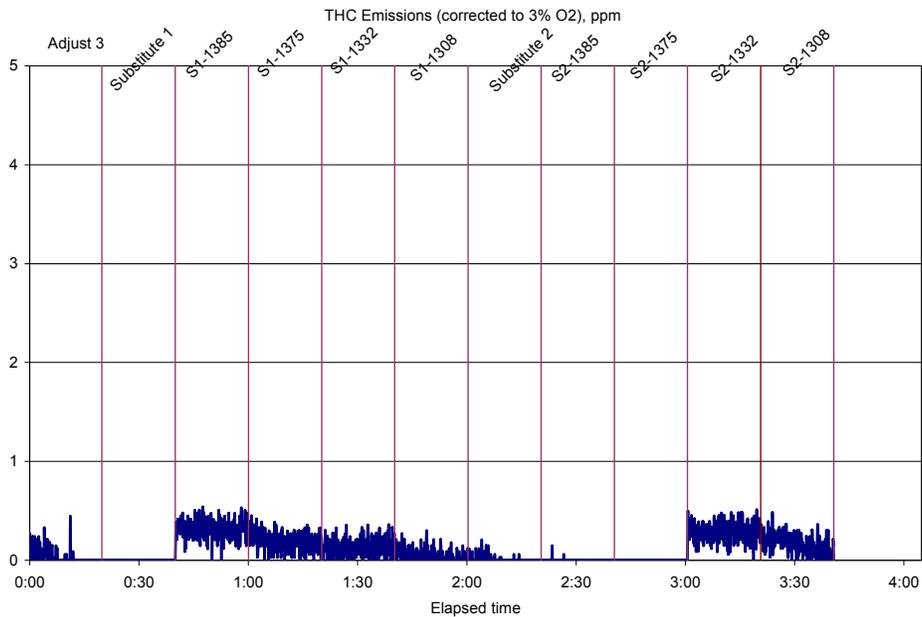


Figure 253. THC Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 3

(Corrected to 3% O₂)

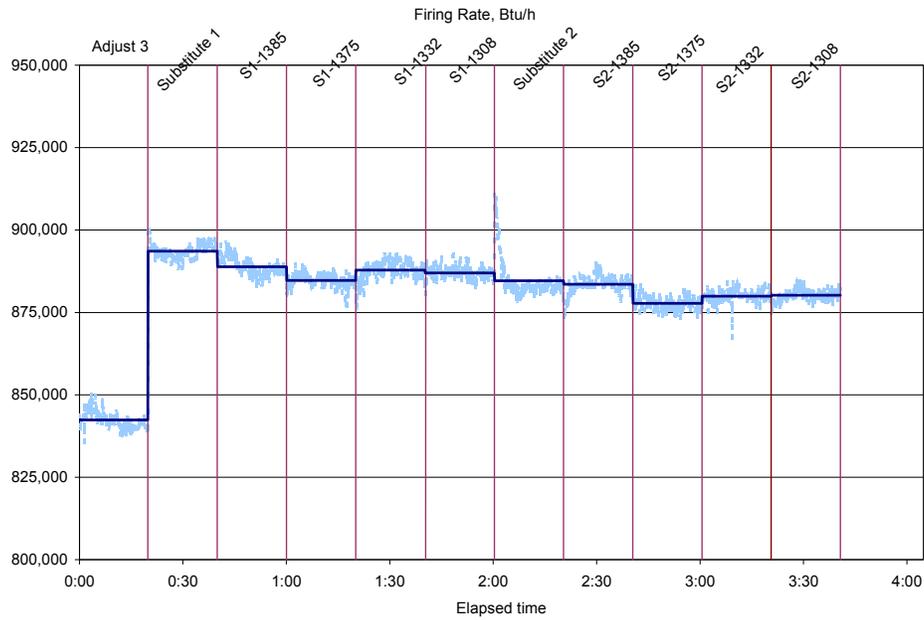


Figure 254. Firing Rate for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature with Burner Tuned for Adjust 3

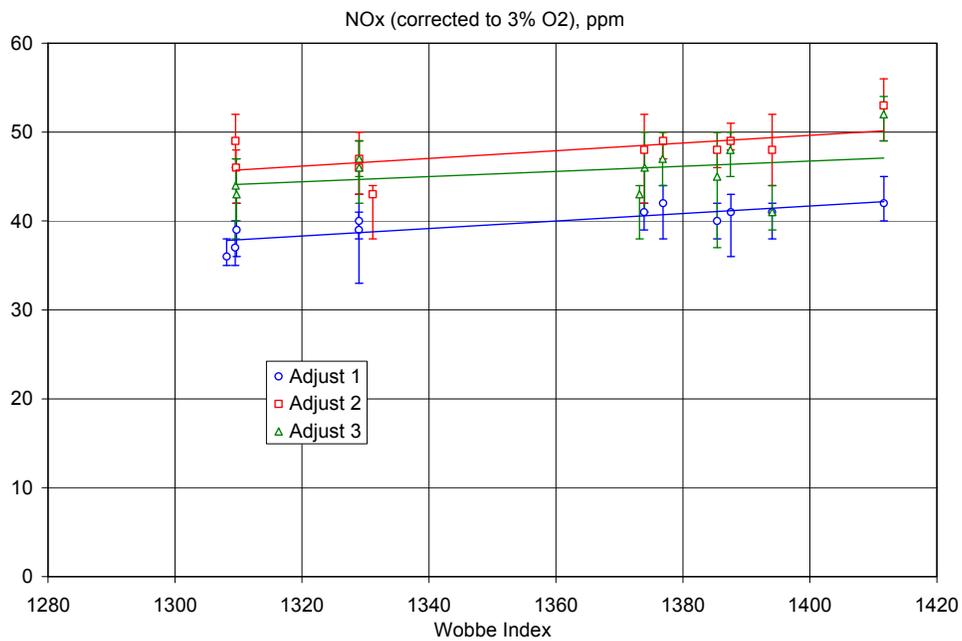


Figure 255. NO_x Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature

(Corrected to 3% O₂)

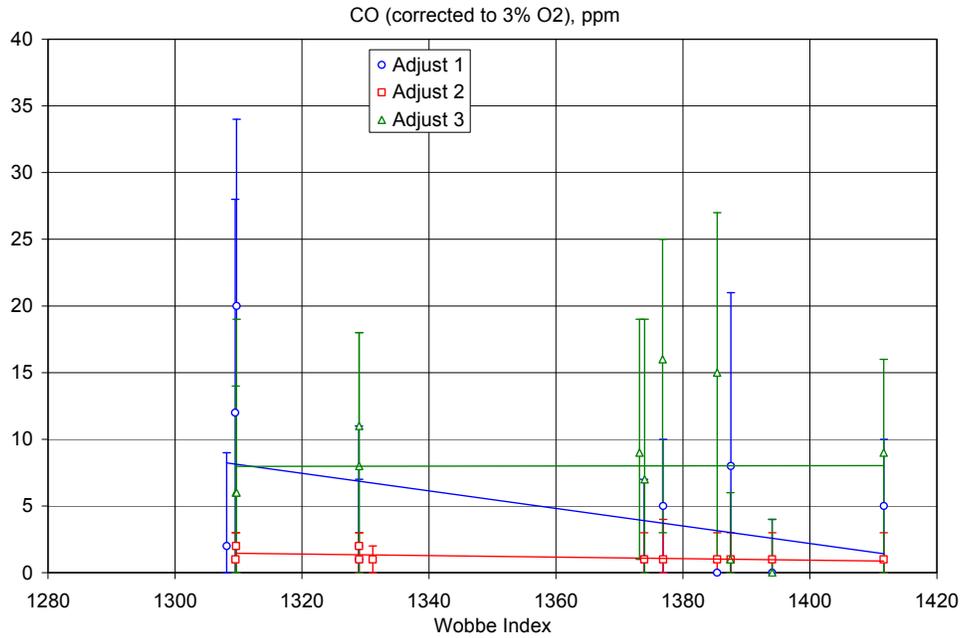


Figure 256. CO Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature

(Corrected to 3% O₂)

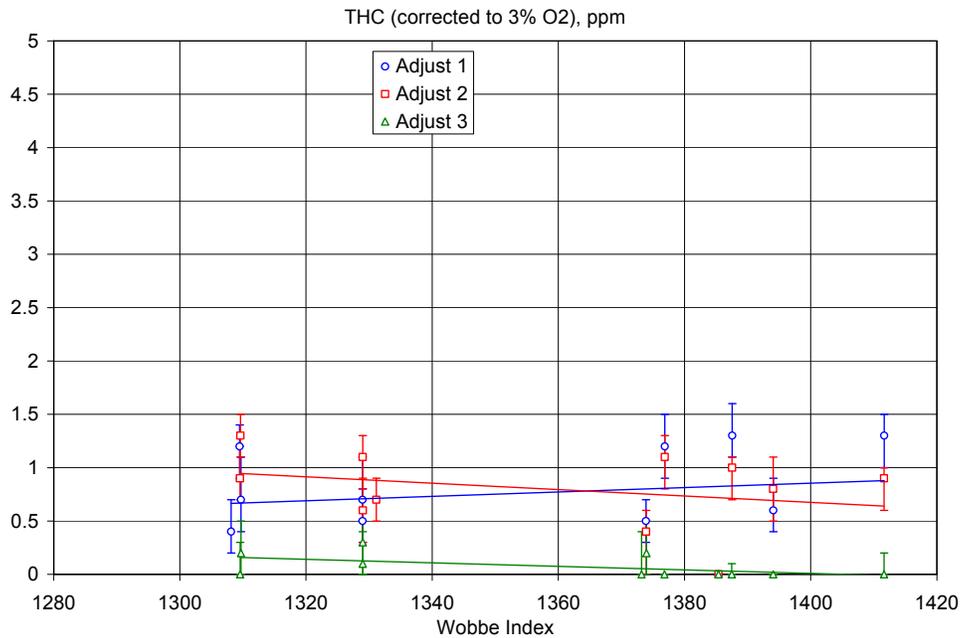


Figure 257. THC Emissions for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature

(Corrected to 3% O₂)

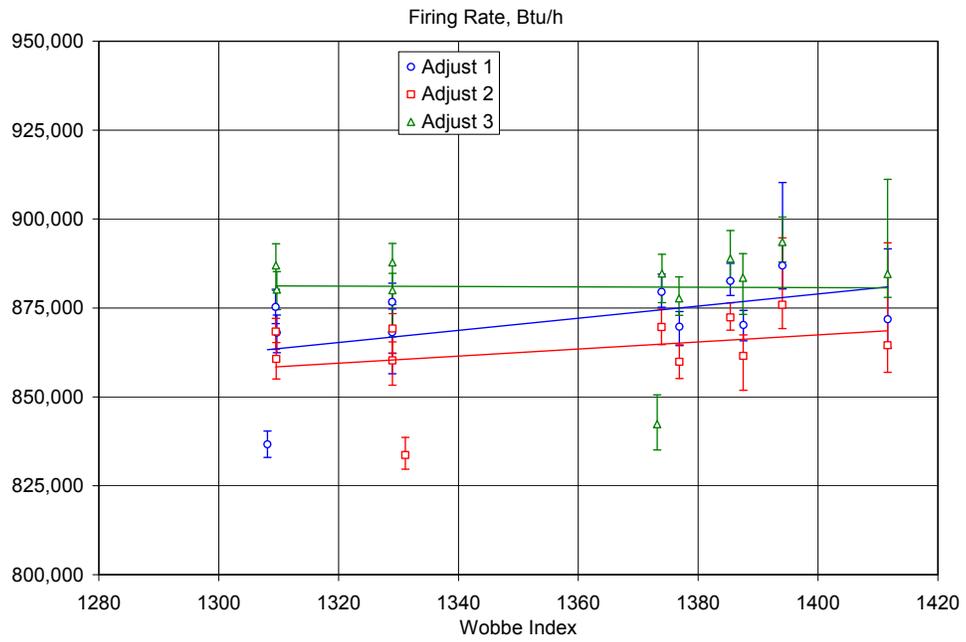


Figure 258. Firing Rate for All Substitute Gases for Continuous Testing with Constant Exhaust Temperature

Ignition Tests

The ignition tests measured whether the burner lights and the rate of heating. All the ignition efforts were successful. No ignition failure was observed during the tests. Figure 46 through Figure 74 show the on-off cycling during the ignition tests. The longer duration shown for the third ignition of each gas is due to switching to the next gas before shut off so that the fuel line is filled with that gas before the first ignition.

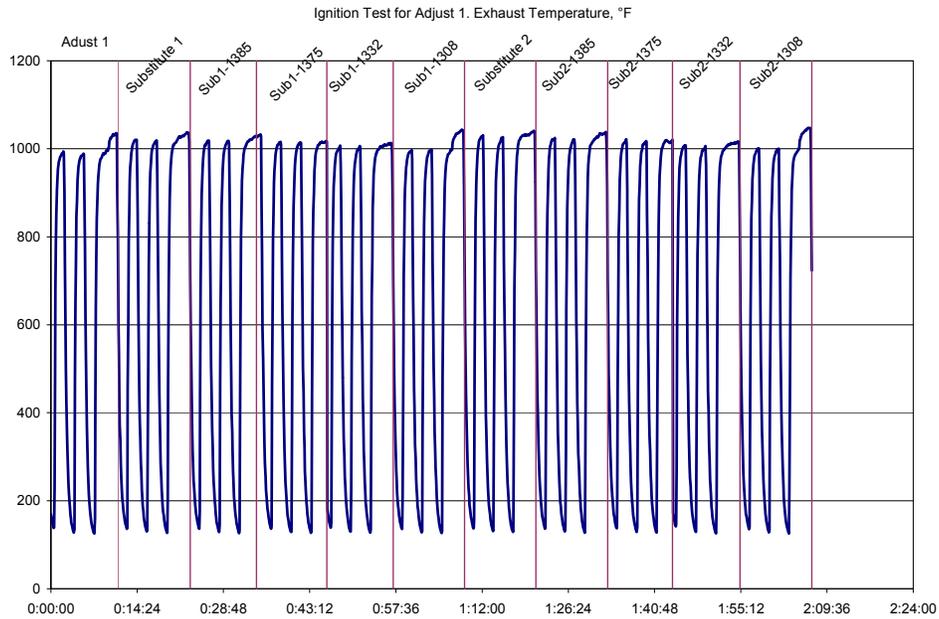


Figure 259. Cycle Pattern during Ignition Testing for Adjust 1 Basis

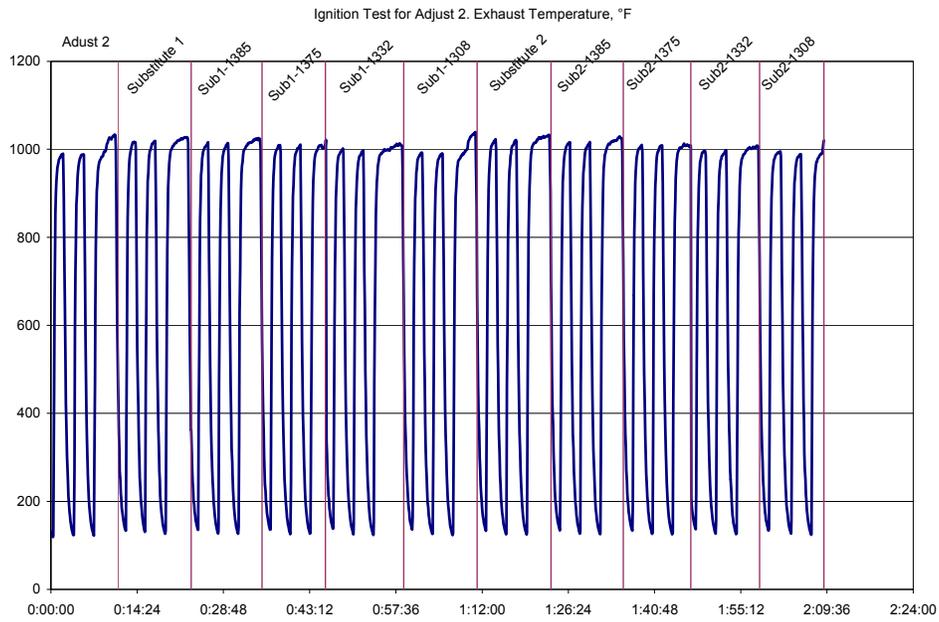


Figure 260. Cycle Pattern during Ignition Testing for Adjust 2 Basis

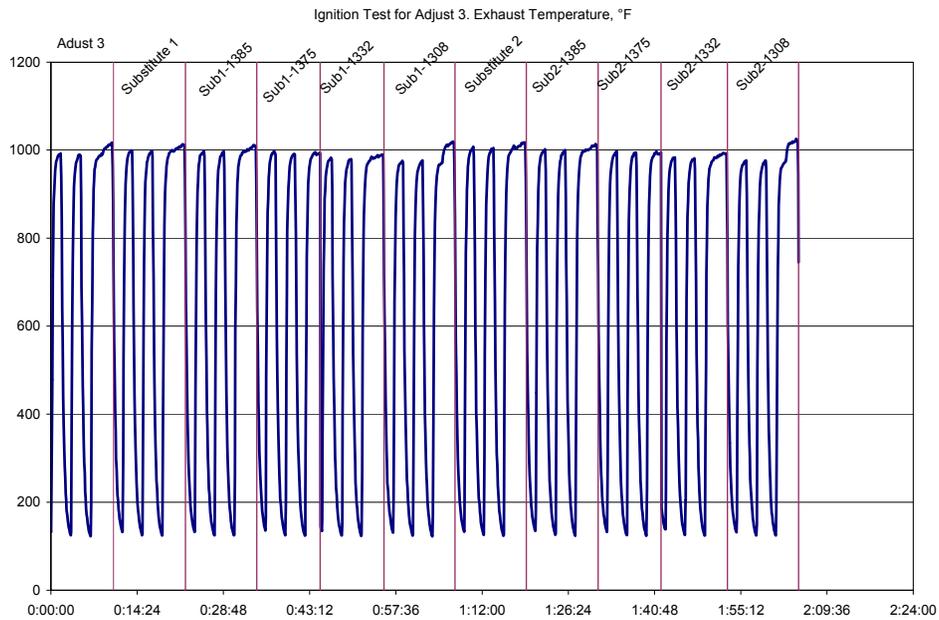


Figure 261. Cycle Pattern during Ignition Testing for Adjust 3 Basis

Calculations

The equation below is the linear correction used to approximately cancel out the analyzer drift;

$$X_{corr} = X_{meas} - \left((Zero\ drift) + (Span\ drift) \frac{X_{meas}}{Span\ value} \right) \frac{T_1}{T_2},$$

where X_{corr} is the corrected emissions value, X_{meas} is the measured value, the drift values are as labeled, T_1 denotes the time elapsed from the previous analyzer calibration, and T_2 denotes the time from the previous analyzer calibration to the next analyzer calibration.

After this correction, the emissions were normalized to 3%O₂ using the formula,

$$X_{3\%O_2} = X_{corr} \left(\frac{21 - 3\%}{21 - \%O_2} \right),$$

where $X_{3\%O_2}$ is the final value after both the correction for drift and the normalization to a common %O₂ in the exhaust.

The Firing Rate was calculated from the actual flow data. The heating value calculation followed the ASTM D 3588 – 98(03) standard at 70°F.

Analysis and Conclusions

The charts and data are analyzed in the same sections below as appear in the Results section.

Continuous Tests – Constant Firing Rate

For all three "adjust" gas tunings, "substitute" gases with higher Wobbe indexes yielded slightly lower NO_x and THC emissions, and yielded slightly higher CO emissions.

The exhaust temperature tended to follow the Wobbe index. This was not unexpected since the heat input to the burner is directly tied to Wobbe index.

Continuous Tests – Constant Exhaust Temperature

For all three "adjust" gas tunings, "substitute" gases with higher Wobbe indexes yielded higher NO_x emissions. There was no trend in CO emissions except for Adjust1, which may have lower CO with higher Wobbe index, but there is a lot of scatter in the data due to the overall low levels of CO emissions. The THC emissions appear to trend slightly lower with higher Wobbe index for Adjust2 and Adjust3, and the opposite for Adjust1, but again the overall values are low.

The firing rate tended to follow the Wobbe index except for Adjust3, which appeared to be invariant.

Ignition Tests

Since all 99 startups (11 gases times 3 ignitions times 3 tuning bases) were successful, comparisons are not possible. With proper setup, the spark ignited pilot does not appear to be affected by the fuel used.

Selected Photographs

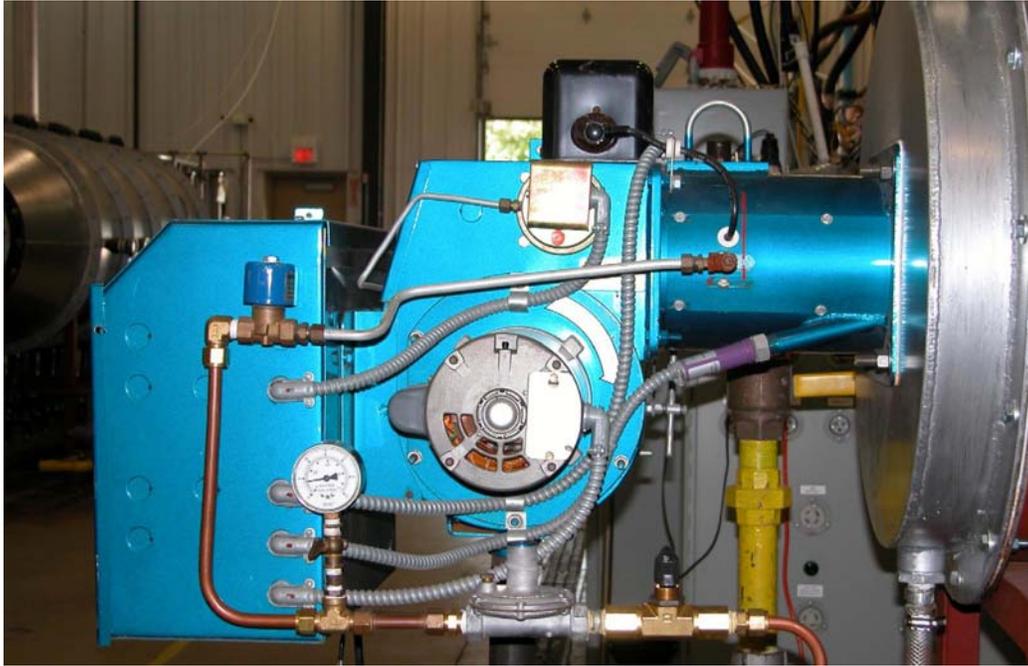


Figure 262. Packaged Boiler Burner



Figure 263. Test Chamber



Figure 264. Continuous Emissions Analyzers



Figure 265. Blending Stat

**NATURAL GAS IN CALIFORNIA: ENVIRONMENTAL IMPACTS
AND DEVICE PERFORMANCE**

**Industrial Field Trials:
Radiant Tube Burner Interchangeability Test Report**

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For

California Energy Commission

Contract No. CEC-500-05-026

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Objective

The purpose of the radiant tube burner interchangeability field trial is to assess the performance of a common industrial burner on an industrial furnace when fired with different natural gas compositions. The burner's performance when firing selected Adjust Gases was compared with its performance when firing selected Substitute Gases with and without different levels of nitrogen ballasting.

Approach

The tests used a portable version of the laboratory setup for blending gas compositions. One burner in a 6-burner zone of the furnace was chosen by the site that fires continuously at a near constant firing rate, that is easily accessible, and that is least likely to disrupt overall furnace operations since other burners in the zone are modulate in firing rate to maintain furnace temperature. The burner was first tuned to operate with an "adjust" gas composition. Operating/switching tests were then performed. During these tests several "substitute" gas compositions were fired in sequence on the burner. These tests were then repeated with the other two "adjust" gases as a basis.

Due the burners continuous use in an industrial furnace, ignition tests were not performed, and operating tests were performed in only one mode, constant firing rate. The constant firing rate tests were performed at a fixed, nearly 100% firing rate. The system's response in terms of emissions, exhaust temperature, and combustion air preheat temperature was recorded. The fuel's composition was also recorded.

For all test sequences, the furnace was operating continuously for at least a day prior to the tests. The fuel was switched from house gas to an "adjust" gas, and the burner was tuned per manufacturer's specifications by adjusting a limiting orifice so that the exhaust gas contained 2.8% O₂.

Table 9 shows the specific performance measurements.

Table 39. Performance Metrics for the Radiant Tube Burner

BASIC PERFORMANCE METRICS
Gaseous Pollutant Emissions
Exhaust Temperature
Combustion Air Preheat Temperature
Fuel Composition

Test Apparatus

The furnace used for this field trial was installed in the #2 continuous galvanizing line at California Steel Industries in Fontana, CA. The furnace had three zones—a preheat section with 24 direct fired, flat flame (wall hugger) burners; a heating zone with indirect heating by 21 "W" shaped radiant tubes, each with a Bloom model 2320 burner and recuperator; and a cooling zone. Burner No. N5 was used for the field trial. The burner used a spark-ignited house gas pilot, which ran continuously.

The fuel supply to the tested burner was fed from a manifold which also supplies fuel to several other (but not all) burners in the heating zone. The line from the header to the burner included a manual shut-off valve and a limiting orifice for tuning.

In parallel to this line, for the purpose of the field trial, a bypass line was installed that included isolation valves at the beginning and end, a mass flow meter, and port for adding blending gases, a static mixer, a limiting orifice, and a port measuring fuel composition. The latter port was originally after the limiting orifice, but was moved to before the limiting orifice since the pressure was too low at the burner to deliver a fuel sample. The bypass line was used during interchangeability testing, while the original line was used for normal operation of the burner when not being tested without having to reset the tuning of the burner.

One thermocouple was added to the combustion air preheat port of the recuperator, and another thermocouple was added to the exhaust port of the recuperator. Also added to the exhaust port of the recuperator was a stainless steel sampling line, which was connected via a Teflon line through a filtering and drying train to a portable combustion analyzer for NO_x, CO₂, CO, and O₂ and a continuous emissions analyzer for THC.

The fuel sampling port was connected via a stainless steel line to a portable gas chromatograph (micro GC), supplied and operated by Southern California Gas Company (SoCalGas).

The experimental setup is shown in Figure 37 through Figure 225.

The field trial used a portable version of the custom-built blending station that used in laboratory tests. The blending station was used to provide simulated natural gas compositions to the radiant tube burner at up to 6 psig. The blending station allowed for a main stream of house gas to which metered amounts of propane and nitrogen could be added. The house gas was the normal natural gas delivered to the site. House gas was used for normal operations of the radiant tube burner when interchangeability tests were not being conducted.

A mass flow meters was used to measure the house gas flow. Mass flow controllers were used to add propane and nitrogen to the main stream. Propane was supplied from the gaseous outlet of a liquid cylinder, and nitrogen was supplied from a gas cylinder. All gases were regulated down to about 15 psig before or upon entering the blending station.

The exhaust and combustion air preheat thermocouples, portable combustion analyzer, continuous emissions analyzer, mass flow meter, and mass flow controllers were connected to a data acquisition and control system. Instruments used to perform this test are listed in Table 3.

Table 40. Summary of Test Instruments

Instrument	Parameter	Range	Accuracy
National Instruments Field Point Modules	Data logging and control	4-20 mA, 0-5 V, 0-10 V, ± 100 mV, on/off (relay)	16 bit input current; 12 bit input voltage; 12 bit output current; 16 bit temperature
LabView software	Data logging	—	—
Custom software	Control	—	—
Laptop computer	Data logging and control	—	—
Type K thermocouple	Exhaust temperature	2502°F	—
Type K thermocouple	Combustion air preheat temperature	2502°F	—
Horiba PG-250	NO _x concentration;	0-250 ppm, Span 201 ppm;	0.5% full scale;
	CO concentration;	0-200 ppm, Span 182.7 ppm;	1.0% full scale;
	CO ₂ concentration;	0-20%, Span 18.01%;	0.5% full scale;
	O ₂ concentration	0-10%, Span 7.93%	0.5% full scale
Rosemount Analytical 400A	THC concentration	0-100 ppm, Span 78.6 ppm	1% full scale
Magnetrol TA2	House gas flow rate	1500 SCFH	1.0% of rate plus 0.5% of full scale
Brooks Instruments 5851S	Propane gas flow rate	68.5 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5851S	Nitrogen gas flow rate	141 SCFH	0.7% of rate plus 0.2% of full scale
Micro GC	Fuel Composition	0-100%	1% full scale

The measured flow rates of the house gas and the fuel gases supplied from the custom blending station to the burner were recorded using National Instruments Field Point Modules and a LabView program running on a laptop computer. The fuel gas compositions were commanded through a separate, custom program on the same laptop computer. The custom program used the measured flow rate of the main stream to determine the flow rates of the added gases. A table of ratios of each added gas to main stream for each "adjust" and "substitute" gas was created for the custom program.

Test Gases

The test gases were selected to match compositions distributed in California, and international compositions that may be imported into California. The compositions

distributed in California are designated “adjust gases” for the purpose of tuning the burner for optimum performance on each of them. The remaining gases are designated “substitute gases” for the purpose of comparing performance with the substitute gases to performance with the adjust gases. Table 4 summarizes the gas compositions. Adjust 1 is representative of natural gas in the Sacramento area, Adjust 2 is an average value for the state of California, and Adjust 3 is representative of some areas in California with higher Btu content due to local natural gas production. The two substitute gases, Sub 1 and Sub 2, were selected from a set of potential LNG compositions available to California; Sub 1 has a relatively low Wobbe Number (1408) compared with the other LNG compositions, and Sub 2 has a relatively high Wobbe Number (1425). Because it is possible that these "substitute" gases will be conditioned with nitrogen prior to distribution in California, additional compositions with nitrogen added to make the Wobbe Number match those of the selected "adjust" gases.

Table 41. Summary of Adjust and Substitute Gases

Name	Gas Composition, mol %							HHV	Wobbe
	C1	C2	C3	C4	C5+	N2	CO2		
Adjust 1	93.2	2.52	0.41	0.14	0.093	2.691	0.920	1010	1309
Adjust 2	94.5	2.55	0.42	0.14	0.094	1.361	0.931	1024	1332
Adjust 3	90.61	2.45	3.41	1.25	0.094	1.305	0.893	1094	1374
Sub 1	92.4	4.9	1.9	0.79	0.0	0.0	0.0	1099	1408
@1385	91.3	4.8	1.9	0.79	0.0	1.2	0.0	1086	1387
@1375	90.7	4.8	1.9	0.79	0.0	1.9	0.0	1080	1375
@1332	88.3	4.8	1.8	0.79	0.0	4.4	0.0	1053	1331
@1308	87.8	4.6	1.8	0.70	0.0	5.5	0.0	1036	1308
Sub 2	89.4	7.1	2.5	1.04	0.0	0.0	0.0	1131	1426
@1385	87.5	7.0	2.4	1.00	0.0	2.1	0.0	1106	1387
@1375	86.9	6.9	2.4	1.00	0.0	2.7	0.0	1098	1376
@1332	84.5	6.7	2.4	1.00	0.0	5.4	0.0	1070	1330
@1308	83.6	6.6	2.3	1.00	0.0	6.5	0.0	1057	1310

For small-scale testing (up to about 40,000 Btu/h), it is practical to purchase cylinders with these exact 13 compositions, or purchase cylinders with the exact 5 compositions for 3 "adjust" gases and 2 "substitute" gases and blend nitrogen with the "substitute" gases to create the "conditioned" gas compositions. For medium-scale testing (up to about 200,000 Btu/h), it is practical to create these compositions from cylinders of pure

gases using a blending station. For large-scale testing (over 1,000,000 Btu/h), the amount of pure methane needed requires a tube trailer, or a means to strip out the inerts (particularly the heavy molecular weight CO₂), which allows most of the composition to be obtained by blending in ethane, propane and butane, and nitrogen into the cleaned house gas. .

For field trials of industrial sized burners, none of these approaches is practical due to either the volume of gases need or the pressure drop required to scrub the house gas. Also, the fact that one burner is being test out of a zone of multiple burners all fed by a common manifold, means that the one burner cannot be fed fuel independently when it is in a controlled industrial operation.

The approach taken was to simply measure the flow rate of the gas being fed to the one burner, and blend in gases downstream of the flow measurement point to create various fuel compositions. The approach works well when there is a pressure regulator or a relatively large pressure drop between the burner and the blending point, the latter being the case here due to the limiting orifice used to tune the burner.

In the laboratory testing, ethane, propane and butane were all used to create the various fuel composition. All three gases affect the Wobbe index in the direction, so any one of them, along with nitrogen, can be used to create an array of higher heating values (HHVs) and Wobbe indices. Since propane is in the middle of the three, is the most readily available, comes in relatively compact liquid tanks with a more than sufficient gas vapor pressure, and there was some expressed desire to have a high propane content in the fired fuel, it was chosen.

The "adjust" gases could be simulated (same heating value and Wobbe index) by blending in propane and nitrogen from cylinders into the site's house gas. However, the pure "substitute" gases and conditioned (nitrogen-diluted) "substitute" gases with higher Wobbe indices could not be simulated this way because of the amount of inerts (CO₂ and N₂) in the house gas. The points of maximum heating value and Wobbe index, along the same lines as the conditioned "substitute" gases, were used in their place. The portable gas chromatograph was used to measure the composition of the house gas for each day of testing. With this information, calculations were made to determine the appropriate amounts of propane and nitrogen to be added to achieve the desired HHV and Wobbe indices. These compositions are shown in Table 12.

Table 42. Summary of Test Gases

05/11/2011	Gas Composition, mol %			HHV	Wobbe
	House Gas	Propane	Nitrogen		
Adj1WH*	96.28%	1.10%	2.62%	1010.0	1309.0
Adj2WH	97.48%	1.17%	1.35%	1024.0	1332.0
Adj3WH*	93.06%	5.71%	1.24%	1094.0	1374.0
Sub1WH-A3M	95.46%	4.11%	0.43%	1078.0	1374.1
Sub1WH-A2	93.02%	4.00%	2.98%	1050.4	1329.2
Sub1WH-A1	91.95%	3.96%	4.09%	1038.2	1309.7
Sub2WH-HiM	93.17%	6.16%	0.66%	1106.8	1387.7
Sub2WH-A3	92.60%	6.12%	1.27%	1100.0	1377.0
Sub2WH-A2	90.03%	5.95%	4.01%	1069.3	1329.2
Sub2WH-A1	88.99%	5.88%	5.13%	1056.9	1309.9

* not used on this date

05/12/2011	Gas Composition, mol %			HHV	Wobbe
	House Gas	Propane	Nitrogen		
Adj1WH	96.46%	0.71%	2.83%	1010.0	1309.0
Adj2WH*	97.66%	0.78%	1.56%	1024.0	1332.0
Adj3WH	93.23%	5.33%	1.44%	1094.0	1374.0
Sub1WH-A3M	95.64%	3.72%	0.64%	1078.0	1374.1
Sub1WH-A2	93.19%	3.63%	3.18%	1050.4	1329.2
Sub1WH-A1	92.12%	3.59%	4.29%	1038.2	1309.7
Sub2WH-HiM	93.34%	5.79%	0.87%	1106.8	1387.7
Sub2WH-A3	92.77%	5.75%	1.48%	1100.0	1377.0
Sub2WH-A2	90.20%	5.59%	4.21%	1069.3	1329.2
Sub2WH-A1	89.15%	5.53%	5.33%	1056.9	1309.9

* not used on this date

Figure 42 illustrates the desired fuel heating values and Wobbe indices to be used for the radiant tube burner field trial.

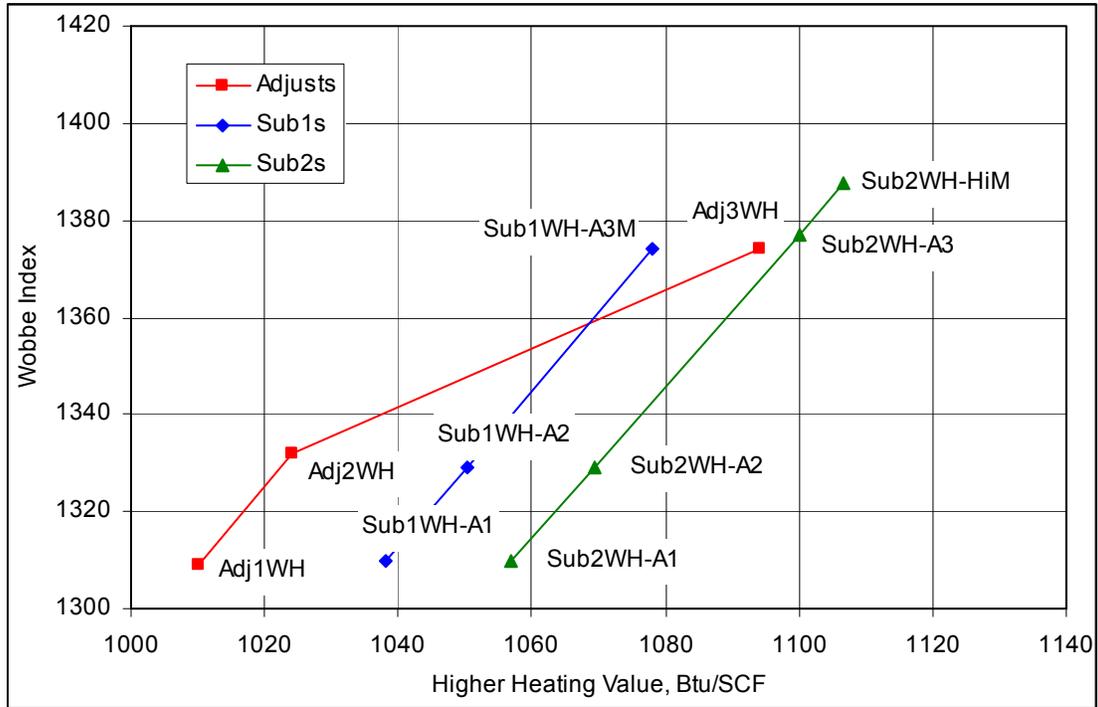


Figure 266. Wobbe Indices and Heating Values for Radiant Tube Burner Field trial

With the elimination of two of the metered fuel gases, and remote monitoring of only one main stream (the house gas), the blending station became simplified enough to made into a "portable" case. Mass flow controllers for propane and nitrogen (from the larger laboratory blending station) and a data acquisition system were placed inside an electrical enclosure (with lid removed during operation), with shut off valves for the propane and nitrogen, and with external connection receptacles added for supply power, propane gas inlet, nitrogen gas inlet, mixed propane/nitrogen gas outlet, power and signal for the remote mass flow meter, signal from the continuous emission analyzer, signals from the thermocouples, and data link to a laptop computer. The laptop computer was connected directly to the portable combustion analyzer to complete the interconnections. The portable gas chromatograph was completely independent, including its own laptop computer.

Test Schedule

The performance tests with constant firing rate were performed for all three "adjust" gases. Table 13 shows the planned schedule of test sequences. The actual sequence was as shown for the Adj1WH and Adj3Wh bases, but for the Adj2WH basis, the Sub1WH-A3M and Sub1-A2 tests had to be re-conducted at the end of that sequence (see Activities Performed section for more details).

Table 43. Planned Test Schedule

Type	Constant Firing Rate		
Basis	Adj2WH	Adj1WH	Adj3WH
Subs	Sub1WH-A3M	Sub1WH-A3M	Sub1WH-A3M
	Sub1WH-A2	Sub1WH-A2	Sub1WH-A2
	Sub1WH-A1	Sub1WH-A1	Sub1WH-A1
	Sub2WH-HiM	Sub2WH-HiM	Sub2WH-HiM
	Sub2WH-A3	Sub2WH-A3	Sub2WH-A3
	Sub2WH-A2	Sub2WH-A2	Sub2WH-A2
	Sub2WH-A1	Sub2WH-A1	Sub2WH-A1

Activities Performed

The field trial of the radiant tube burner was performed over the course of a week in May 2011.

Setup

On the first two days of the week, GTI's test equipment and instrumentation and SoCalGas's portable gas chromatograph was set up at the site.

During the first day, the gas piping bypass line, with mass flow meter, blending gas port, static mixer, and limiting orifice, was installed in parallel to the existing gas supply line from the header to the burner. Branch tees and isolation valves has already been installed prior to GTI's visit by site personnel along with a port near the burner for sampling the house gas or fuel gas. A thermocouple was added to combustion air preheat port of the recuperator, and another thermocouple was added to the exhaust port of the recuperator along with a sampling line.

The portable combustion analyzer and THC emissions analyzer were placed on table near the burner along with the portable blending station. Flow switch boxes were attached to the two analyzers to allow for selection of sample gas, zero gas, or span gas. A drying train and sampling pump was placed between the sampling line and the flow switch boxes.

The fuel and calibration gas cylinders were placed near the instrumentation and tubing lines were run to the flow switch boxes and portable blending station. A tubing line was run from the outlet of the portable blending station to the blending gas port on the gas piping bypass line. Thermocouple wires were run from the thermocouples at the recuperator to the dedicated connection jacks for the data acquisition system in the portable blending station. Power and signal lines were run from the mass flow meter in the gas piping bypass line to the dedicated connection jacks on the portable blending station along with a signal line from the THC analyzer. An Ethernet cable was run from the portable blending station to a laptop computer placed on a second table along with a serial cable from the portable combustion analyzer.

SoCalGas's portable gas chromatograph (GC) was placed on a third table, and a sampling line was connected from it to the gas sampling port.

The second day at the site was spent debugging, troubleshooting, and practice testing. The first two feet of the Teflon sampling line from the exhaust port was replaced by stainless steel. The portable combustion analyzer was replaced with an identical back analyzers since the original analyzer was now holding calibration and would not communicate with the laptop computer. The outlet of the sampling pump was moved to first feed the THC analyzer and then the portable combustion analyzer instead of the other way around since the THC analyzer needed positive pressure and the portable combustion analyzer need negative pressure at their respective inlets.

A new port for sampling house gas or fuel gas was added to the gas piping bypass line between the static mixer and limiting orifice because the pressure in the supply line at the burner was insufficient to convey a sample down to the GC. A coalescing filter was added to the sampling for the GC.

The portable and THC analyzers were connected to the sampling line. The gas piping bypass line was activated and, simultaneously, the original burner supply line was deactivated. The limiting orifice in the gas piping bypass line was adjusted to roughly tune the burner. A GC sample of the then flowing house gas was taken. Based on the GC analysis, a calculation was made to create the Adj2WH composition. This procedure involved transferring the data from the computer attached to the GC to another computer, running a spreadsheet with iterative calculations to determine the proper amounts of propane and nitrogen to blend into the house gas for the 10 "adjust" and "substitute" gases, and transferring these ratios from this computer to the computer connected to the blending station.

The blending station was then commanded to flow the proper amounts of propane and nitrogen based on the amount of house gas flowing. The added amounts of propane and nitrogen cause the amount of house gas flow to slow down, but the propane and nitrogen flows are automatically recalculated by the program running on the computer to keep the ratios (and composition) constant. The burner was then more finely tuned.

The propane and nitrogen were then switched off, and the original burner supply line was reactivated while simultaneously deactivating gas piping bypass line. With the analyzers still connected to the sampling line, the limiting orifice in the original burner supply line was adjusted to tune the burner to 2.85% oxygen in the exhaust as a courtesy to the site.

Continuous Tests – Constant Firing Rate

Testing began on the third day of the week. The furnace had been running continuously for at least a day at this point.

The portable combustion and THC analyzers and the GC were calibrated. The gas piping bypass line was activated and a sample of the house gas was taken with the GC. The blending ratios were calculated and transferred to the blending station for the 10 "adjust" and "substitute" gases using the procedure described above. The Adj2WH composition was now fed to the burner. The burner was tuned to 2.85% oxygen in the exhaust. Twenty minutes of readings were collected by the data acquisition system at 5 second intervals. Five minutes into the data collection period another sample was taken and analyzed by the GC. The five minutes was deemed necessary to assure that the sample, which was being continuously sent to the GC's sample loop, contained the fuel gas under test. At the end of the data collection, the calibration of the analyzers was checked.

The fuel was next switched to Sub1WH-A3M, and another 20 minutes of readings were collected along with a GC sample at the 5 minute point. This was repeated for Sub1WH-A2, followed by another check of the analyzers. At this point it became apparent the flow rates of nitrogen and propane were too low for the Sub1WH-A3M and Sub1WH-A2 runs. A check of the spreadsheet eventually showed that the wrong column of data was referenced in the calculations of the "substitute" gas compositions (the "adjust" gas compositions were correct). The calculations were corrected and the new ratios were transferred to the blending station. Testing then continued with the Sub1WH-A1, Sub2WH-HiM, Sub2WH-A3, Sub2WH-A2, and Sub2WH-A1 compositions, with GC samples for every fuel gas and with calibrations checks after every other fuel gas. After switching back to Adj2WH, the tests were conducted with the proper Sub1WH-A3M and Sub1WH-A2 compositions. The reason these two compositions were not immediately repeated was that it was deemed more important to finish the test sequence as planned because there could be insufficient time at the end of the day. That is, it would be better to complete the test sequence with two points somewhat off than to completely miss the last two points if time was not available.

Testing continued on the fourth day of the week, with an earlier start time. The furnace was still running continuously.

Testing on this day proceed in the same manner as the previous day, but without the composition calculation problem. The house gas composition was measured with the GC. The blending ratios were calculated and transferred to the blending station for the 10 "adjust" and "substitute" gases. The Adj1WH composition was now fed to the burner. The burner was tuned to 2.9% oxygen in the exhaust. Data was collected for 20 minutes of operation on Adj1WH along with a GC sample. Testing then proceeded with the Sub1WH-A3M, Sub1WH-A2, Sub1WH-A1, Sub2WH-HiM, Sub2WH-A3, Sub2WH-A2, and Sub2WH-A1 compositions, with GC samples for every fuel gas and with calibrations checks after every other fuel gas. After switching back to Adj2WH, it was determined that the next sequence of tests could be completed the same day with the site allowance of the testing proceeding into the evening hours.

The Adj3WH composition was now fed to the burner. The burner was tuned to 2.95% oxygen in the exhaust. Data was collected for 20 minutes of operation on Adj3WH along with a GC sample. Testing then proceeded with the Sub1WH-A3M, Sub1WH-A2, Sub1WH-A1, Sub2WH-HiM, Sub2WH-A3, Sub2WH-A2, and Sub2WH-A1 compositions, with GC samples for every fuel gas and with calibrations checks after every other fuel gas. The fuel was switched back to Adj3WH composition before going back to the house gas.

The original burner supply line was reactivated and the limiting orifice in the original burner supply line was adjusted to retune the burner to 2.75% oxygen in the exhaust as a courtesy to the site.

Breakdown

The fifth day of the week was spent disconnecting the tubing runs and wiring, removing the mass flow meter from the gas piping bypass line and plugging off the ports on this line, relocating the calibration gas cylinders, packing the analyzers and test equipment into their containers, having the site palletize the containers for shipment, and (by SoCalGas) disconnecting and removing the GC.

Results

Continuous Tests – Constant Firing Rate

The major results from the continuous tests with constant firing rate are the emissions and the exhaust and combustion air preheat temperatures (the system's response) when the radiant tube burner is tuned with a particular "adjust" gas, and the fuel is switched to various "substitute" gases. Figure 48 through Figure 200 show the emissions, exhaust and combustion air preheat temperatures over the 20 minute data collection intervals for each gas. Average values for the three test sequences are shown in Figure 103 through Figure 287. The highest and lowest values indicated for each point, along with a linear trend line. The calculated values of the higher heating value and Wobbe index for all the test gases based on the measurements made by the gas chromatograph are shown in Figure 288.

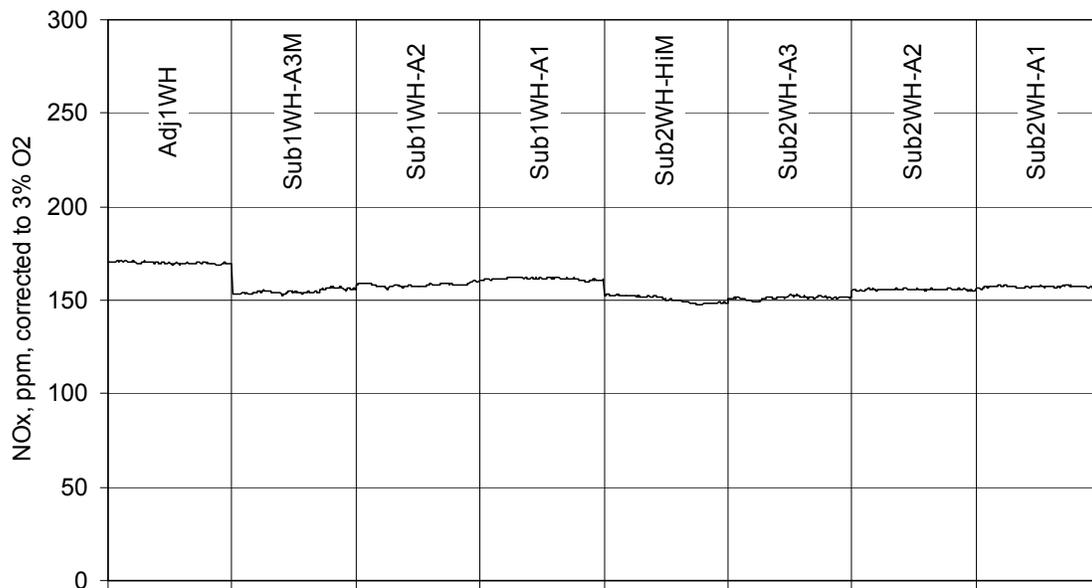


Figure 267. NOx Emissions for Adjust1 Tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

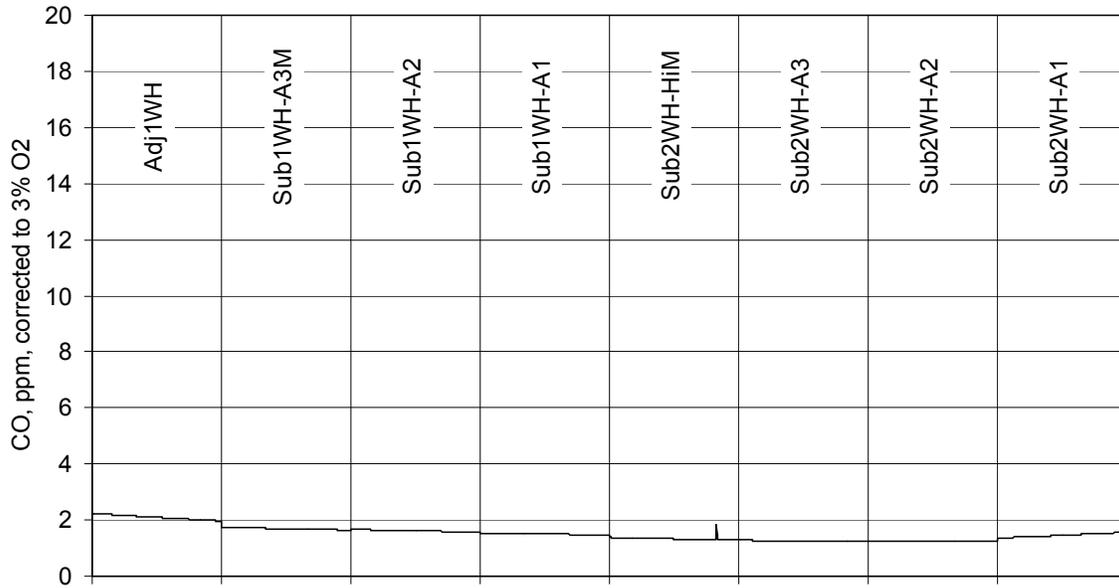


Figure 268. CO Emissions for Adjust1 Tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

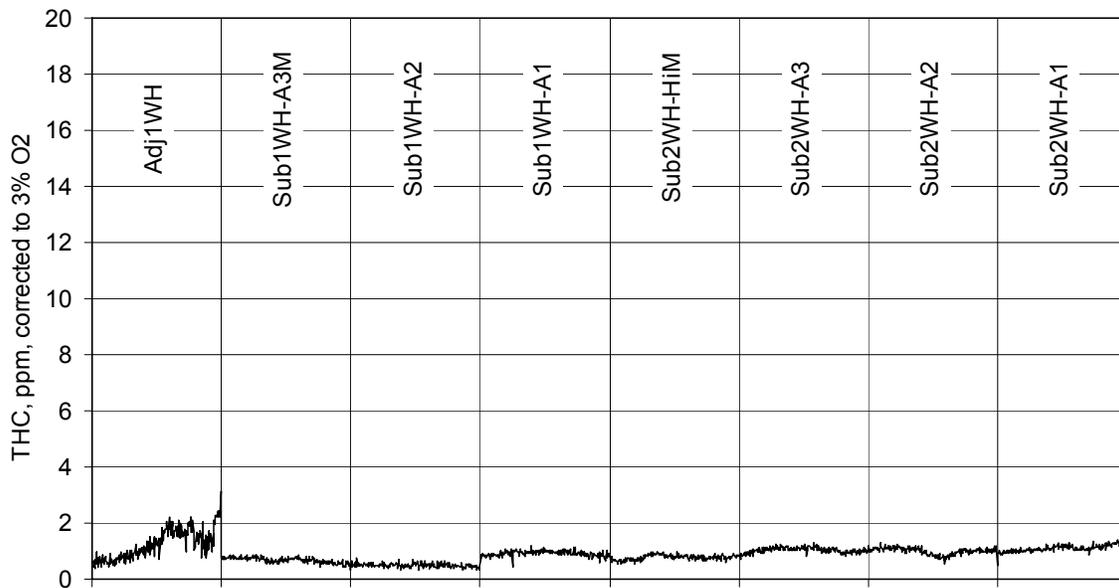


Figure 269. THC Emissions for Adjust1 Tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

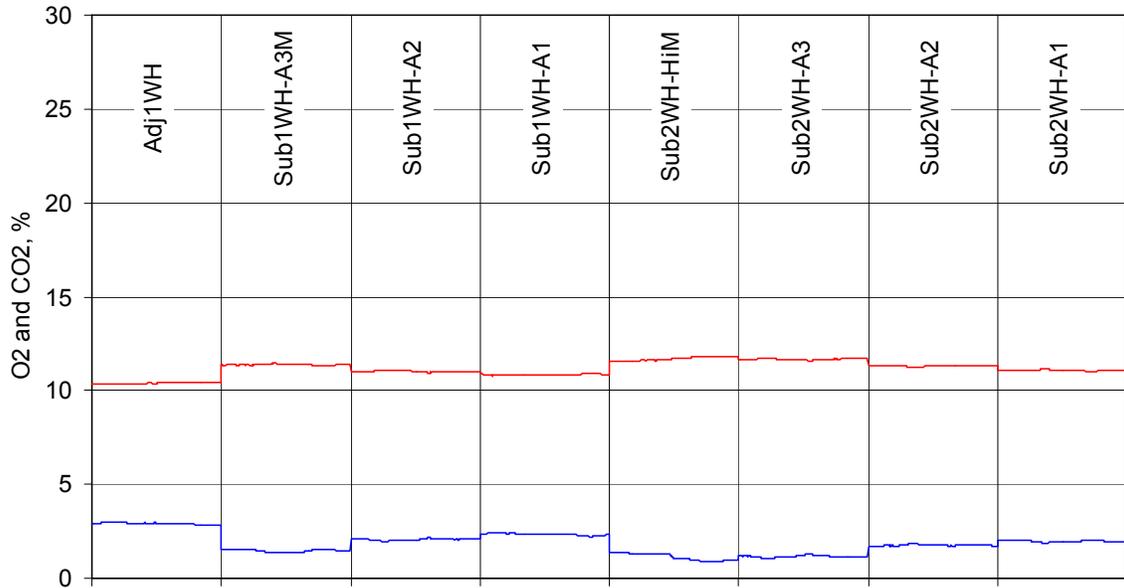


Figure 270. CO₂ and O₂ Emissions for Adjust1 Tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

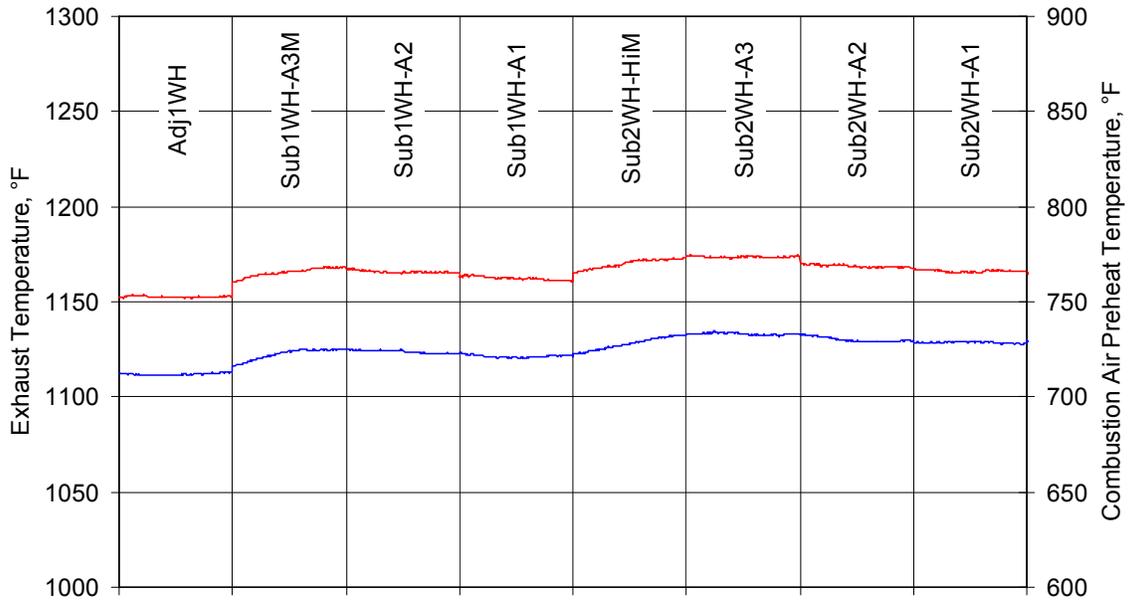


Figure 271. Exhaust and Combustion Air Preheat Temperature for Adjust1 Tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

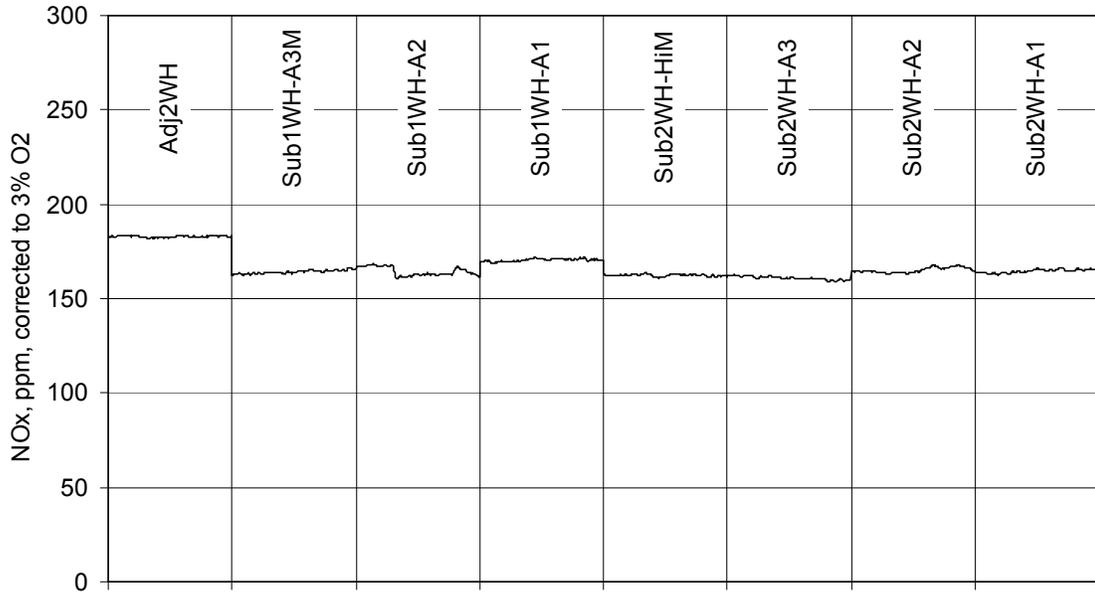


Figure 272. NOx Emissions for Adjust2 Tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

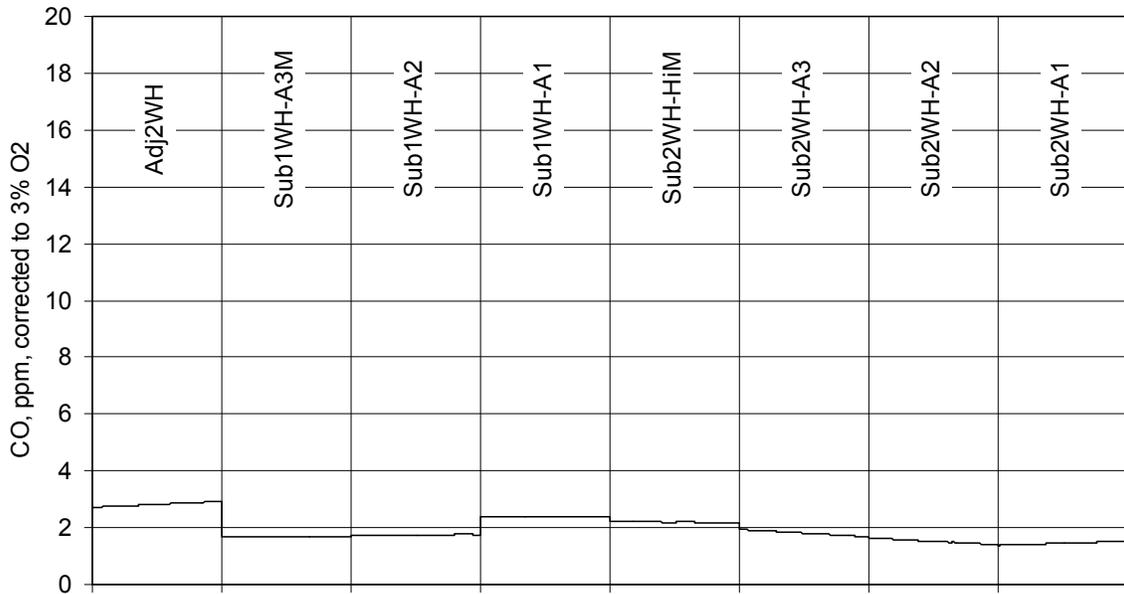


Figure 273. CO Emissions for Adjust2 Tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

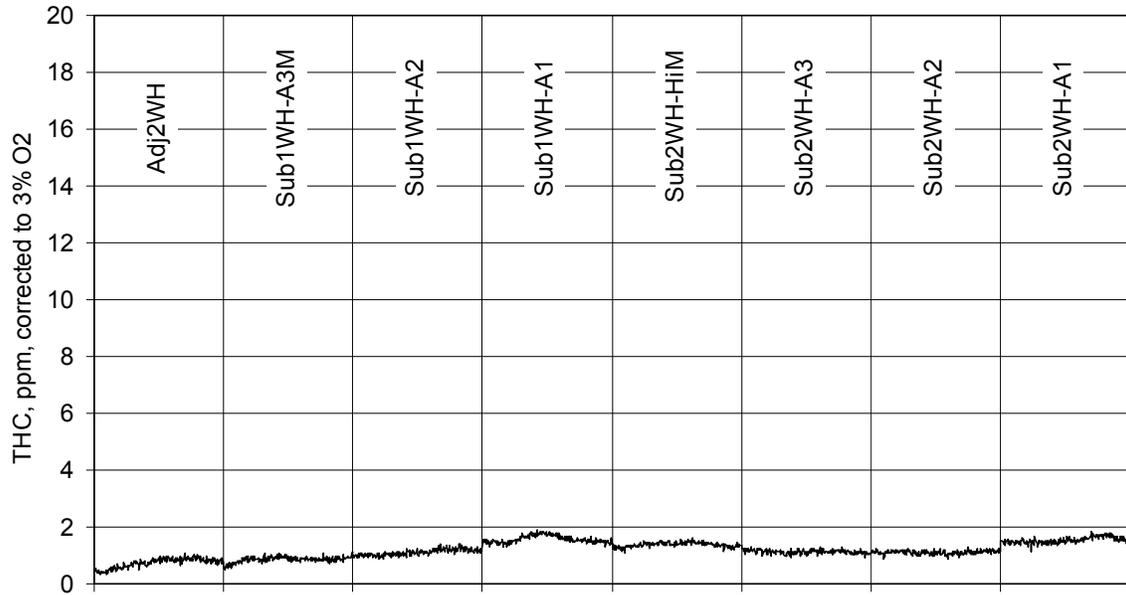


Figure 274. THC Emissions for Adjust2 Tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

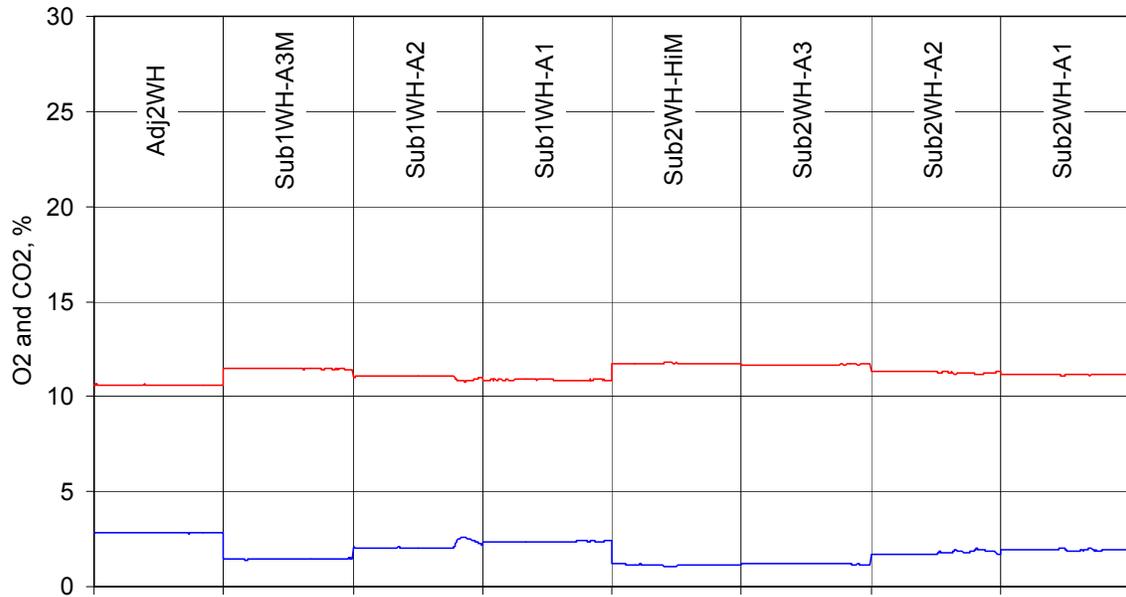


Figure 275. O₂ and CO₂ Emissions for Adjust2 Tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

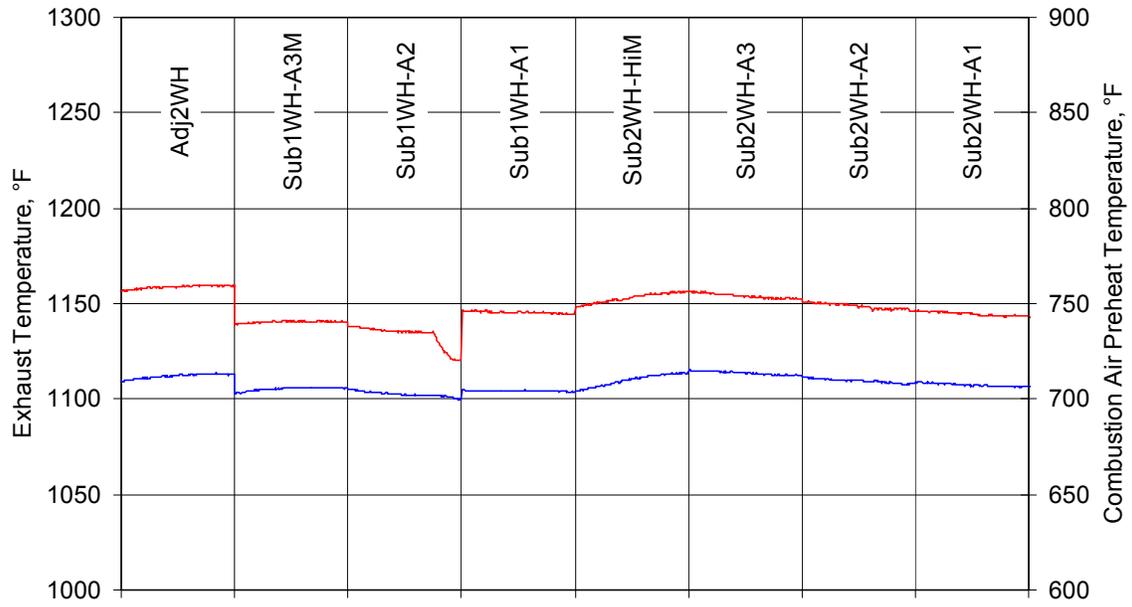


Figure 276. Exhaust and Combustion Air Preheat Temperature for Adjust2 Tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

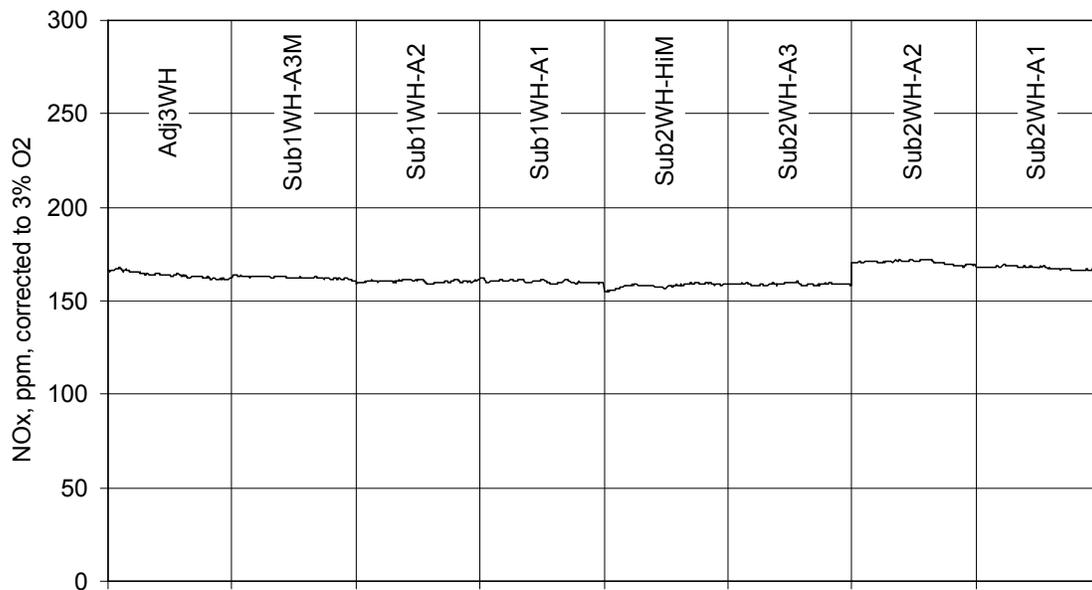


Figure 277. NOx Emissions for Adjust3 Tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

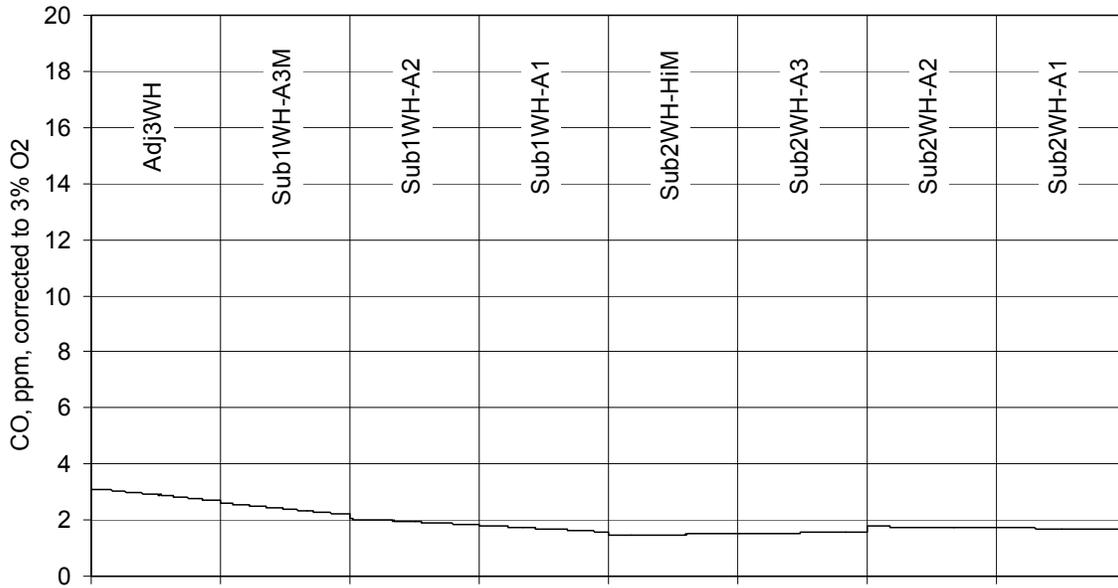


Figure 278. CO Emissions for Adjust3 Tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

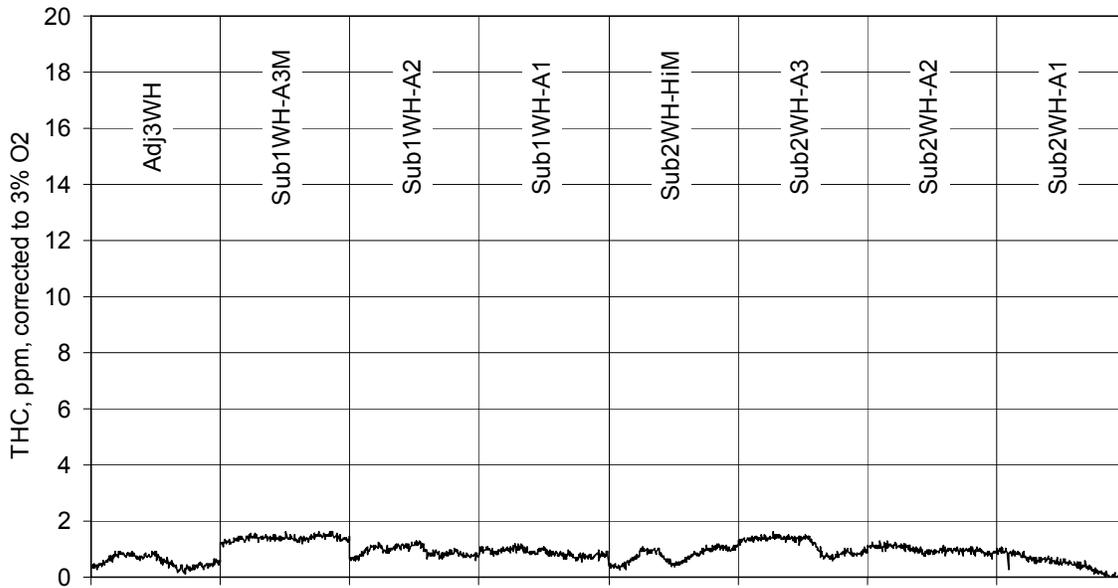


Figure 279. THC Emissions for Adjust3 Tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

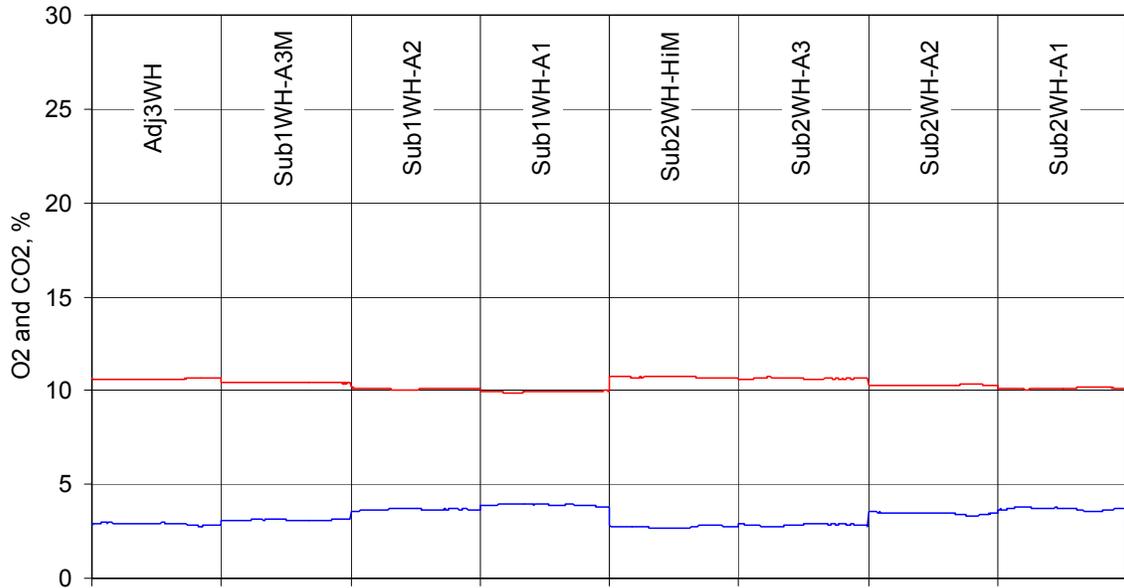


Figure 280. O₂ and CO₂ Emissions for Adjust3 Tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

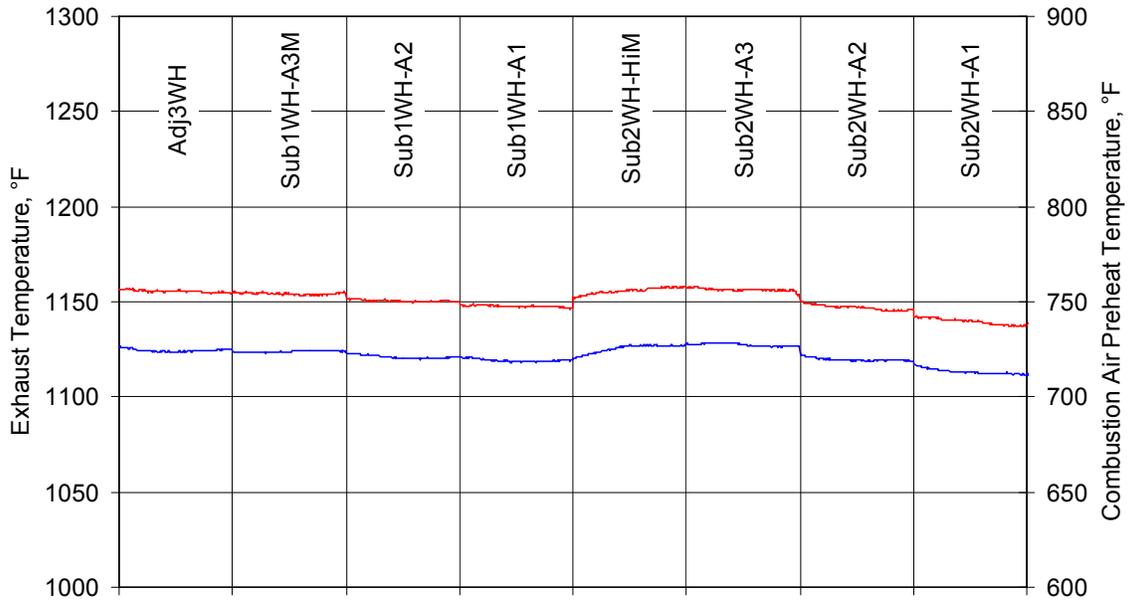


Figure 281. Exhaust and Combustion Air Preheat Temperature for Adjust3 Tuning and All Substitute Gases for Continuous Testing with Constant Firing Rate

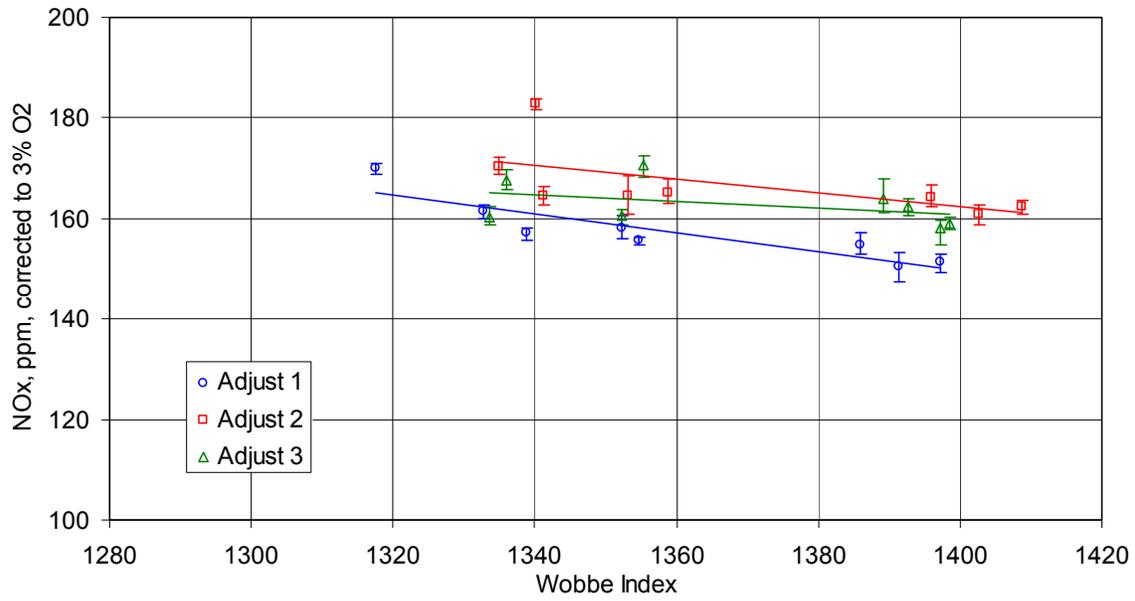


Figure 282. NOx Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate
(Corrected to 3% O₂)

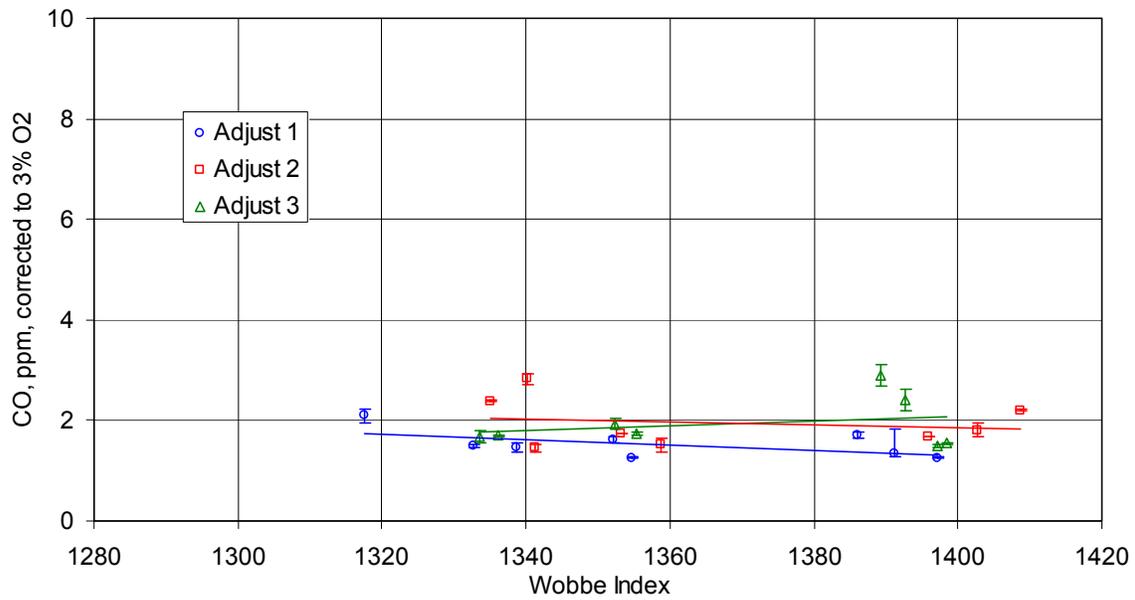


Figure 283. CO Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate
(Corrected to 3% O₂)

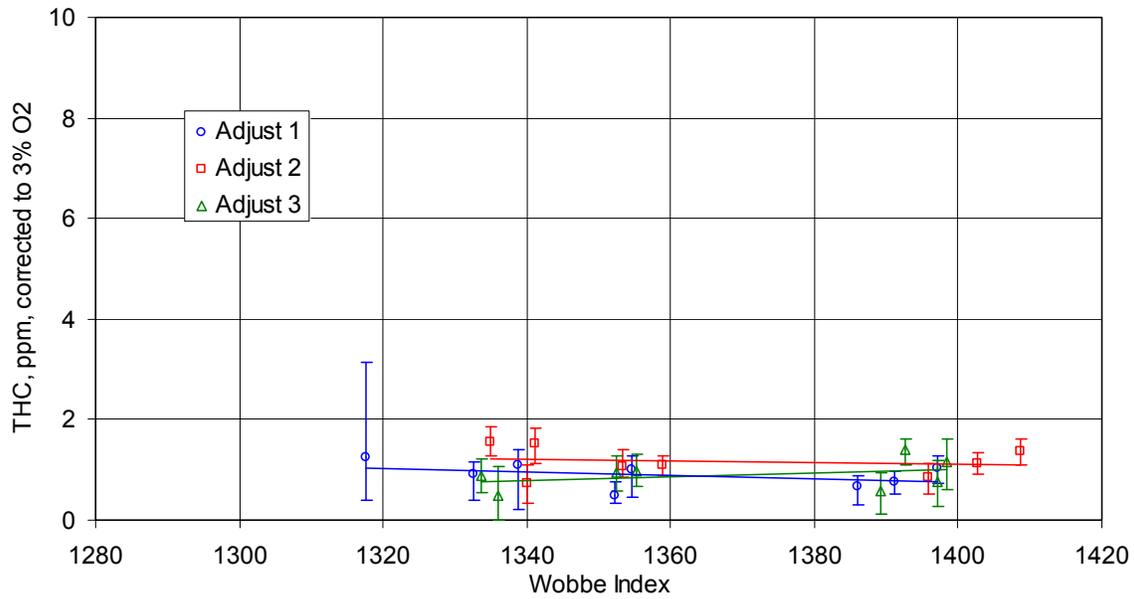


Figure 284. THC Emissions for All Substitute Gases for Continuous Testing with Constant Firing Rate (Corrected to 3% O₂)

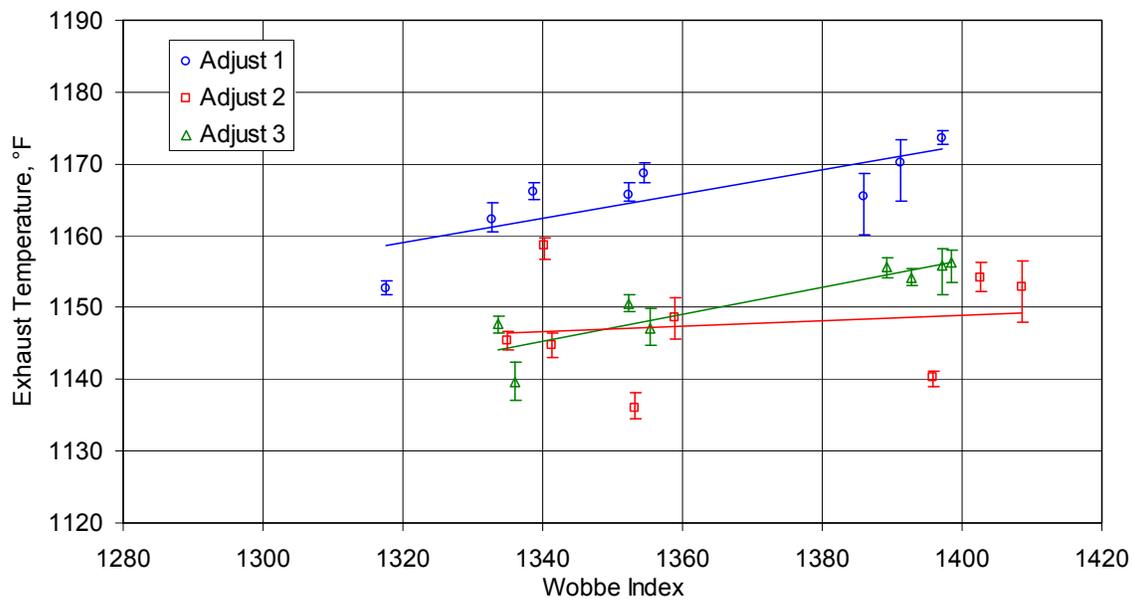


Figure 285. Exhaust Temperature for All Substitute Gases for Continuous Testing with Constant Firing Rate

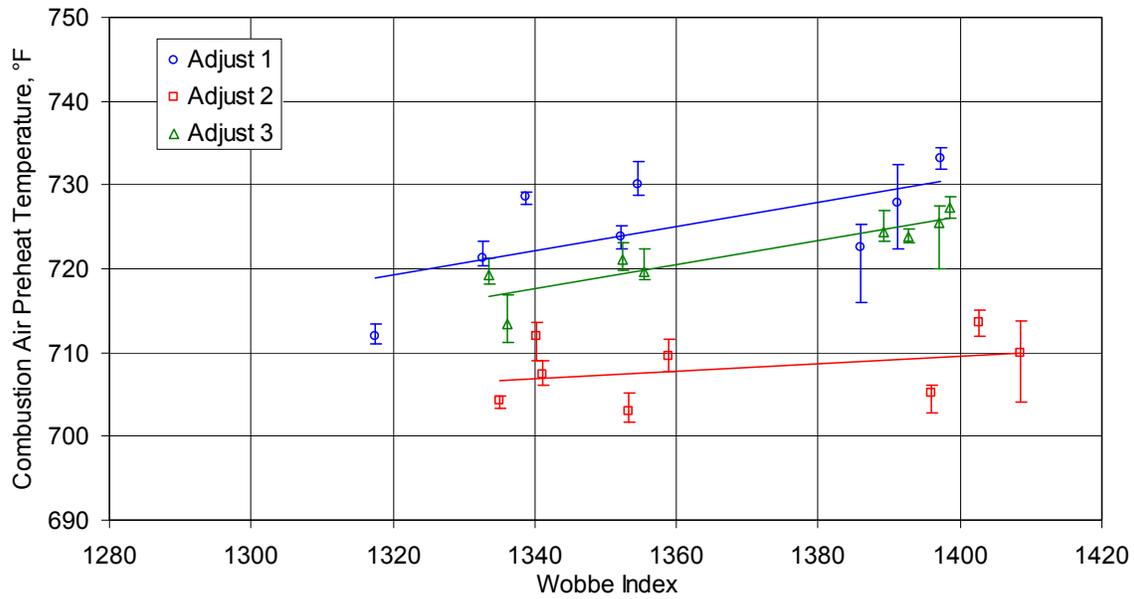
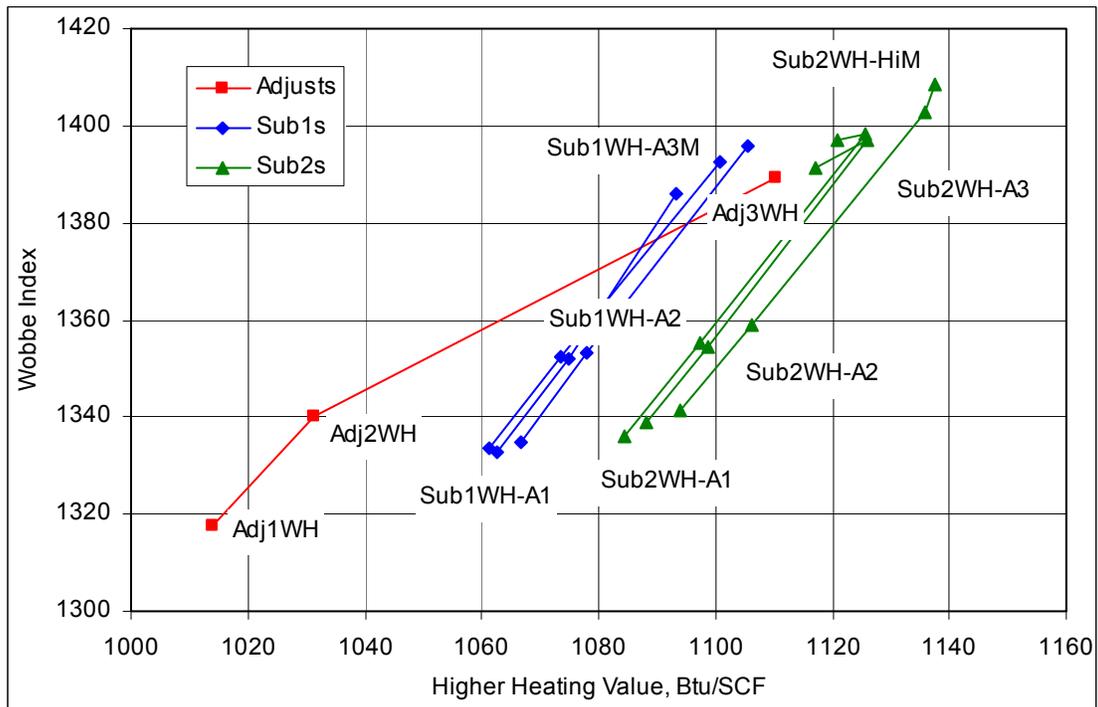


Figure 286. Combustion Air Preheat Temperature for All Substitute Gases for Continuous Testing with Constant Firing Rate



Calculations

All concentrations of emissions were measured on a dry basis. The equations below is the linear correction used to approximately cancel out analyzer drift;

$$X_{corr}(t) = (X_{meas}(t) - Z(t)) \frac{C}{S(t)},$$

where

$$Z(t) = Z_1 + (Z_2 - Z_1) \frac{(t - t_{z1})}{(t_{z2} - t_{z1})},$$

$$S(t) = S_{c1} + (S_{c2} - S_{c1}) \frac{(t - t_{s1})}{(t_{s2} - t_{s1})},$$

$$S_{c1} = S_1 - Z(t_{s1}),$$

$$S_{c2} = S_2 - Z(t_{s2}),$$

where $X_{corr}(t)$ is the corrected emissions value and $X_{meas}(t)$ is the measured value at time t , $Z(t)$ is the zero drift correction, $S(t)$ is the span drift correction, C is the span gas concentration, Z_1 and Z_2 are the instrument readings on zero gas at times T_{z1} and T_{z2} , respectively, S_1 and S_2 are the instrument readings on span gas at times T_{s1} and T_{s2} , respectively, and S_{c1} and S_{c2} are the values of the span readings corrected for zero drift, respectively.

After this correction, emissions were normalized to 3%O₂ using the formula,

$$X_{3\%O_2}(t) = X_{corr}(t) \cdot \left(\frac{21\% - 3\%}{21\% - \%O_{2,corr}(t)} \right),$$

where $X_{3\%O_2}(t)$ is the final value after both the correction for analyzer drift and the normalization to a common 3% oxygen concentration in the dried exhaust.

Analysis and Conclusions

The charts and data are analyzed in the same sections below as appear in the Results section.

Continuous Tests – Firing Rate

About 15 minutes into the 20 minute run for the "substitute" gas Sub1WH-A2 with Adj2WH tuning basis, which was actually the last gas tested on that day, the firing rate on the test burner was throttled back due to a production rate change. This effect is most notable in Figure 277. Only the first 15 minutes of data for this test were averaged for Figure 103 through Figure 287.

Even though tests with "substitute" gases Sub1WH-A3M and Sub1WH-A2 with Adj2WH tuning basis were performed at the end of the test sequence, their data are shown in their planned spots in Figure 273 through Figure 277 to be consistent with Figure 48 through Figure 272 and Figure 278 through Figure 200.

The gas chromatograph analysis of the fired fuels (see Figure 288) showed larger higher heating values and Wobbe indices than desired. The general qualitative pattern of the values still matched the desired pattern (see Figure 42), so the analyses below are still based on a proper sequence of higher heating values and Wobbe indices, but simply with a broader range of values. The values in Figure 288 may indicate that more propane was flowing relative to natural gas than desired since there is consistency in the results, the gas chromatograph was not tuned for high levels of propane, or a combination of both. The software for the gas chromatograph did have trouble recognizing the peak for propane as propane. More than half of the time it did not report a value for propane when the concentration was over 6%, and the concentration had to be manually determined long after the tests were completed from the reported area under the unrecognized peak. For two of the three runs with the "substitute" gas Sub2WH-HiM there appears to be a kink in the sequences in the graph, but the flow rate data from the mass flow meters and controllers do not show this kink, so the kink may just be an artifact of the limitations of the gas chromatograph being tuned for normal natural gas compositions.

For the most part, "substitute" gases with higher Wobbe indices than the "adjust" gas that the radiant tube burner was tuned for yielded slightly (~6%) lower NO_x emissions. Emissions of CO and THC were always low during the testing and showed no discernable trends with Wobbe index. Exhaust and combustion air preheat temperatures were slightly higher (~9 °F and ~8 °F, respectively) with gases with higher Wobbe indices.

Selected Photographs



Figure 288. Radiant Tube Burner and Recuperator

(Middle Burner Tested)

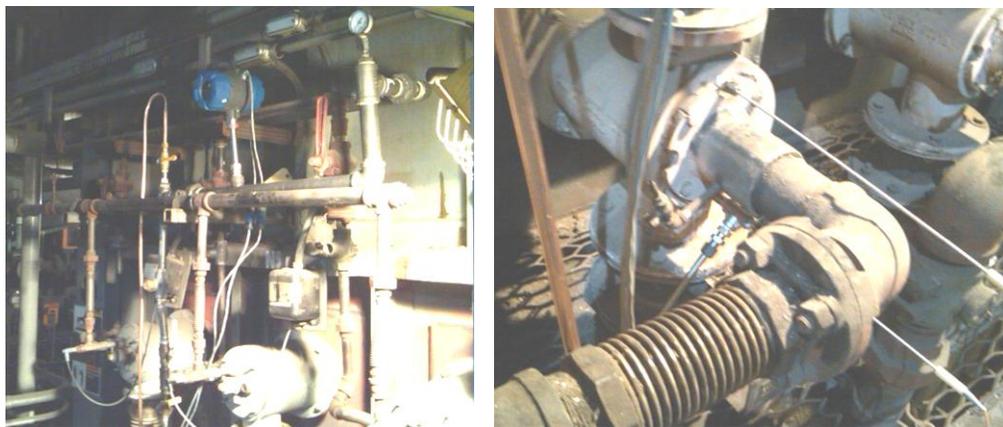


Figure 289. Gas Piping Bypass Line and Thermocouples



Figure 290. Gas Piping Bypass Line Rework



Figure 291. Gas Cylinders, Analyzers, and Blending Station

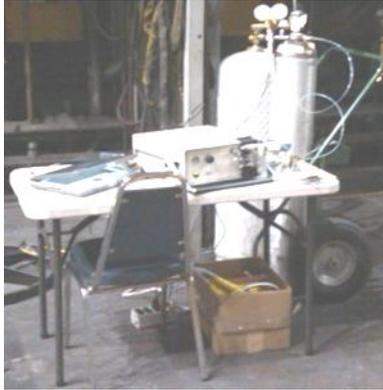


Figure 292. Gas Chromatograph

**NATURAL GAS IN CALIFORNIA: ENVIRONMENTAL IMPACTS
AND DEVICE PERFORMANCE**

**Industrial Field Trials:
Water Tube Boiler Interchangeability Test Report**

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(GTI Project No. 20352)

For

California Energy Commission

Contract No. CEC-500-05-026

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April 2012

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Objective

The purpose of the water tube boiler interchangeability field trial is to assess the performance of an industrial packaged steam boiler when fired with different natural gas compositions. The boiler's performance when firing selected Adjust Gases was compared with its performance when firing selected Substitute Gases with and without different levels of nitrogen ballasting.

Approach

The tests used a portable version of the laboratory setup for blending gas compositions. A recently installed boiler at the site was suggested for the field trial by the boiler manufacturer. A steam bypass line was installed to vent excess steam so that the boiler fired continuously at a nearly constant firing rate. Other, older boilers still installed at the site were being used at the time for process steam, so normal operations at the facility were not disrupted. Since GTI personnel were not allowed to tune the boiler, operating/switching tests were then performed in a mode similar to the commercial appliance tests by firing the "adjust" gas compositions in sequence followed by the "substitute" gas compositions in sequence. These tests were then repeated with all the "adjust" gas compositions and selected "substitute" gas compositions, plus two super-low-Wobbe gas compositions to simulate a retuning of the boiler. On the final day of testing, a boiler representative was present to retune the boiler temporarily for the highest Wobbe gas composition and selected gas compositions were then fired.

Due to the boiler's continuous use, ignition tests were not performed, and operating tests were performed in only one mode, constant firing rate. The constant firing rate tests were performed at a nearly fixed rate of 70% to 75% of the boiler rated firing rate. Some variation occurred due to the controls modulating the firing rate when the steam pressure neared its setpoint. The system's response in terms of emissions and exhaust temperature was recorded. The natural gas composition was also recorded at a nearby station by the local gas utility.

Table 9 shows the specific performance measurements.

Table 44. Performance Metrics for the Water Tube Boiler

BASIC PERFORMANCE METRICS
Gaseous Pollutant Emissions
Exhaust Temperature
Natural Gas Composition

Test Apparatus

The boiler used for this field trial was installed at the Manufacturing Center of MeriCal, Inc. in Vista, CA. The boiler was a recently installed Parker Boiler 104 Series (104L Series) Model 48L industrial packaged steam boiler. The boiler had eight premixed metal fiber burners. The burners used a spark-ignited pilot with stringer tubes to carryover the pilot from burner to burner

A 2" pipe supplied natural gas to this boiler. For the purpose of the field trial, a pair of pipe tees was inserted into this line with a manual shut off valve in between. A bypass line

was installed between the branches of the tees. The bypass line included isolation valves at the beginning and end, a mass flow meter, and port for adding blending gases, a static mixer, and a port measuring fuel pressure. Both ports included manual shut off valves. The pressure port also included a secondary port from which a sample of the fuel could be drawn, but this was not used since the local gas utility was able to provide the local natural gas composition. The bypass line was used during interchangeability testing. The original line was intended to be used for normal operation of the boiler when not being tested, but this mode was not used since the site did not need to operate the boiler between the interchangeability tests.

A thermocouple was inserted into a port in the stack below the dilution inlet to measure the boiler's exhaust gas temperature. A stainless steel sampling line probe was inserted into another port in the stack below the dilution inlet. The sampling probe was connected via a Teflon line through a filtering and drying train to a portable combustion analyzer for NO_x, CO₂, CO, and O₂ and a continuous emissions analyzer for THC.

The experimental setup is shown in Figure 37 through Figure 320.

The field trial used a portable version of the custom-built blending station that was used in laboratory tests. The blending station was used to provide simulated natural gas compositions to the water tube boiler at up to 5 psig. The blending station provided metered amounts of propane and nitrogen that were added to the house gas. The house gas was the normal natural gas delivered to the site. House gas was used for normal operations of the water tube boiler before and after the interchangeability tests.

A mass flow meter was used to measure the house gas flow. Mass flow controllers were used to add propane and nitrogen to this main stream. Propane was supplied from the gaseous outlet of a liquid cylinder, and nitrogen was supplied from a gas cylinder. All gases were regulated down to about 15 psig before entering the blending station.

The exhaust gas thermocouple, portable combustion analyzer, continuous emissions analyzer, mass flow meter, and mass flow controllers were connected to a data acquisition and

control system, which was installed in the same panel as the mass flow controllers. Instruments used to perform this test are listed in Table 3.

Table 45. Summary of Test Instruments

Instrument	Parameter	Range	Accuracy
National Instruments Field Point Modules	Data logging and control	4-20 mA, 0-5 V, 0-10 V, ±100 mV, on/off (relay)	16 bit input current; 12 bit input voltage; 12 bit output current; 16 bit temperature
LabView software	Data logging	—	—
Custom software	Control	—	—
Laptop computer	Data logging and control	—	—
Type K thermocouple	Exhaust temperature	2502°F	—
Type K thermocouple	Combustion air preheat temperature	2502°F	—
Horiba PG-250	NOx concentration; CO concentration; CO ₂ concentration; O ₂ concentration	0-100 ppm, Span 39.0 ppm; 0-200 ppm, Span 182.7 ppm; 0-20%, Span 18.01%; 0-10%, Span 7.93%	1.0% full scale; 1.0% full scale; 0.5% full scale; 0.5% full scale
Rosemount Analytical 400A	THC concentration	0-100 ppm, Span 78.6 ppm	1% full scale
Magnetrol TA2	House gas flow rate	1500 SCFH	1.0% of rate plus 0.5% of full scale
Brooks Instruments 5853S	Propane gas flow rate	157 SCFH	0.7% of rate plus 0.2% of full scale
Brooks Instruments 5851S	Nitrogen gas flow rate	141 SCFH	0.7% of rate plus 0.2% of full scale

The measured flow rates of the house gas and the fuel gases supplied from the custom blending station to the boiler were recorded using National Instruments Field Point Modules and a LabView program running on a laptop computer. The fuel gas compositions were commanded through a separate,

custom program on the same laptop computer. The custom program used the measured flow rate of the main stream to determine the flow rates of the added gases. A table of ratios of each added gas to the main stream for each "adjust" and "substitute" gas was created for the custom program.

Test Gases

The test gases were selected to match compositions distributed in California, and international compositions that may be imported into California. The compositions distributed in California are designated "adjust gases" since these are the gases that systems are tuned for. The remaining gases are designated "substitute gases" for the purpose of comparing the system's performance with these gases to its performance with the adjust gases. Table 4 summarizes the gas compositions. Adjust 1 is representative of natural gas in the Sacramento area, Adjust 2 is an average

value for the state of California, and Adjust 3 is representative of some areas in California with higher Btu content due to local natural gas production. The two substitute gases, Sub 1 and Sub 2, were selected from a set of potential LNG compositions available to California; Sub 1 has a relatively low Wobbe Number (1408) compared with the other LNG compositions, and Sub 2 has a relatively high Wobbe Number (1425). Because it is possible that these "substitute" gases will be conditioned with nitrogen prior to distribution in California, additional compositions with nitrogen added to make the Wobbe Number match those of the selected "adjust" gases were tested.

Table 46. Summary of Adjust and Substitute Gases

Name	Gas Composition, mol %							HHV	Wobbe
	C1	C2	C3	C4	C5+	N2	CO2		
Adjust 1	93.2	2.52	0.41	0.14	0.093	2.691	0.920	1010	1309
Adjust 2	94.5	2.55	0.42	0.14	0.094	1.361	0.931	1024	1332
Adjust 3	90.61	2.45	3.41	1.25	0.094	1.305	0.893	1094	1374
Sub 1	92.4	4.9	1.9	0.79	0.0	0.0	0.0	1099	1408
@1385	91.3	4.8	1.9	0.79	0.0	1.2	0.0	1086	1387
@1375	90.7	4.8	1.9	0.79	0.0	1.9	0.0	1080	1375
@1332	88.3	4.8	1.8	0.79	0.0	4.4	0.0	1053	1332
@1308	87.8	4.6	1.8	0.70	0.0	5.5	0.0	1036	1308
Sub 2	89.4	7.1	2.5	1.04	0.0	0.0	0.0	1131	1426
@1385	87.5	7.0	2.4	1.00	0.0	2.1	0.0	1106	1387
@1375	86.9	6.9	2.4	1.00	0.0	2.7	0.0	1098	1376
@1332	84.5	6.7	2.4	1.00	0.0	5.4	0.0	1070	1332
@1308	83.6	6.6	2.3	1.00	0.0	6.5	0.0	1057	1310

For small-scale testing (up to about 40,000 Btu/h), it is practical to purchase cylinders with these exact 13 compositions, or purchase cylinders with the exact 5 compositions for 3 "adjust" gases and 2 "substitute" gases and blend nitrogen with the "substitute" gases to create the "conditioned" gas compositions. For medium-scale testing (up to about 200,000 Btu/h), it is

practical to create these compositions from cylinders of pure gases using a blending station. For large-scale testing (over 1,000,000 Btu/h), the amount of pure methane needed requires a tube trailer, or a means to strip out the inerts (particularly the heavy molecular weight CO₂), which allows most of the composition to be obtained by blending ethane, propane and Wobbe, and nitrogen into the cleaned house gas. For field trials of industrial sized systems, none of these approaches is practical due to either the volume of gases needed or the pressure drop required to scrub the house gas. The approach taken was to simply measure the flow rate of the gas being fed to the boiler, and blend in gases downstream of the flow measurement point to create various fuel compositions. The approach works well when there is a pressure regulator or a relatively large pressure drop between the blending

point and the boiler, the former being the case here due to the house gas supply being at 5 psig and the boiler needing no more than 0.5 psig.

In the laboratory testing, ethane, propane and butane were all used to create the various fuel composition. All three gases affect the Wobbe index and higher heating value in the same direction, so any one of them, along with nitrogen, can be used to create an array of higher heating values (HHVs) and Wobbe indices. Since propane is in the middle of the three, is the most readily available, comes in relatively compact liquid tanks with a more than sufficient gas vapor pressure, and there was some expressed desire to have a high propane content in the fired fuel, it was chosen.

The "adjust" gases could be simulated (same heating value and Wobbe index) by blending propane and nitrogen from cylinders into the site's house gas. However, the pure "substitute" gases and conditioned (nitrogen-diluted) "substitute" gases with higher Wobbe indices could not be simulated this way because of the amount of inerts (CO₂ and N₂) in the house gas. The points of maximum heating value and Wobbe index, along the same lines as the conditioned "substitute" gases, were used in their place. The gas chromatograph measurements of the compositions of the local house gas for each prior day of testing were averaged. With this information, calculations were made to determine the appropriate amounts of propane and nitrogen to be added to achieve the desired HHV and Wobbe indices. These compositions are shown in Table 12.

Table 47. Summary of Test Gases

10/ 12/ 20 11	Gas Composition, mol %			H H V, Bt u/ S C F	W o b b e , Bt u/ S C F
	H o u s e G a s	P r o p a n e	N i t r o g e n		
A d j 1X H	9			1	1
	6.	1.		0	3
	3	6	2.	1	0
2X H	2	4	04	0.	9.
	%	%	%	0	0
A d j 2X H	9			1	1
	7.	1.		0	3
	5	7	0.	2	3
3X H	2	1	76	4.	2.
	%	%	%	0	0
A d j 3X H	9			1	1
	3.	6.		0	3
	1	2	0.	9	7
Su b1 X H- A3 M	0	3	68	4.	4.
	%	%	%	0	0
Su b1 X H- A2	9			1	1
	3.	4.		0	3
	0	5	2.	5	2
Su b1 X	6	2	42	0.	9.
	%	%	%	4	2
Su b1 X	9			1	1
	1.	4.	3.	0	3
	9	7	54	3	0
		%			

H-A1	9%	%		8.2	9.7
Sub2X	9.3	6.6		1.1	1.3
H-HiM	2.1	6.8	0.10	0.6	0.7
Sub2X	9.2	6.6		1.1	1.3
H-HiM	4.4	4.72		0.0	0.7
Sub2X	9.0	6.4	3.47	0.9	0.9
H-HiM	8.9	6.3	4.59	0.6	0.9

A0			
Sub2YH-A0	87.95%	6.17%	5.88%

10/14/2011	Gas Composition, mol %			HHV, Btu/SCF	Wobbe, Btu/SCF
	House Gas	Propane	Nitrogen		
Adj2ZHG	1.0	0.0	0.0	1.0	1.3
Sub2ZHG	9.3	6.2	0.0	1.1	1.3
H-HiM	7.7	7.7	0.0	0.5	0.8
H-HiM	3.3	%	%	5.4	5.5

10/13/2011	Gas Composition, mol %			HHV, Btu/SCF	Wobbe, Btu/SCF
	House Gas	Propane	Nitrogen		
Adj1YH	96.58%	1.51%	1.90%	1010.0	1309.0
Adj2YH	97.79%	1.59%	0.63%	1024.0	1332.0
Adj3YH	93.35%	6.11%	0.55%	1094.0	1374.0
Sub2YH-HiM	93.44%	6.56%	0.00%	1106.5	1387.3
Sub2YH-A1	89.26%	6.27%	4.47%	1056.9	1309.9
Adj0YH	95.35%	1.45%	3.20%	996.0	1286.0
Sub1YH-	90.92%	4.29%	4.79%	1023.4	1286.0

Figure 42 illustrates the desired fuel heating values and Wobbe indices to be used for the water tube boiler field trial.

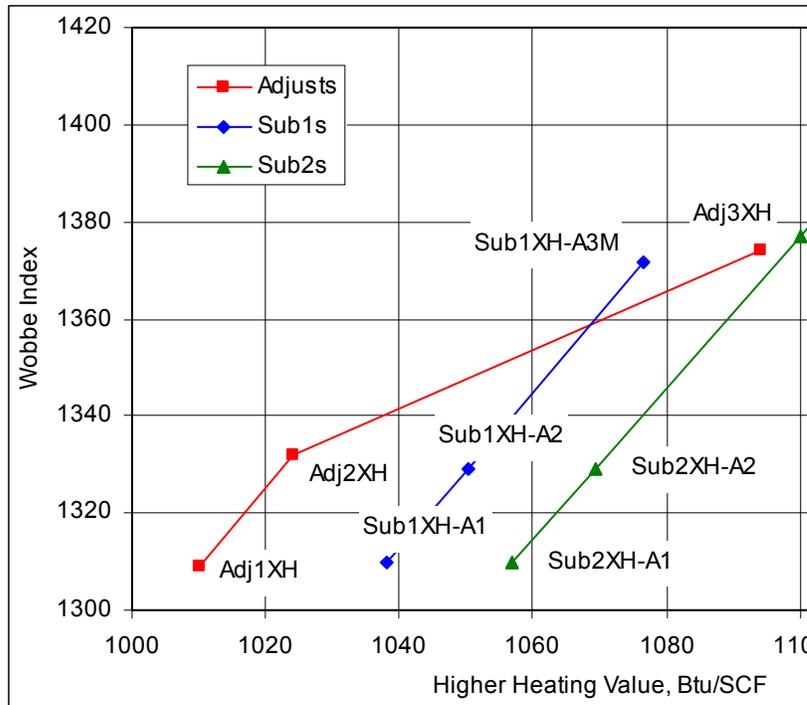


Figure 293. Wobbe Indices and Heating Values for Water Tube Boiler Field Trial

firing the boiler with the sequence of fuel blends shown in the first column. The second day of testing involved repeating some of the first day's tests and also firing the boiler with some lower Wobbe fuel blends shown in the second column to simulate the boiler being tuned for a higher Wobbe fuel. The third day of testing involved testing with the basis fuel and with the highest Wobbe fuel, without and with retuning the boiler for the highest Wobbe fuel.

With only two metered fuel gases, and remote monitoring of only one main stream (the house gas), the blending station was simple enough to be made into a "portable" unit. Mass flow controllers for propane and nitrogen (from the larger laboratory blending station) and a data acquisition system were placed inside an electrical enclosure (with lid removed during operation), with shut off valves for the propane and nitrogen, and with external connection receptacles added for supply power, propane gas inlet, nitrogen gas inlet, mixed propane/nitrogen gas outlet, power and signal for the remote mass flow meter, signal from the continuous emission analyzer, signals from the thermocouples, and data link to a laptop computer. The laptop computer was connected directly to the portable combustion analyzer to complete the interconnections.

Test Schedule

The performance tests with fixed firing rate were performed for all three "adjust" gases. Table 13 shows the planned schedule of test sequences. The first day of testing involved

Table 48. Planned Test Schedule

Type	Fixed Firing Rate			
Basis	House Gas	House Gas	House Gas	Hottest Gas
Fuels	Adj2XH	Adj2YH	Adj2ZHG	Sub2ZH-HiM
	Adj1XH	Adj1YH	Sub2ZH-HiM	Adj2ZHG
	Sub1XH-A3M	Adj3YH		
	Sub1XH-A2	Adj0YH		
	Sub1XH-A1	Sub1YH-A0		
	Adj3XH	Sub2YH-A0		
	Sub2XH-HiM	Sub2YH-A1		
	Sub2XH-A3	Sub2YH-HiM		
	Sub2XH-A2			
	Sub2XH-A1			

Activities Performed

The field trial of the water tube boiler was performed over the course of a week in October 2011.

Setup

On the first two days of the week, GTI's test equipment and instrumentation was set up at the site.

During the first day, the mass flow meter was installed into the gas piping bypass line. The gas piping bypass line included a blending gas port, static mixer, and a pressure/gas sample port. The gas piping bypass line had already been installed in the header to the boiler prior to GTI's visit by the boiler installers along with a steam bypass line from the steam line to the deaerator. A thermocouple was added to one pre-existing port of the exhaust stack of the boiler. A sampling probe was added to a second pre-existing port.

The portable combustion analyzer and THC emissions analyzer were placed on a table provided by the host site and situated near the boiler along with the portable blending station. Flow switch boxes were attached to the two analyzers to allow for selection of sample gas, zero gas, or span gas. A sample conditioning train and sampling pump were placed in the sampling line between the exhaust stack sampling port and the flow switch boxes. The sample conditioning train was hung on the side of the boiler. A nitrogen cylinder was placed near the sample conditioning train, and tubing was run from this cylinder to the semi-permeable membrane dryer in the sample conditioning train. A peristaltic pump was connected to a coalescing filter in the sample conditioning train to remove accumulated water.

The fuel and calibration gas cylinders were placed near the instrumentation, and tubing lines were run to the flow switch boxes and portable blending station. A tubing line was run from the outlet of the portable blending station to the blending gas port on the gas piping bypass line. Thermocouple wire was run from the thermocouple at the exhaust stack to the dedicated connection jack for the data acquisition system in the portable blending station. Power and signal lines were run from the mass flow meter in the gas piping bypass line to the dedicated connection jacks on the portable blending station

along with a signal line from the THC analyzer. An Ethernet cable was run from the portable blending station to a laptop computer also placed on the table along with a serial cable from the portable combustion analyzer. Power lines were run from a nearby wall outlet to the analyzers, portable blending station, and laptop computer. The analyzers were powered up.

A canopy provided by the host site was erected over the test equipment to protect the test equipment and the test personnel from the weather since the installation was outside. The host site also provided chairs for GTI personnel and tarps to cover GTI's equipment.

The second day at the site was spent debugging, troubleshooting, leak checking, setting up the steam bypass flow rate, practice testing, and arranging for the receiving of gas chromatograph data

from the nearby gas utility station .

Final sampling line connections were made at the analyzers. The data acquisition system was started. The analyzers were calibrated. The sampling line was leak checked. The boiler was started on house gas by site personnel. The gas piping bypass line was activated and, simultaneously, the original boiler supply line was deactivated. No gases were blended into the house gas at this point. The boiler was allowed to build up steam pressure and cycle at the steam pressure setpoint. The steam bypass line was opened slightly and then adjusted to maintain a consistent rate of steam flow to the deaerator and out its vent line while maintaining a consistent though not constant steam pressure in the boiler below the steam setpoint so that the boiler would not cycle.

The blending station was then set to fire the boiler with the Adjust2 gas composition used during the last field test. The system commanded the mass flow controllers to flow the proper amounts of propane and nitrogen based on the amount of house gas flowing. The added amounts of propane and nitrogen caused the amount of house gas flow to slow down, but the propane and nitrogen flows were automatically lowered to match since they are continuously recalculated by the program running on the computer to keep the ratios (and composition) constant. This composition was maintained for 20 minutes while the boiler operation was monitored.

The blending station was next set to fire the boiler with the Adjust1 gas composition used during the last field test. This was fired for 10 minutes, followed by the three Substitute1 gas compositions, the Adjust3 gas composition, and the four Substitute2 gas compositions, all for at least 10 minutes. Calibration checks of the analyzers were performed between every third or fourth gas composition. While not an "official" full interchangeability test, since each gas compositions was fired for only 10 minutes, and the exact house gas composition was unknown at the time, sufficient data was successfully gathered on boiler performance for all of the planned gas compositions that this data could be reported upon in the event that testing could not be continued.

The blending station was then set to fire the boiler with the house gas before it was shut down. The analyzers were put in

stand by mode, the gas cylinders were shut, and the data collected was secured.

A reading from the gas chromatograph (GC) at the nearby gas utility station was received. Based on this GC analysis, calculations were made that evening to create the XH series of interchangeability gas compositions (see Table 4) for the next day's test campaign. This procedure involved running a spreadsheet on one computer with iterative calculations to determine the proper percentages of propane and nitrogen to blend into the house gas for Wobbe indices and heating values of the 10 "adjust" and "substitute" gases, converting these percentages into ratios of blended gas to house gas, and transferring these ratios from this computer to the computer connected to the blending station.

Continuous Tests – Constant Firing Rate

Testing began on the third day of the week. The portable

combustion and THC analyzers were started. The boiler was started on house gas by site personnel. The portable combustion and THC analyzers were calibrated. During the calibration, the boiler was allowed to build up steam pressure and then the steam bypass line was opened slightly and then adjusted to maintain a consistent rate of steam flow to the deaerator and out its vent line. After 12 minutes, the steam bypass was adjusted slightly to maintain the steam pressure closer to the steam setpoint but still below that which would make the boiler cycle. The Adj2XH composition computed the evening before was now fed to the boiler. Twenty minutes of readings were collected by the data acquisition system at 5 second intervals.

The fuel was next switched to Adj1XH, and another 20 minutes of readings were collected. The calibration of the analyzers was checked, with adjustments made only to the THC analyzer. Data collection was next performed for Sub1XH-A3M and for Sub1XH-A2, followed by another calibration check of the analyzers. Testing then continued with the Sub1XH-A1, Adj3XH, Sub2XH-HiM, Sub2XH-A3, Sub2XH-A2, and Sub2WH-A1 compositions, with calibrations checks after every other fuel gas. This completed the "official" full interchangeability test, since each of the ten planned gas compositions was fired for at least 20 minutes, and the house gas composition was known ahead of time.

Readings from the gas chromatograph (GC) at the nearby gas utility station were received on an hourly basis. The HHV reading averaged within 1 Btu/SCF of the previous day's reading, while the Wobbe index reading averaged within 2 Btu/SCF of the previous day's reading. Based on the new GC analysis, calculations were made that evening to create the YH series of interchangeability gas compositions for the next day's test campaign. In addition to the 10 standard gas compositions, blending ratios were calculated for 3 new gas compositions with super-low Wobbe indices. These were created so that testing could be performed simulating the boiler being tuned for higher-Wobbe/HHV gas and fired with lower-Wobbe/HHV gas. The data collected on the third day of the week was with the boiler tuned for lower-Wobbe/HHV gas and mostly fired with a higher-Wobbe/HHV gas since the house gas on which the boiler had been tuned had a Wobbe close to that of Adjust2 and a HHV close to that of Adjust1.

Of the 3 new gas compositions, one was labeled "Adjust0". This gas composition had a Wobbe index equal to the Wobbe index of Adjust1 minus the difference between the Wobbe indices of Adjust2 and Adjust1, i.e., about 1286 Btu/SCF. This Adjust0 composition also had a HHV equal to the HHV of Adjust1 minus the difference between the HHVs of Adjust2 and Adjust1, i.e., about 996 Btu/SCF. The other 2 new gas compositions were based off of Substitute1 and Substitute2, with nitrogen diluting to bring the Wobbe down to that of Adjust0.

Testing continued on the fourth day of the week. The somewhat depleted propane and nitrogen cylinders were replaced by fresh cylinders. The portable combustion and THC analyzers were started. The boiler was started on house gas by site personnel. After the steam pressure was built up, the steam bypass line was opened slightly and then adjusted to maintain a consistent rate of steam

flow to the deaerator and out its vent line. The portable combustion and THC analyzers were calibrated. The Adj2YH composition computed the evening before was now fed to the boiler. Twenty minutes of readings were collected by the data acquisition system at 5 second intervals. Testing then proceeded with the Adj1YH, Adj3YH, Adj0YH, Sub1YH-A0, Sub2YH-A0, Sub2YH-A1, and Sub2YH-HiM compositions, with 20 minutes of data recording for each fuel gas and calibrations checks after every other fuel gas. The tested compositions on this date included the 3 new super-low Wobbe gases plus the compositions at the corners of the operational envelope.

Also during the fourth day, GTI arranged for a representative of the boiler's manufacturer to be on site the next day, with the consent of the host site, for tuning of the boiler while running the hottest gas composition and restoring the tuning of the boiler after testing was completed.

Readings from the gas chromatograph (GC) at the nearby gas utility station were again received on an hourly basis. The HHV reading averaged within 4 Btu/SCF of the previous day's reading, while the Wobbe index reading averaged within 1 Btu/SCF of the previous day's reading. Based on the new GC analysis, calculations were made that evening to create the ZH series of interchangeability gas compositions for the next day's test campaign. For this series, the normal house gas was included as Adj2ZHG since it was representative of a cooler gas composition as its HHV and Wobbe index were somewhat in between that of Adjust2 and Adjust1.

Testing concluded on the fifth day of the week. The boiler was started on house gas by site personnel. The portable combustion and THC analyzers were started and calibrated. After the steam pressure was built up, the steam bypass line was opened slightly and then adjusted to maintain a consistent rate of steam flow to the deaerator and out its vent line. The Adj2ZHG composition computed the evening before was now fed to the boiler. Ten minutes of readings were collected by the data acquisition system at 5 second intervals. Ten minutes of data collection were chosen instead of the typical 20 minutes since the host site closes earlier on this day of the week and GTI wanted to make sure data was collected for all the planned compositions while still leaving time to pack up the equipment at the end of the test. The blending

station was then set to fire the boiler with the hottest gas composition, Sub2ZH-HiM, and ten minutes of readings were collected by the data acquisition system at 5 second intervals.

The boiler was now retuned by the representative of the boiler's manufacturer while still running on Sub2ZH-HiM. Another ten minutes of readings were collected by the data acquisition system at 5 second intervals.

The blending station was then set to fire the boiler again with the cooler gas composition, Adj2ZHG, and another ten minutes of readings were collected by the data acquisition system at 5 second intervals.

The tuning of the boiler was now restored by the representative of the boiler's manufacturer while still running on Adj2ZHG, i.e., the house gas. Calibration checks of the analyzers were then performed as the final step of testing.

Breakdown

The latter part of the fifth day of the week

was spent disconnecting the tubing runs and wiring, removing the gas piping bypass line from the main line and plugging off the ports on the main line, gathering the calibration gas cylinders together, packing the analyzers and test equipment into their containers, palletizing the containers for shipment, and folding up the canopy, tarps, table, and chairs.

Results

Continuous Tests – Constant Firing Rate

The major results from the continuous tests with constant firing rate are the emissions and the exhaust temperature (the system's response) when the water tube boiler is tuned with house gas, and the fuel is switched to various "adjust" and "substitute" gases. Figure 48 through Figure 272 show the emissions and exhaust temperature over the 20 minute data collection intervals for each gas for the main data set. Figure 273 through Figure 277 show the emissions and exhaust temperature over the 20 minute data collection intervals for each gas for the second data set that included the fuel gases with super-low Wobbe indices. Figure 278 through Figure 200 show the emissions and exhaust temperature over the 10 minute data collection intervals for each gas for the third data set that included retuning the boiler for the hottest fuel gas. Average values for the three test sequences are shown in Figure 103 through Figure 313. The highest and lowest values indicated for each point are shown, along with a linear trend line. The calculated values of the higher heating value and Wobbe index for all the test gases based on the measurements made by the gas chromatograph are shown in Figure 288.

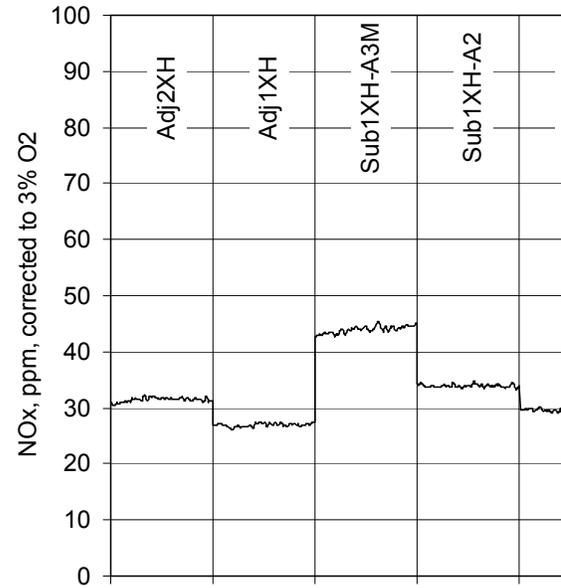


Figure 294. NOx Emissions with House Gas Tuning for All Adjust and Substitute Gases for Continuous Testing with Constant Firing Rate (Corrected to 3% O₂)

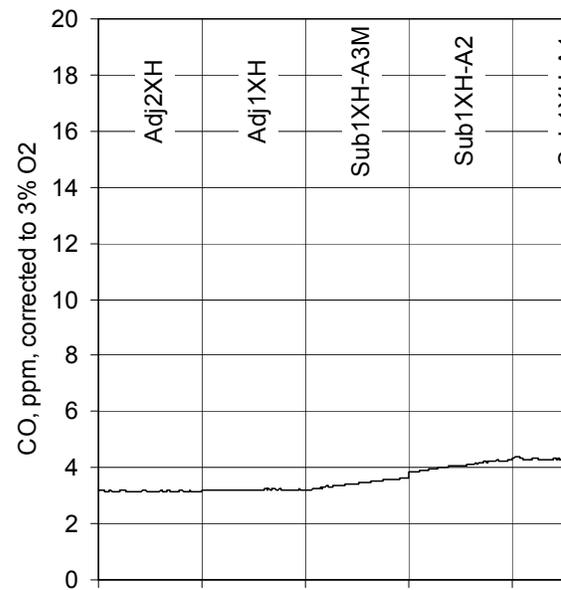


Figure 295. CO Emissions with House Gas Tuning for

All Adjust and Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

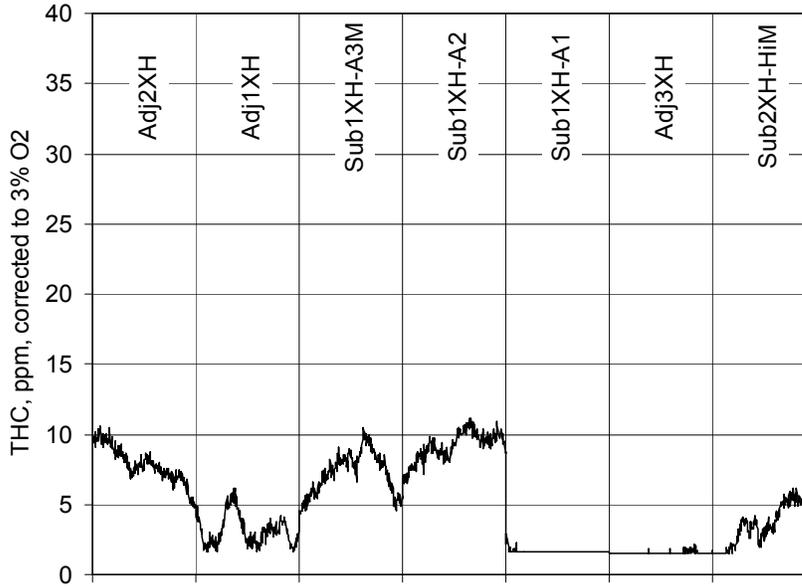


Figure 296. THC Emissions with House Gas Tuning for All Adjust and Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

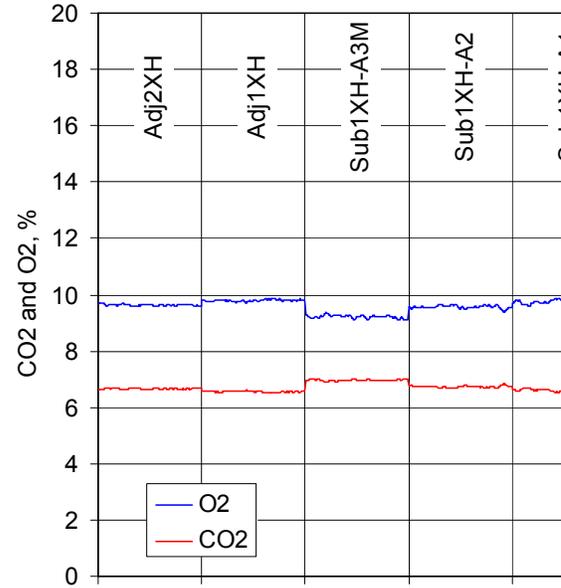


Figure 297. CO₂ and O₂ Emissions with House Gas Tuning for All Adjust and Substitute Gases for Continuous Testing with Constant Firing Rate

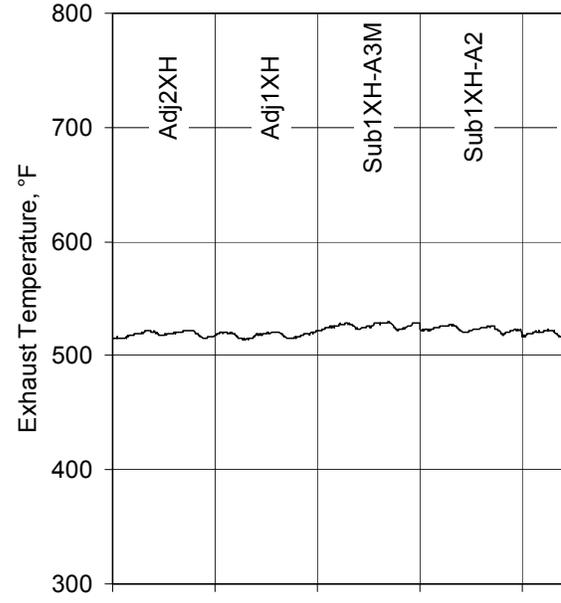


Figure 298. Exhaust Temperature with House Gas Tuning for All Adjust and

Substitute Gases for Continuous Testing with Constant Firing Rate

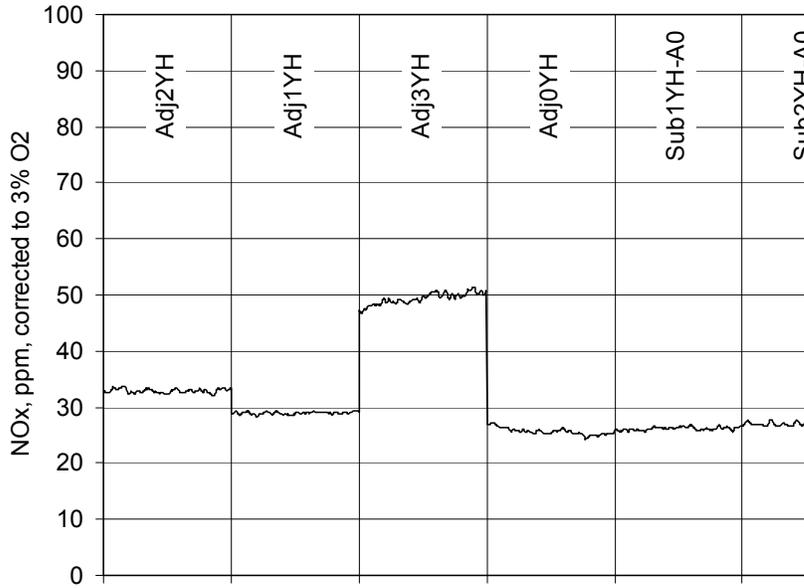


Figure 299. NOx Emissions with House Gas Tuning for Super-Low Wobbe Index Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

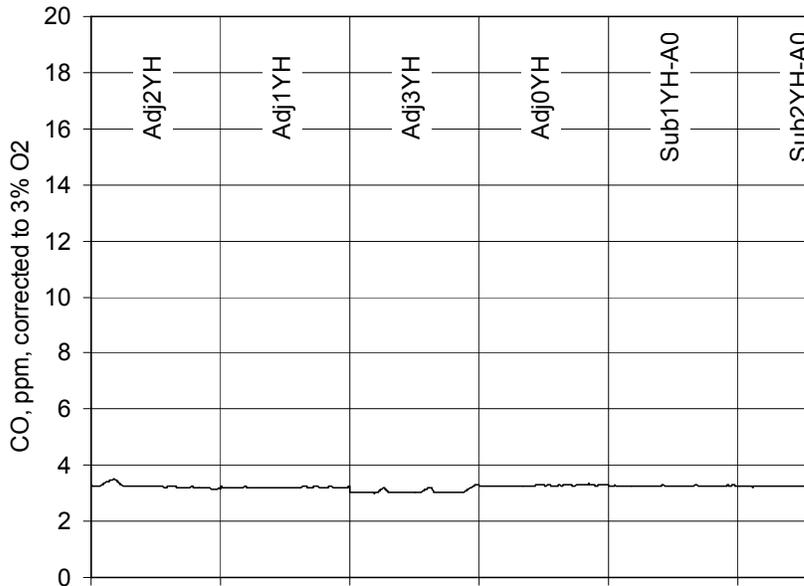


Figure 300. CO Emissions with House Gas Tuning for Super-Low Wobbe Index Gases Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

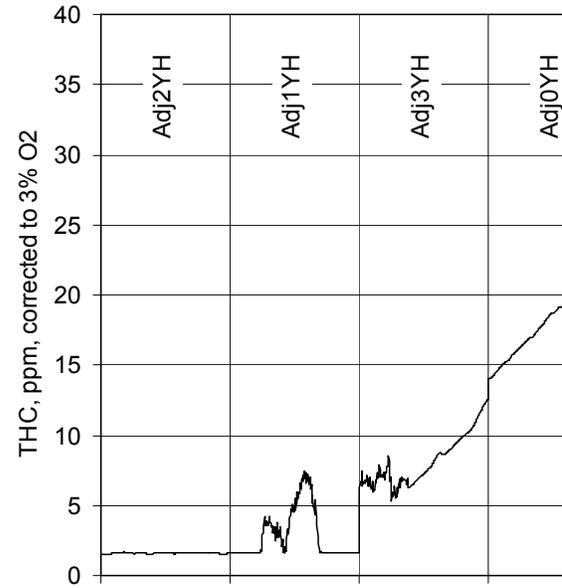


Figure 301. THC Emissions with House Gas Tuning for Super-Low Wobbe Index Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

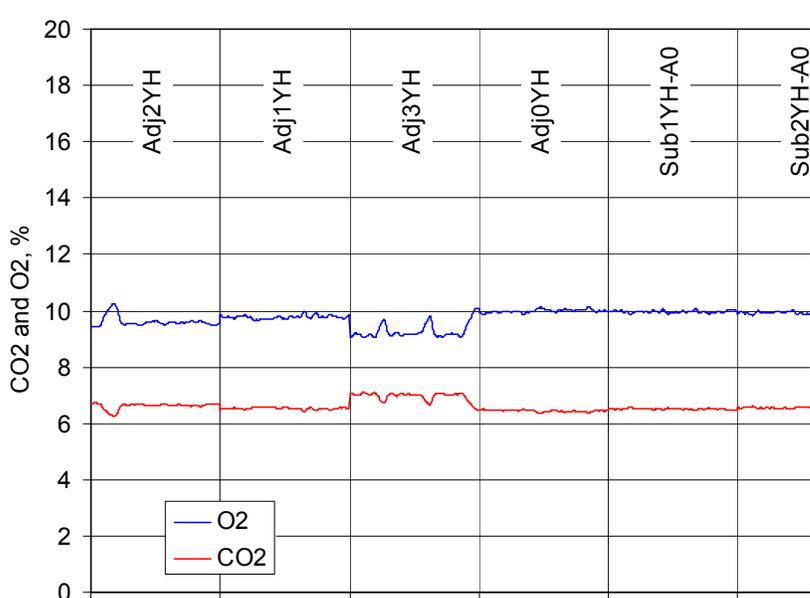


Figure 302. CO₂ and O₂ Emissions with House Gas Tuning for Super-Low Wobbe Index Gases for Continuous Testing with Constant Firing Rate

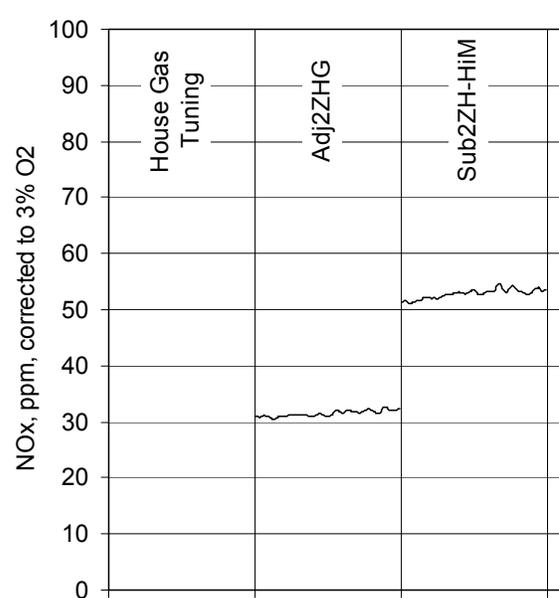


Figure 304. NO_x Emissions with House Gas Tuning and Hottest Gas Tuning for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

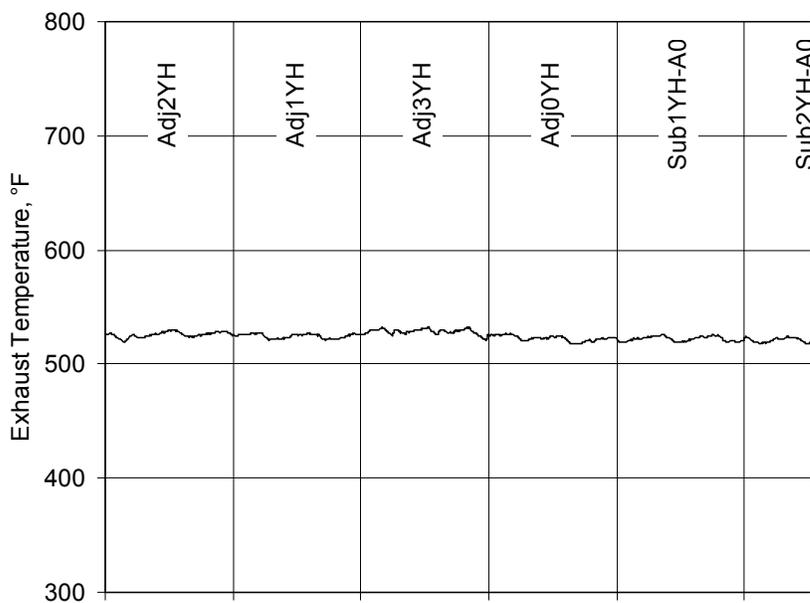


Figure 303. Exhaust Temperature with House Gas Tuning for Super-Low Wobbe Index Gases for Continuous Testing with Constant Firing Rate

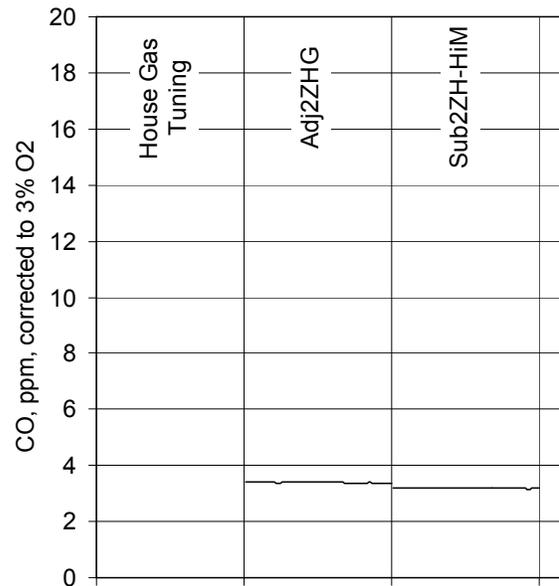


Figure 305. CO Emissions with House Gas Tuning and Hottest Gas Tuning

for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)



Figure 306. THC Emissions with House Gas Tuning and Hottest Gas Tuning for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

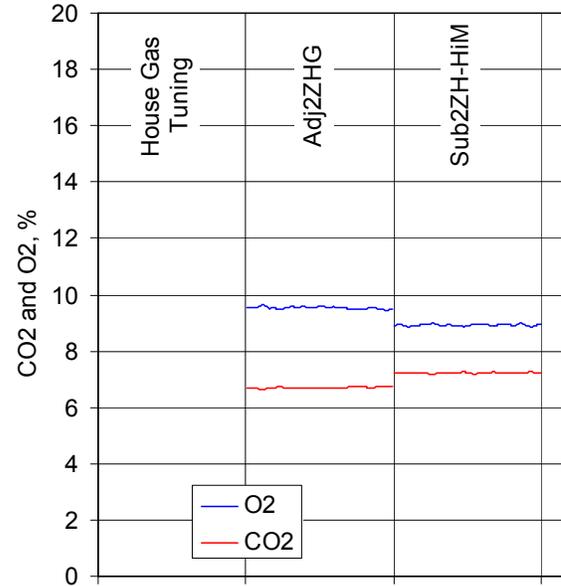


Figure 307. CO₂ and O₂ Emissions with House Gas Tuning and Hottest Gas Tuning for Continuous Testing with Constant Firing Rate

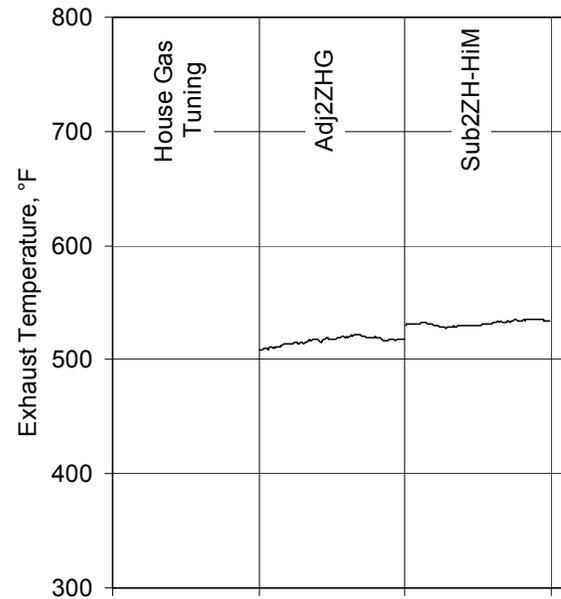


Figure 308. Exhaust Temperature with House Gas Tuning and Hottest Gas Tuning

for Continuous Testing with Constant Firing Rate

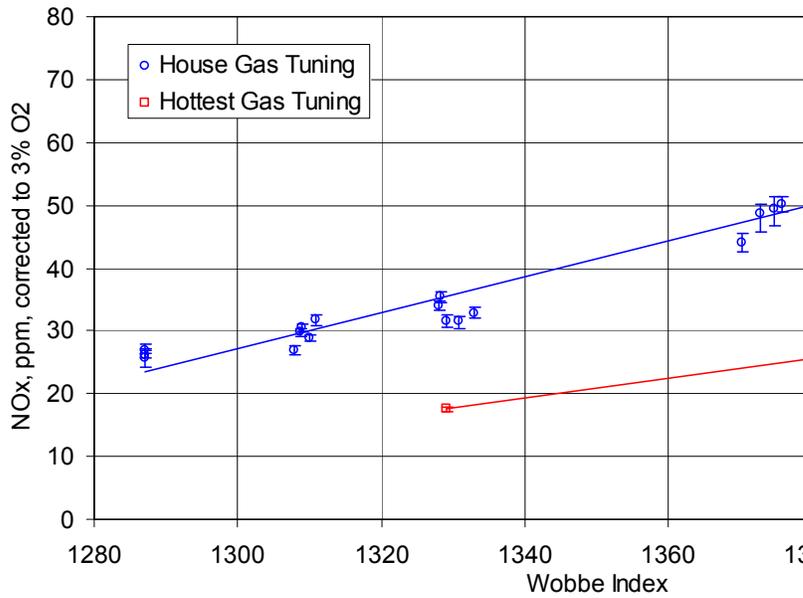


Figure 309. NOx Emissions for All Adjust and Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

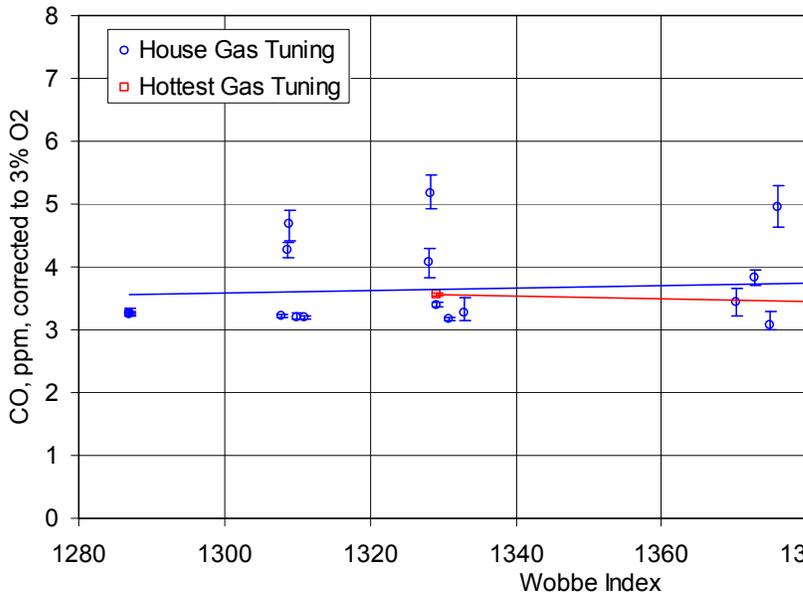


Figure 310. CO Emissions for All Adjust and Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

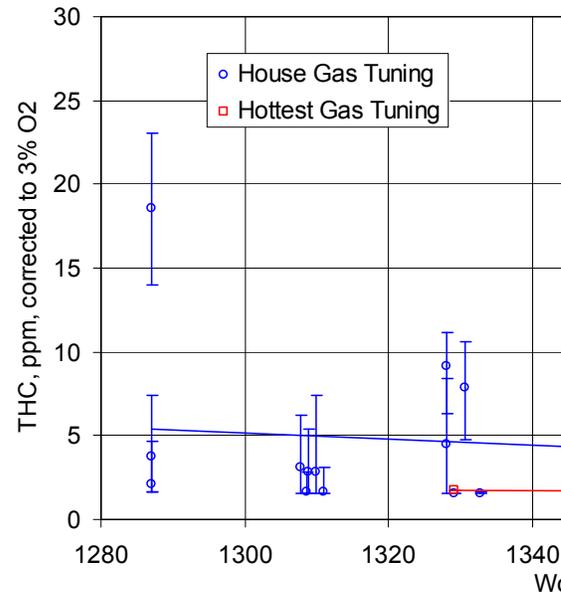


Figure 311. THC Emissions for All Adjust and Substitute Gases for Continuous Testing with Constant Firing Rate

(Corrected to 3% O₂)

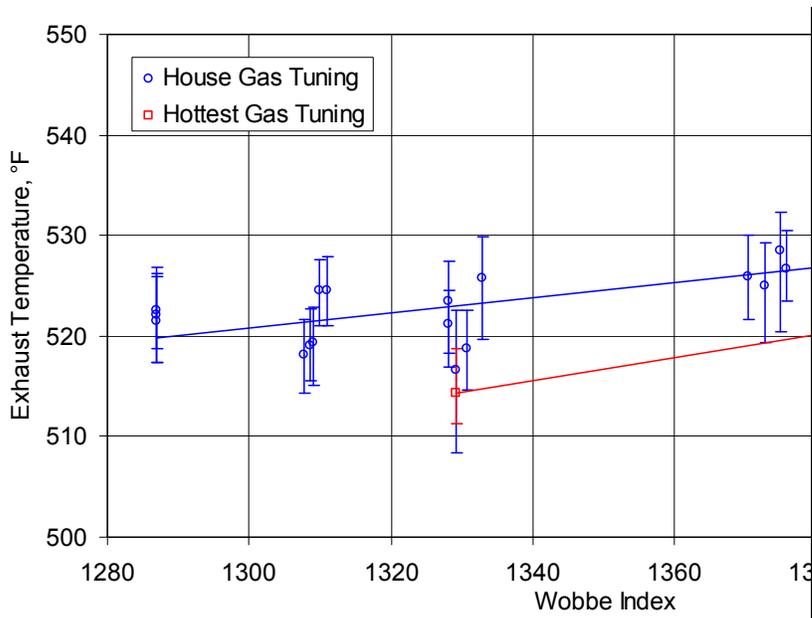


Figure 312. Exhaust Temperature for All Adjust and Substitute Gases for Continuous Testing with Constant Firing Rate

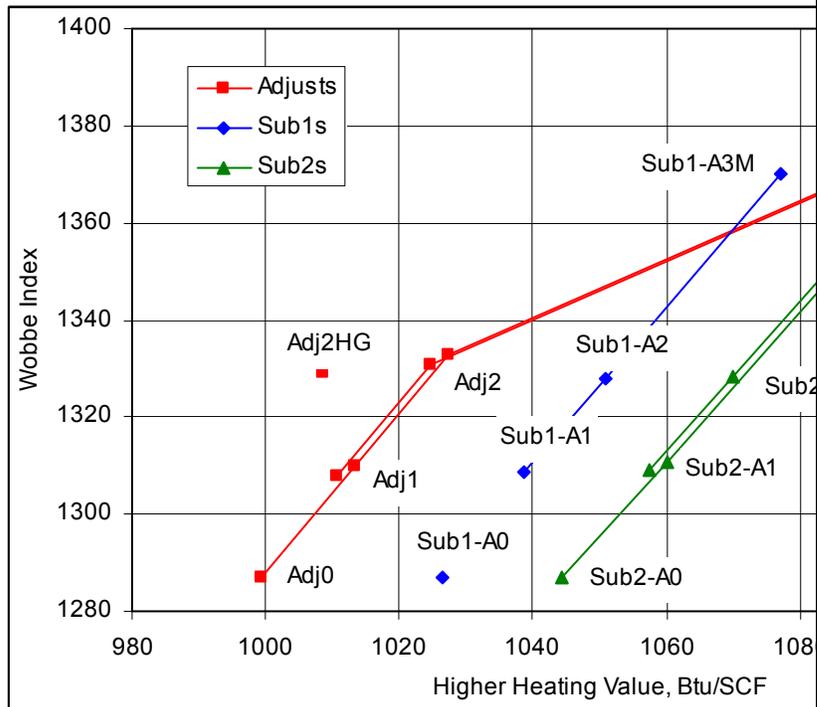


Figure 313. Fuel Properties Based on Gas Chromatographic Analysis

Calculations

All concentrations of emissions were measured on a dry basis. The equations below is the linear correction used to approximately cancel out analyzer drift;

$$X_{corr}(t) = (X_{meas}(t) - Z(t)) \frac{C}{S(t)},$$

where

$$Z(t) = Z_1 + (Z_2 - Z_1) \frac{(t - t_{z1})}{(t_{z2} - t_{z1})},$$

$$S(t) = S_{c1} + (S_{c2} - S_{c1}) \frac{(t - t_{s1})}{(t_{s2} - t_{s1})},$$

$$S_{c1} = S_1 - Z(t_{s1}),$$

$$S_{c2} = S_2 - Z(t_{s2}),$$

where $X_{corr}(t)$ is the corrected emissions value and $X_{meas}(t)$ is the measured value at time t , $Z(t)$ is the zero drift correction, $S(t)$ is the span drift correction, C is the span gas concentration, Z_1 and Z_2 are the instrument readings on zero gas at times T_{z1} and T_{z2} , respectively, S_1 and S_2 are the instrument readings on span gas at times T_{s1} and T_{s2} , respectively, and S_{c1} and S_{c2} are the values of the span readings corrected for zero drift, respectively.

After this correction, emissions were normalized to 3%O₂ using the formula,

$$X_{3\%O_2}(t) = X_{corr}(t) \cdot \left(\frac{21\% - 3\%}{21\% - \%O_{2,corr}(t)} \right),$$

where $X_{3\%O_2}(t)$ is the final value after both the correction for analyzer drift and the normalization to a common 3% oxygen concentration in the dried exhaust.

Analysis and Conclusions

The charts and data are analyzed in the section below.

Continuous Tests – Constant Firing Rate

For the most part, gases with higher Wobbe indices when fired in the water tube boiler yielded higher NO_x emissions. The NO_x emissions approximately doubled from the lowest to the highest Wobbe indices (approximately 26 to 54 ppmv).

Retuning the water tube boiler with the hottest gas lowered NO_x emissions, but required operation at a higher excess air level. This may result in a small energy efficiency decrease. Emissions of CO and THC were almost always low during the testing and showed no discernable trends with Wobbe index. Exhaust temperatures were slightly higher (~8 °F) with gases with higher Wobbe indices.

The increased values of THC in Figure 191 for the third and fourth fuel gases are due to a combination of analyzer drift (showing negative values) and the data acquisition system not being able to record negative values. Actual emissions were comparable to other fuel gases. The fluctuations in CO₂ and O₂ in Figure 303 are due to modulations in boiler firing rate near the steam pressure setpoint and not reflective of fuel gas composition changes.

Selected Photographs



Figure 314. Water Tube Boiler

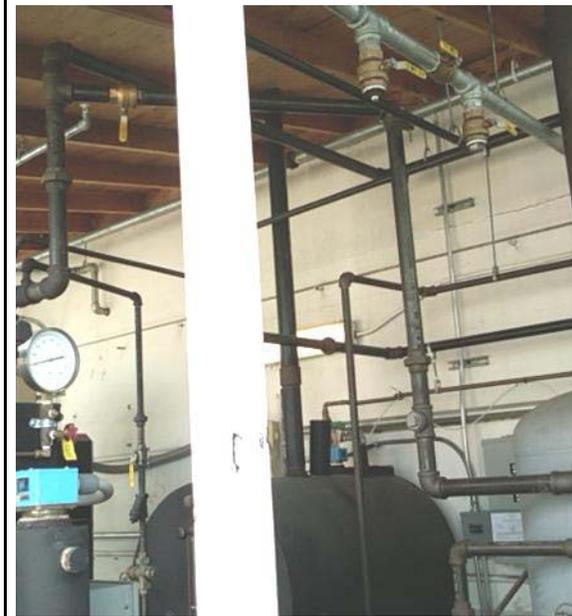


Figure 315. Gas Piping
Bypass Line and Steam
Bypass Line



Figure 316. Sample Probe and Thermocouple



Figure 318. Gas Cylinders

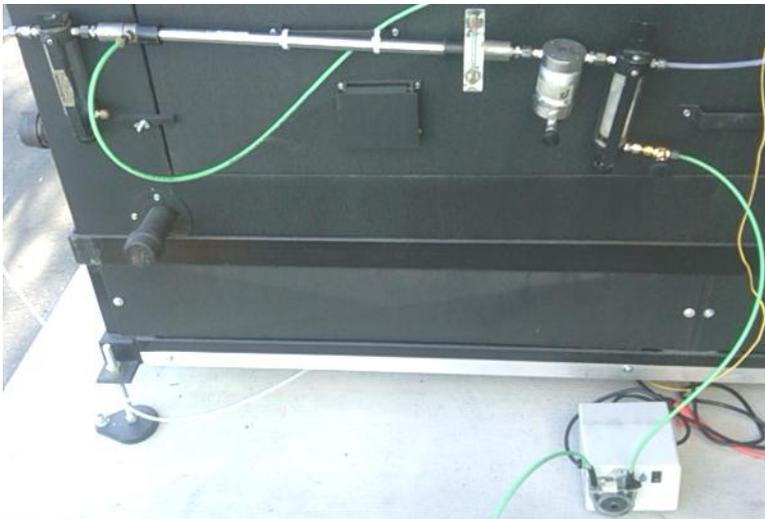


Figure 317. Sample Drying Train



Figure 319. Analyzers and Blending Station

**APPENDIX E:
Commercial Foodservice
Equipment**

NATURAL GAS IN CALIFORNIA:
ENVIRONMENTAL IMPACTS AND
DEVICE PERFORMANCE



Jerry Brown
Governor

**Commercial Foodservice Equipment
Evaluation Task 17**

Prepared for:
California Energy Commission
Prepared by:
Gas Technology Institute



Task 17 Report

December 2011
CEC-500-05-026

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Abstract

Foodservice in California represents a significant commercial natural gas use. Commercial kitchens consume five times more energy per square foot than other types of commercial spaces. Natural gas consumption in commercial kitchens is dominated by the cook line. Of the 1 million commercial foodservice equipment installed and operating in California, roughly 80% are powered by natural gas, with an estimated 480 million therms of natural gas consumed annually. This report presents natural gas and liquefied natural gas (LNG) interchangeability testing results for ten common foodservice cooking appliances operating in restaurants in California.

Executive Summary

To address concerns of potential interchangeability issues in the commercial foodservice industry, GTI conducted a series of interchangeability tests on ten appliances. The appliances were chosen based on existing population, gas load and burner designs. The specific types of appliances tested were: fryer (two), griddle, convection Oven, steamer, braising Pan, combi-oven (steamer and oven), range top, and oven.

The results for the different commercial foodservice equipment showed that changing the composition of the fuel led to a range of changes in terms of burner performance. For all of the appliances, the firing rate proportionally increased with the increase in the heating value. In some cases, the firing rate exceeded the recommended limit of more than 10% of the faceplate rating, but strategic temperature readings on the appliances did not suggest excessive overheating for short term appliance operation. Studying the long term effects of a higher firing rate and resulting temperatures was not in the scope of this project and thus conclusions cannot be made in this area. No appliance experienced ignition or operational difficulties over the full range of gas compositions tested.

Results are presented for specific foodservice equipment tested, but the more general conclusion is that the interchangeability capability of appliances was found to vary. Results should be regarded as examples of commercial appliances and not be considered as a pass/fail scoring of particular appliances. From this perspective, the appliances can be divided into groups that showed no emissions variations, small variations, and significant variations with changes in fuel gas composition and Wobbe Number. The appliances showing full interchangeability with no changes in CO and NO_x emissions over the range of gases tested were the two fryers, the range top, and the convection oven. Moderate interchangeability concerns with large changes in gas composition and Wobbe Number producing some emissions changes were found for the griddle and the combi oven operate in steam mode and oven mode. Larger interchangeability concerns with large increases in emissions with changes in gas composition and Wobbe Number were found for the oven, braising pan, and steamer. Results are equipment specific. No data is yet available to determine if the observed results represent the behavior of a specific appliance or for the appliance model. Insufficient data is available to draw general conclusions regarding classes of burner systems and classes of foodservice equipment.

Background

With more than 90,000 eating and drinking establishments currently operating in California, an estimated \$54 billion in food and drink sales in 2007 and the generation of \$4.5 billion in California sales tax per year, restaurants are indisputably a driving force in both the state employment and revenue sectors. Over 1.4 million people are currently employed in food industry jobs in California. The data is from Fisher-Nickel, inc. [FNi] an engineering consulting firm owned and operated by Don Fisher and Judy Nickel. Fisher-Nickel, inc. operates the PG&E Foodservice Technology Center (FSTC).

The FSTC estimates that the total gas load for commercial kitchens approaches half the overall commercial gas consumption in the state. There are many types of commercial foodservice equipment. The four most common and their California populations are listed in the table below.

Appliance	California Population (units)	Baseline Efficiency, %	Annual Energy Use per Unit, therms	Total Annual Energy, million therms
Convection Oven	65,000	30	860	56
Deep Fat Fryers	110,000	30	1,390	153
Griddles – standard	41,000	30	810	33
Steamers - pressureless	29,000	15	2,190	63
Total				305

Natural gas usage in California by convection ovens, fryers, griddles, and steamers combined is over 305 million therms per year. The four appliances will represent about 64% of commercial cooking usage. Understanding the impact of changing gas composition on the performance of these appliances and on their emissions is important in generating a full understanding of the impacts of LNG use in California.

Objective

The objective of this Task is to conduct a series of controlled laboratory interchangeability tests with eight to ten pieces of commercial foodservice equipment: two convection ovens, two griddles, two steamers, and two or three fryers. More fryers are proposed because this appliance accounts for around half of the gas use of these four types of foodservice equipment. The appliances chosen are to be among the most common in the food industry and are to be common in California. All appliances are to undergo ANSI tests to measure performance and emissions under changing gas (natural gas to LNG) compositions. ANSI does not specify interchangeability tests, but the ANSI tests can be conducted with gas having different compositions. A series of cycling tests is also recommended for each appliance. Finally, sensitive cooking tests are recommended for each appliance: sheet cakes with ovens, ice tests

with steamers, pancakes with griddles, and French fries with fryers. The sensitivity of the cooking tests will reveal performance changes when gas composition is changed.

GTI was to measure carbon monoxide, oxides of nitrogen and formaldehyde. Formaldehyde tests were to be carried out with support from Lawrence Berkeley National Laboratory (LBNL) staff. They were to provide guidance on sample collection procedures, sample collection equipment, and sample analyses. Emission tests were to be conducted with three adjustment natural gases and two LNG's. The LNG's were to be blended with nitrogen to produce a series of emission results. GTI was to analyze the data collected in the interchangeability testing and generate a report that shows the results.

The interchangeability tests were to be carried out with foodservice equipment loaned to GTI by North American Association of Foodservice Equipment Manufacturers (NAFEM)-member companies. Testing will be conducted by GTI in test cells in GTI's newly refurbished Residential-Commercial (ResCom) laboratory. GTI will share the test results with representatives of the appliance manufacturers.

Before starting this Task, GTI met with members of the North American Food Equipment Manufacturers Association (NAFEM) technical committee and found the group supportive of conducting LNG interchangeability tests with commercial foodservice equipment. Commercial foodservice equipment is often made by small companies that do not have the resources to study the impacts of changing gas composition on appliance performance. Gaining an understanding of the impacts of changing gas compositions would help them diagnose concerns that are raised that cannot be linked directly to appliance designs.

Testing Setup

To address concerns of potential interchangeability issues in the commercial foodservice industry, GTI conducted a series of interchangeability tests on ten appliances. The appliances were chosen based on existing population, gas load and burner designs. The specific types of appliances tested were:

- Fryer (two)
- Griddle
- Convection Oven
- Steamer
- Braising Pan
- Combi Oven (steamer and oven)
- Range Top
- Oven.

The appliances for testing were supplied by commercial foodservice manufacturers that have previously worked with GTI and with assistance from the North American Association of Foodservice Equipment Manufacturers (NAFEM)-member companies.

The interchangeability tests were completed using ANSI defined tests to measure performance and emissions changes with changing gas (natural gas to LNG) compositions. ANSI does not

specify interchangeability tests, but the combustion tests from the ANSI were used as a basis for testing in this program. Specific modifications to ANSI tests for the various appliances are described in detail in the sections for each appliance. The fuels chosen (Figure 1) for testing represent natural gas compositions for a range of heating values and Wobbe numbers found in California. For each appliance data was acquired for each test gas including emissions (O₂, CO₂, NO_x, CO and hydrocarbons), burner firing rate and selected temperatures.

The types of appliances chosen were based on population and total annual energy usage in California. When possible, the appliance design for each category was chosen based on the typical or most common combustion design for each. The Combi Oven, Convection Oven, Griddle, Oven and Braising Pan all have very typical burner compared to different manufacturers. The appliance categories for the Fryers, Steamer and Range Top have a much more diverse set of combustion system designs. The results reported for this project are for the specific appliance models tested and while some results are typical for the entire appliance types, subtle to major differences in the results would occur when testing different models. Below is an overview of the results and observations on the specific results with a general discussion for each appliance category.

Fryers (1 and 2)

Fryers represent the most diverse set of burners design in the commercial foodservice industry. The designs vary from infrared (Fryer 1), cast iron, pulse, mesh powered, down fired inshot (Fryer 2), inshot and several others. The main driver for this diversity is that fryers were the first appliances to be pushed toward being more efficient in terms of energy use. Chain restaurants “encouraged” manufacturers to develop designs there were more efficient than initial designs, typically cast iron burners fired into tubes submerged in the oil. Because of this driver, manufacturers tended to develop their own distinct designs, leading to diversity in the combustion system designs. Because of this diversity, the results for the two fryers in this study are going to be very different from the other fryers on the market. The burner performance data for each would be considered typical compared to other fryers tested at GTI, relating to the similar efficiencies achieved by different appliances because the air to fuel ratios were about the same. However; specific conclusions cannot be derived for the entire population of fryers based on the results of just two fryer designs.

Griddle

The griddle tested represents the most typical design currently on the market. The burner is a tube style located under the griddle surface with a blue flame. Another common design is a radiant panel burner located under the griddle surface. Despite the similarity in designs, different manufacturers use different burner tube suppliers, burner configurations and spacing between the burners and cooking surface. Because of these differences, different models would show subtle differences in performance. However; the limit data set collected by GTI has shown similar results to this griddle. In all case the griddle was very tolerant to changes in natural gas compositions.

Convection Oven

Designs for the combustion systems in convection ovens vary by whether the burner is indirect fired, direct fired or both (like the oven tested in this study). Indirect fired system typically uses a burner firing into a heat exchanger that transfers heat to the air circulated in the oven. The designs of the burner in these ovens vary significantly but typically operate at similar air to fuel ratios. Direct fired systems do not use a heat exchanger, but mixes the hot products of combustion with the air circulated in the oven. Because direct fired systems required more excess air (and thus a higher air to fuel ratio), they tend to be more tolerant to changes in fuel gas composition. This was observed with the convection oven tested that uses a dual system, but the products of combustion eventual blend with the air in the oven and had a high air to fuel ratio.

Oven

The vast majority of commercial foodservice ovens without forced air circulation use the same basic combustion system design. Burner tubes located below the oven cavity directly heat the bottom of the cavity and the hot products of combustion flow through the cavity to further cook food products. Some variations exist in the burner tube designs with the most common being drilled port cast iron (as in this project) or pierced port sheet metal. One common characteristic of the oven tested and all of the other ovens tested by GTI have been that the appliances are tolerant to changes in the natural gas until the flames elongate to the point that they impinge on the bottom of the oven cavity. At this point, CO begins to rapidly increase. Some ovens never reach this point, like the one tested. The spacing between the burner and oven cavity appears to be the critical factor in determining interchangeability for this appliance type.

Range Top

The materials used to build range top burners are typically either stamped metal with pierced ports or cast iron with drilled ports. However; each manufacture and each different model typically has its own specific design and configuration. This makes extrapolating results for one specific range top to the entire population difficult. But the one design feature that all of the range tops tested by GTI is that all range top burners have a large air to fuel ratio due to the availability of secondary air around the pot sitting in the open on the range top. As observed with other appliances, a higher air to fuel ratio results in a more tolerant burner to changes in fuel composition. The negative aspect of this design is higher air to fuel ratios also result a less efficient burner, as is the case with range top burners.

Steamer

The type of steamer tested, a boilerless or connectionless steamer, is a relatively new appliance in the commercial foodservice industry. Gas-fired units started to gain popularity around ten years ago and have steadily grown since. Because units were being developed during a time frame when efficiency was being emphasized, the combustion systems tended to be more sophisticated and operating at a lower air to fuel ratio. As discussed with other appliances, a lower air to fuel ratio appliances tend to be less tolerant with changes in natural gas

composition, as was the case with this steamer. At 3% oxygen in the flue gas sample, this unit has the lowest air to fuel ratio of the appliances tested in this study. This model of steamer is the only one tested for interchangeability by GTI, so the results cannot be compared to other units and the combustion system does vary significantly in design and burner type compared to other units on the market.

Braising Pan

The braising pan tested is similar to other know units currently on the market with a series of pierced port, tube burners under the bottom of the cooking pan. The basic setup is very similar to several griddles. However; because of the high heat output required to cook specific food types (i.e. soups and chili) the number of burners is higher than a griddle and the spacing between is much less. This type of burner system has interchangeability issues when the either the flames impinges and becomes quenched on the bottom of the pan and/or when there is lack of secondary air to complete combustion. The results for this braising pan showed there were issues using the higher heat content natural gases. The data suggests that issue with the burner is not a quenching problem that has been observed with other tested appliances (see Oven), but an issue with available oxygen to complete combustion. As the heat content of the fuel is increased, the flames grew in size and required more oxygen to complete combustion. If the oxygen is unavailable, the mechanism that converts CO to CO₂ in the combustion process is not completed and the CO production increases. GTI has not tested nor does it have available the specific combustion system design for other braising pans and thus cannot compare results. But, generally any combustion system with this density of flames will have issues with higher heat content gases.

Combi Oven

The unit tested had two combustion systems, one for providing heat to the air circulating through the cooking chamber and another for the steam generator. Both burners used indirect heating for the air and water and had separate flues. Despite some differences in the burner design, the combustion system for this oven using a heat exchanger and for the steam generator was typical for other combi ovens currently available. Both the steam generator and oven burner performed satisfactory over the entire range of gases tested, but extrapolating the results to other models would be difficult without knowing the air to fuel ratios. Despite being a higher efficient unit, the air to fuel ratio for these burners were high enough to help prevent interchangeability issues. Another design for a combi oven on the market uses a water spray on a hot surface in the oven instead of a separate steam generator.

Test Gases

To evaluate interchangeability performance, each cooking appliance was operated with a range of gas compositions. These pieces of equipment are not built for field adjustment, so no adjustments were made to shutters, baffles, air to fuel ratios, or other combustion controls when switching between gases. Table 1 provides analyses of the gas compositions used for testing. Three 'adjust gases' (Adj 1, Adj 2, and Adj 3) were selected as representative of the range of natural gas in California. Adj 2 is the average gas composition in the Southern California Gas

Company gas territory and is also similar to the gas available from the local utility to the GTI laboratory. For these reasons, Adj 2 was selected as the baseline gas. Two ‘substitute gases’ (Sub1 and Sub2) were selected as having similar compositions to Pacific basin LNGs. Both Sub1 and Sub2 having higher Wobbe Numbers than allowed in California, so each gas was diluted with nitrogen to match the Wobbe Numbers of the three selected adjust gases. While Wobbe Numbers are matched, the compositions are different and heating values are not matched. Figure 1 shows the heating values and Wobbe Numbers of:

- Adjust gases (Adj1, Adj2, Adj3)
- Substitute gas 1 (Sub1)
- Sub1 with varying N2 levels to match adjust gases (Sub1-A1, Sub1-A2, Sub1-A3)
- Substitute gas 2 (Sub2)
- Sub2 with varying N2 levels to match adjust gases (Sub2-A1, Sub2-A2, Sub2-A3)

Figure 1. Composition of Test Natural Gases

	Adj1H	Adj2H	Adj3H	Sub1	Sub1-Hi	Sub1-A2	Sub1-A1	Sub2	Sub2-Hi	Sub2-A2	Sub2-A1
	mol%										
Methane	0.92	0.94	0.89	0.92	0.91	0.88	0.87	0.89	0.87	0.85	0.84
Ethane	0.02	0.03	0.04	0.05	0.05	0.05	0.05	0.07	0.07	0.07	0.07
Propane	0.01	0.01	0.03	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02
n-Butane	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Nitrogen	0.04	0.03	0.03	0.00	0.01	0.04	0.06	0.00	0.02	0.05	0.07
HHV	1010.04	1024.05	1094.00	1098.85	1084.97	1050.37	1038.25	1130.58	1106.77	1069.35	1056.88
Wobbe Index	1308.97	1331.97	1373.98	1408.42	1385.49	1329.16	1309.70	1425.57	1387.73	1329.20	1309.93

Gas heating value and Wobbe Number data from Figure 1 is presented in graphical form in Figure 2. The plot shows the range of heating value and Wobbe data covered and includes the 1385 Wobbe limit currently mandated in southern California as an upper limit on gas. Several compositions with Wobbe Number above 1385 were included to learn interchangeable impacts on appliances and trends on appliance behavior. These hotter gases do not represent gases that will be supplied to customers in California. Points for each gas show how nitrogen dilution decreases both Wobbe number and heating value. Dilution with nitrogen does not match both the heating value and the Wobbe number for two gases. For that reason, the investigators elected to match Wobbe number because Wobbe is generally accepted as a better predictor of interchangeability than heating value alone.

On the left side of Figure 2 is a table repeating the heating values and Wobbe numbers for all of the test gases. The table also provides a ratio of the Wobbe number of each gas to the Wobbe of Adj2. Adj2 was selected as the baseline gas, so this ratio provides a ready indication of the variation of the Wobbe of each test gas relative to the baseline gas. Test data on emissions for

the commercial foodservice equipment is plotted as emissions on the y-axis and the Wobben number ratio on the x-axis. The same results would be observed if Wobbe number was plotted on the x-axis. But the data presentation method utilized enables the reader to quickly see the relationship of emissions as a function of the fractional variation in Wobbe number.

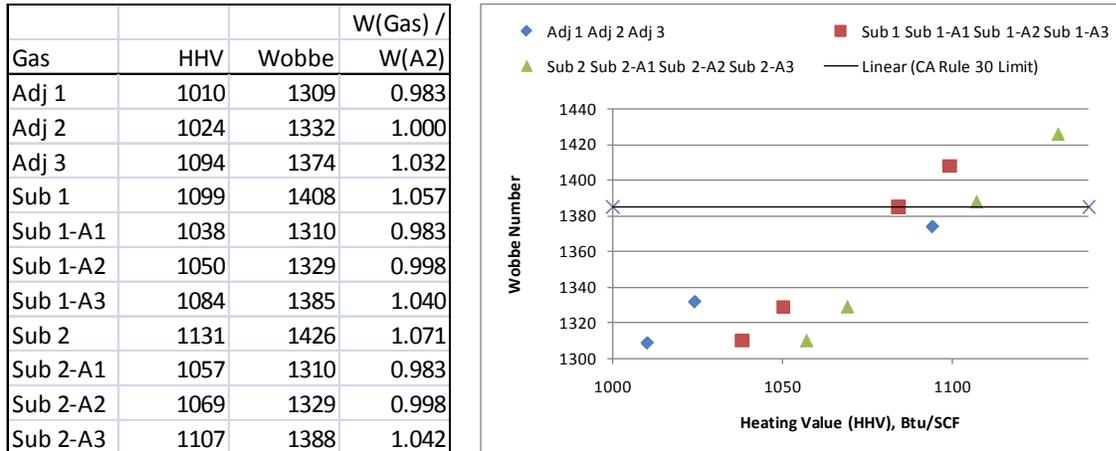


Figure 2. Range of Test Gas HHV and Wobbe Number

Testing Conclusions

The results for the different commercial foodservice equipment showed that changing the composition of the fuel led to a range of changes in terms of burner performance. For all of the appliances, the firing rate proportionally increased with the increase in the heating value. In some cases, the firing rate exceeded the recommended limit of more than 10% of the faceplate rating, but strategic temperature readings on the appliances did not suggest excessive overheating for short term appliance operation. Studying the long term effects of a higher firing rate and resulting temperatures was not in the scope of this project and thus conclusions cannot be made in this area. No appliance experienced ignition or operational difficulties over the full range of gas compositions tested.

The primary measure of interchangeability is carbon monoxide (CO) emissions. ANSI Z83 stipulates for the gas-fired commercial foodservice equipment tested in this program that emissions are not to exceed 800 ppm corrected to 0% O₂ (oxygen) for steady state burner operation and/or before burner cycling. Interchangeability goes beyond ANSI requirements by evaluating changes in emissions as the composition of the gas changes. Therefore, an appliance can be well within the 800 ppm ANSI requirement but still be of concern because 1) appliances are not built to be adjusted and 2) increases in emissions are undesirable.

For some tests, CO emissions for test gases of greater than Wobbe of 1350, the CO emissions exceeded the ANSI limit. As discussed in the results section for each appliance, the cause for the increased CO emissions varied for the different burner designs. Figure 3 shows a summary of the CO emissions from the foodservice equipment tested by showing their CO emissions at the lowest Wobbe tested (1309 for Adj 1) and at the California Rule 30 limit of 1385. Four

appliances showed significantly increases in CO emissions with increases in Wobbe number. The steamer, the braising pan, and the oven all showed CO levels near of above 800 ppm for 1385 Wobbe gas. The griddle showed an increase in CO from 25 to 40 ppm when increasing Wobbe from 1309 to 1385. This presents no issues relative to the ANSI limit but does indicate a large percentage increase in CO emissions.

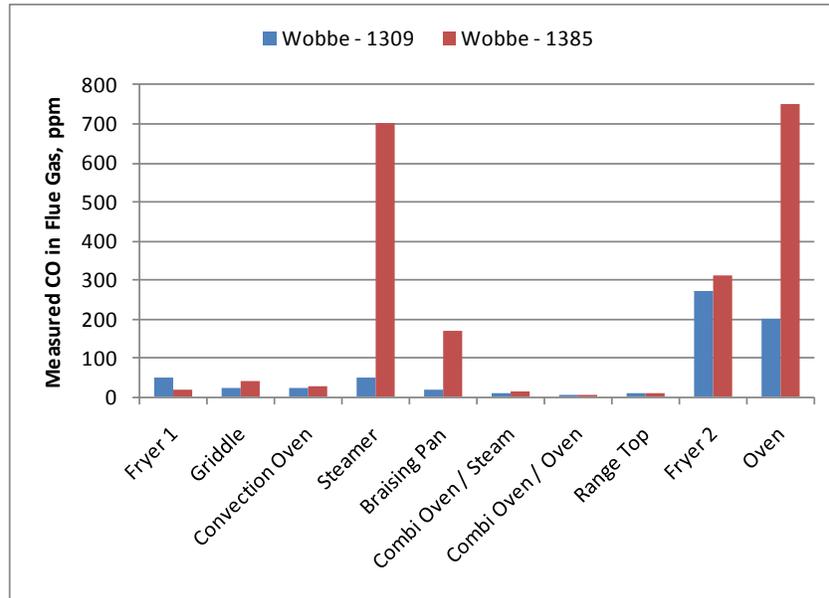


Figure 3. Range of CO in Flue over Wobbe Range of Gases

Emissions of NO_x are also of concern to in interchangeability analyses. Figure 4 shows the NO_x emissions of the foodservice equipment for gases with Wobbe of 1309 and 1385. Unlike CO emissions, the NO_x emissions did not vary as much with changing fuel gas. However, the NO_x did increase for the steamer, the combi oven in steam generation mode, and the combi oven in oven mode. While the increases were modest, any increase for an appliance that can no be adjusted in t he field is of concern in a tight regulatory environment.

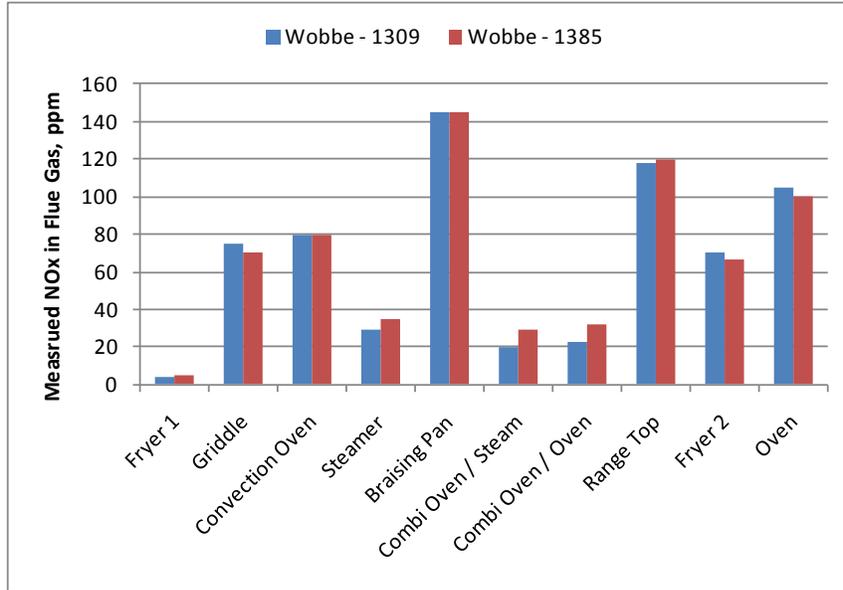


Figure 4. Range of NOx in Flue over Wobbe Range of Gases

Data on both CO and NOx are combined in Figure 5 to determine which foodservice equipment is of concern for interchangeability. None of the appliances has operational or ignition issues. Short term temperatures were higher than recommended in some circumstances, but long term testing was beyond the scope of this project. Emissions concerns can be divided into three groups. Fryer 1, the convection oven, the range top, and fryer 2 did not show any interchangeability emissions issues. The griddle and the combi oven in both steam generation and oven modes showed some increases in emissions and are therefore of mild concern for interchangeability emissions. The steamer, the braising pan, and the oven showed large emissions increases, particularly in CO, and are therefore of strong concern regarding interchangeability emissions.

Appliance	CO at		NOx at		CO Concern	NOx Concern
	W - 1309	W - 1385	W - 1309	W - 1385		
1 Fryer 1	50	20	4.5	5		
2 Griddle	25	40	75	70	x	
3 Convection Oven	25	30	80	80		
4 Steamer	50	700	29	35	x	x
5 Braising Pan	20	170	145	145	x	
6 Combi Oven / Steam	12	15	20	29		x
7 Combi Oven / Oven	7	8	23	32		x
8 Range Top	9	9	118	120		
9 Fryer 2	270	310	70	67		
10 Oven	200	750	105	100	x	

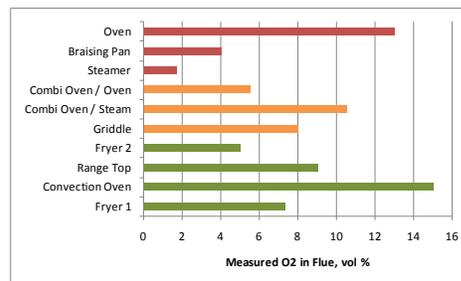


Figure 5. Interchangeability Summary of Foodservice Equipment

The graph in Figure 5 divides the foodservice equipment into the three groups of little concern (green), some concern (orange), and strong concern (red) and plots the appliances against the O₂ concentration measured in the flue. With the notable exception of the oven, the appliances show a weak but noticeable relationship between level of concern and O₂ in the flue. As O₂ in the flue decreases, the level of concern regarding emissions interchangeability (particularly for CO) tends to increase. This is expected since higher Wobbe gas needs more oxygen and CO is generated when insufficient oxygen is present for complete combustion. The oven had high measured O₂ in the flue, but the O₂ present in the closed oven combustion chamber may have been much lower. This could explain the unexpected result of strong CO emissions vs. Wobbe relationship for the oven while O₂ was also high in the flue. As discussed in the results section for the Oven, the excess CO production in this appliance could also be due to flame elongation and quenching and not a lack of oxygen for completing combustion. The two explanations for the oven behavior both fit the available data.

Based on the results from this project, the gas-fired commercial foodservice equipment was able to operate for the range of test gases with Wobbe less than 1350 without significant increases in emissions to be out of compliance with the standards set in ANSI Z83. However, for the test gases with a Wobbe greater than 1350, the CO emissions increased to levels that present significant issues with the performance of the burner system for the Steamer and Braising Pan that eventually performed to levels that would not be in compliance with standards established by ANSI. The Griddle, Fryer2 and Oven did not exceed 800 ppm of CO, but exhibited behavior suggesting emissions were tending toward levels of concern. The results show that within the population of commercial foodservice equipment there is a significant population that could have interchangeability issues with higher Wobbe number natural gases.

Results for Fryer1

Fryer1 was a Frymaster FH155CSD, Figure 6, with faceplate firing rate of 80,000 BTU/hr.



Figure 6. Fryer1

The burner is an infrared burner that heats the sides of a vat in contact with the oil. Figure 7 shows burner blower mounted to the front of the unit.



Figure 7. Fryer1 Burner System

Data was acquired using a flue gas sampling tube with evenly spaced sampling ports and thermocouples positioned in the flue along the back of the unit. Figure 8 shows the sampling probe in the flue before the thermocouples were added. Water temperature was recorded during testing at the middle of the vat.



Figure 8. Flue Sample for Fryer1

Testing and Results

Fryer1 was tested from a cold start with the thermostat set to 350 °F with water in the vat filled to the max fill line. Data was continuously collected until the water temperature reached 212 °F. Testing revealed that the burner had two distinctive transitive performance patterns. Figure 9 for the fryer using test gas S2 shows the flue temperatures rapidly increasing while the water temperature steadily increases. These profiles are typical in shape and performance observed for other fryers. However, for some gases, the temperature profiles were like Figure 10 for test gas A2. In this figure, the flue temperatures are not as rapidly increasing as for Figure until just before the 5 minute mark. Then the profiles are shaped more like the other data sets. There is also an inflection in the slope of the water temperature profile showing the rate of rise to increase after 5 minutes. Figure 11 and Figure 12 for the transient emissions for test gases S2 and A2 also show a very distinct difference in the burner behavior. Both tended toward similar steady state values, but the initial behavior was very different. The fryer using S2 had the initial CO peak associated with most gas-fired appliances, but the values reached steady state by 7 minutes. The fryer using A2 had a much more pronounced peak and the CO value varied until reaching a steady state at the 17 minute mark. The shift in O₂ and CO₂ at the 5 minute mark indicates the operational characteristics of the burner changed during testing. GTI spoke with Frymaster, who indicated this behavior had not been observed in any other testing. Various causes were discussed and are being investigated by Frymaster, but because the burner eventually reached a steady state, GTI continued the testing.

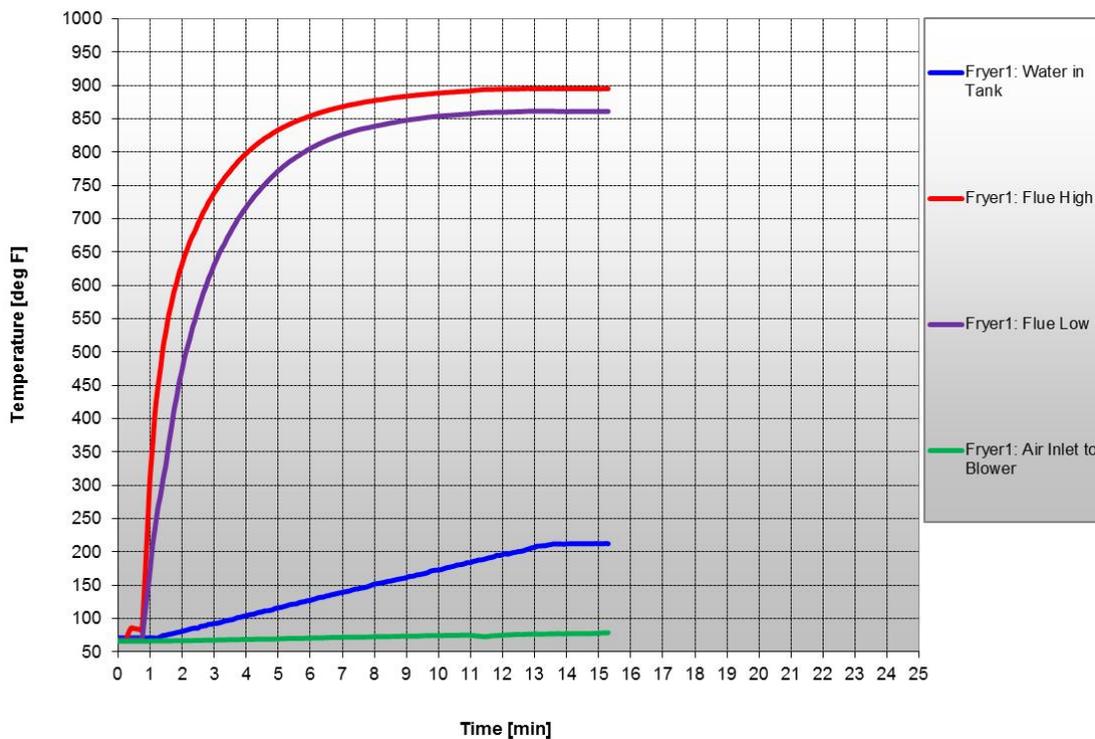


Figure 9. Transient Temperature Profile for Fryer1 (S1)

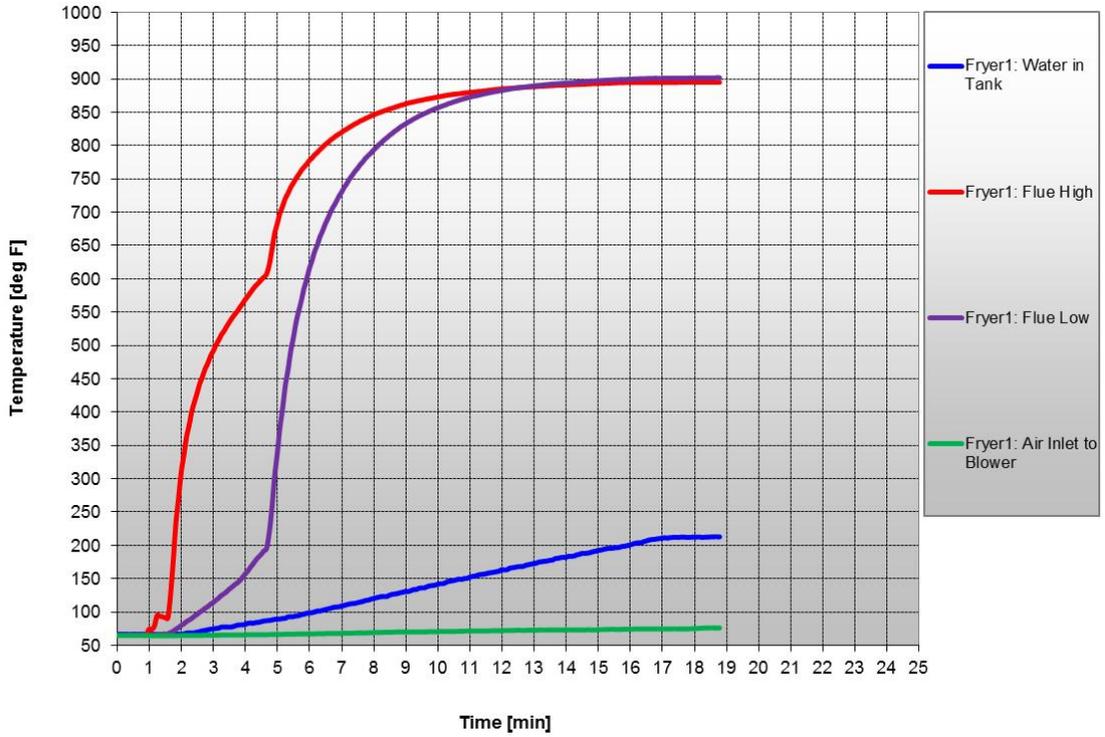


Figure 10. Transient Temperature Profile for Fryer1 (A2)

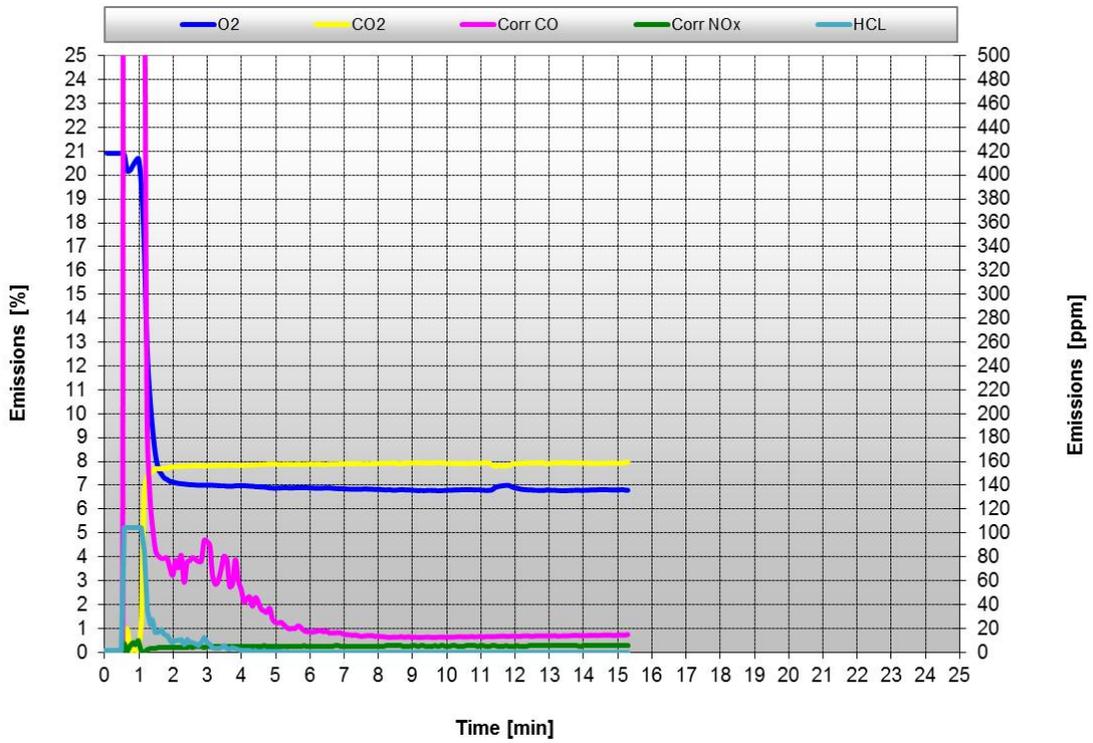


Figure 11. Transient Emissions Profile for Fryer1 (S1)

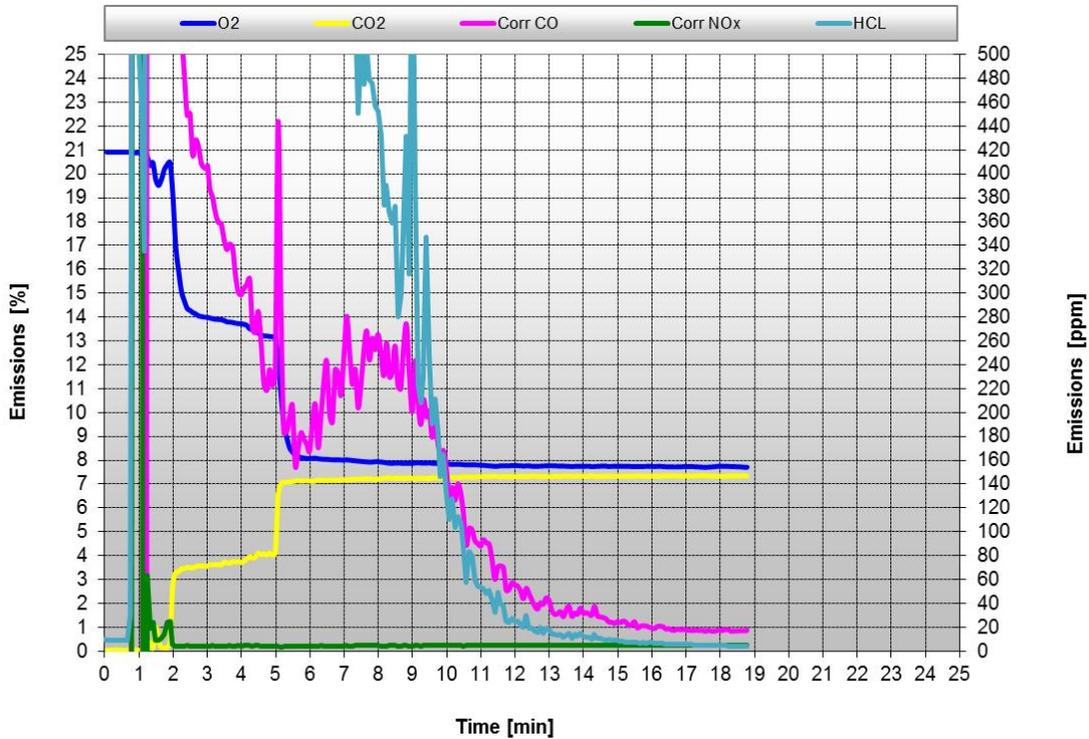


Figure 12. Transient Emissions Profile for Fryer1 (A2)

In order to compare specific performance characteristics of the fryer for the different test gases on a single chart, experimental values for each test gas was taken as the average for the last minute before the end of the test. These values should be similar to the values used in ANSI Z83.11 for determining the performance of the appliance. Below are figures for Firing Rate, Carbon Monoxide emissions (CO), Nitrogen Oxide emissions (NO_x) and Total Hydrocarbon as a function of a Wobbe ratio. The Wobbe ratio for each data point is the Wobbe value for the test gas divided by the Wobbe value for test A2, which was chosen as the baseline gas for data calculations. The CO and NO_x emissions values are corrected to 0% oxygen or to an air free value thus standardizing the values to remove dilution due to variations in excess air in the flue. Total Hydrocarbon is a measurement in ppm (parts per million) of the total amount of hydrocarbons or fuel that was not consumed in the combustion process. For a process with complete combustion, the Total Hydrocarbon should be near 0 ppm.

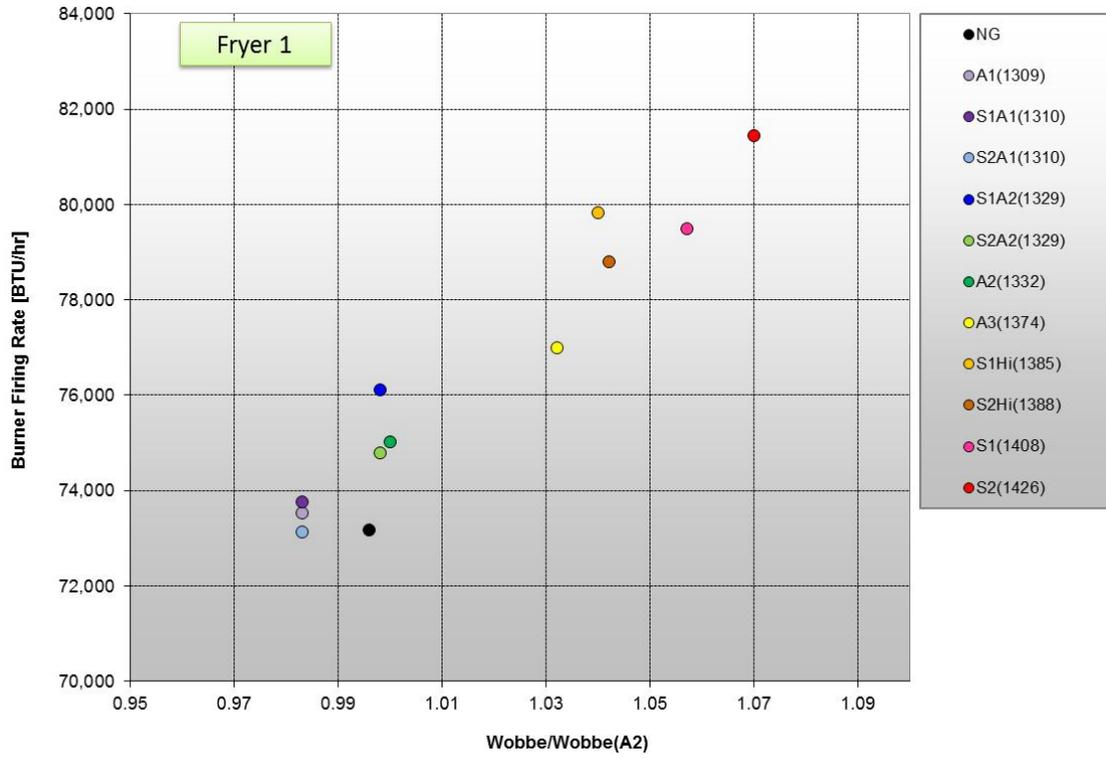


Figure 13. Fryer1 Firing Rate vs. Wobbe Ratio

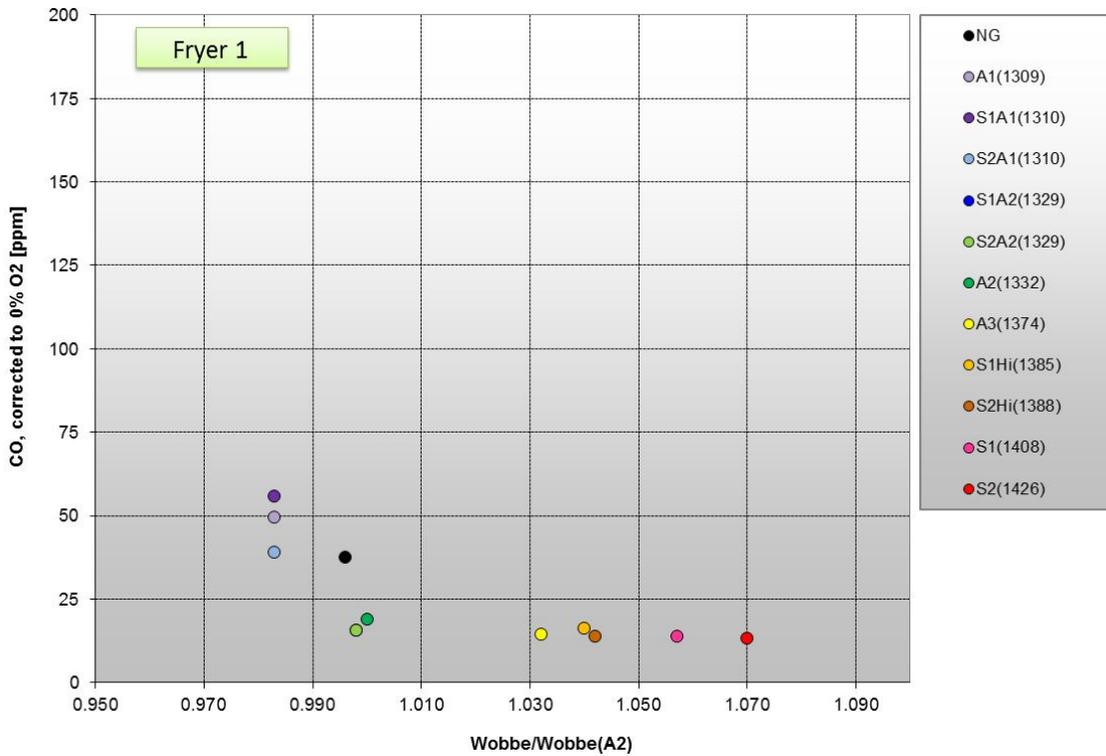


Figure 14. Fryer1 CO Emission vs. Wobbe Ratio

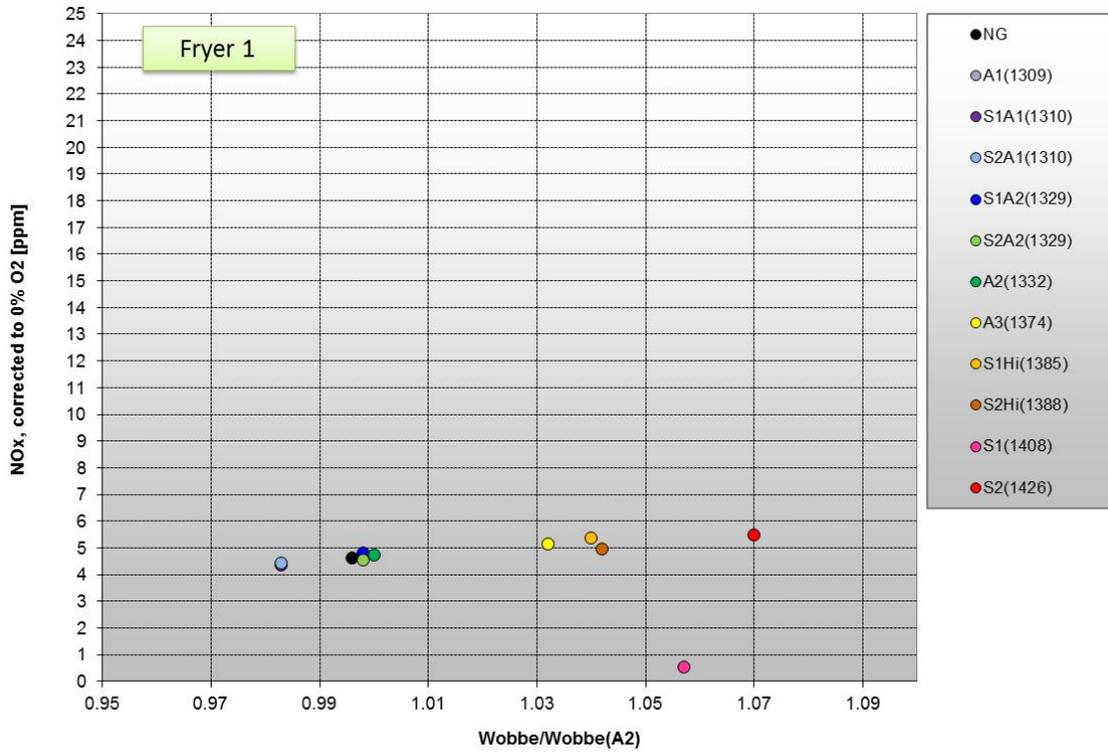


Figure 15. Fryer1 NOx Emission vs. Wobbe Ratio

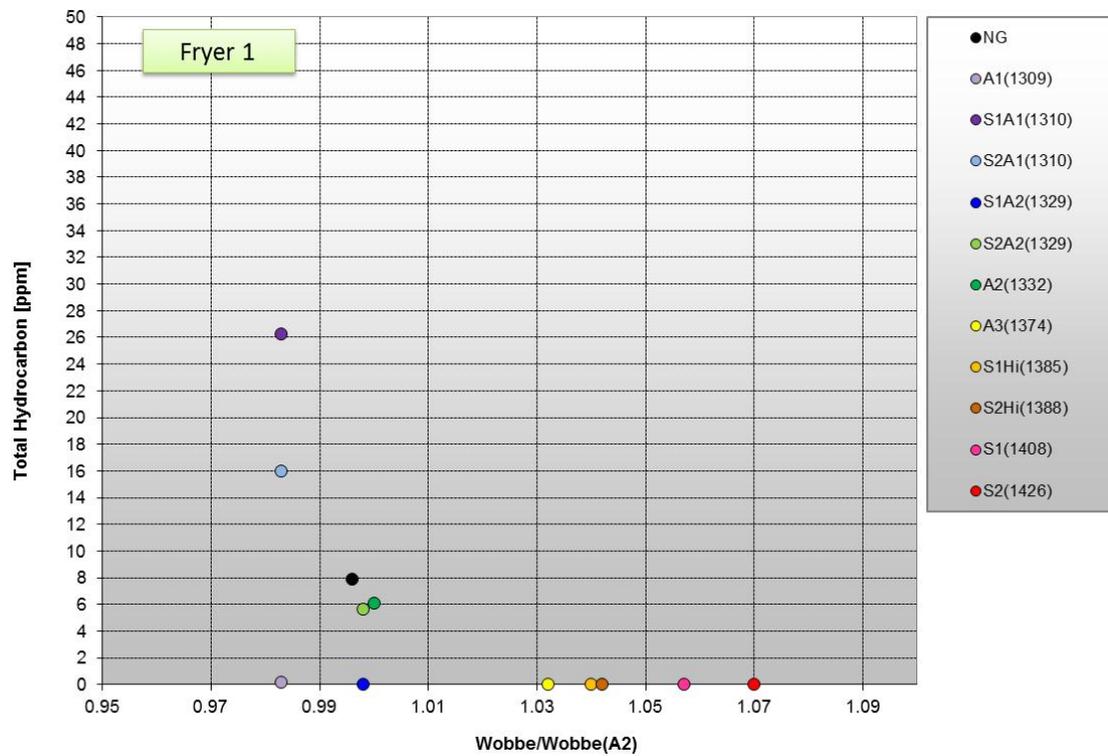


Figure 16. Fryer1 Total Hydrocarbon Emission vs. Wobbe Ratio

Visual Data

Fryer1 allowed only a limited view of the flame during testing, but some images were still taken. Figure 17 shows the flame through the viewing port on the front of the unit. The figure shows images of the burner for S1A2 just after ignition and just before the end of the test. As with other gases, the burner shifted from a blue flame to red-radiant flame as the unit heated up.



Figure 17. Fryer1 Flame Images (A1 and S1Hi)

Comparing visual and experimental data suggests that the differences in the transient behavior of this burner are related to the shifting of the burner from blue to red. The shape of the performance curves (Figures 9 through 12) appears to indicate a delay in the process of the burner becoming radiant. The data was given to the manufacturer for their review.

Analysis and Conclusions

Despite the differences in the transient behaviors for the burners, the steady state results showed consistent trends. The firing rate for the fryer burner steadily increased from about 73,000 to about 82,000 for the range of the Wobbe ratio, Figure 13. The scatter in the data is consistent with the accuracy of the total gas usage measured using the gas flow meter. CO data tended to decrease over the range of Wobbe ratio, Figure 14, starting at close to 50 ppm and decreasing to a minimum of near 15 ppm for high Wobbe number gas. All of the values for CO were well under the 800 ppm, corrected limit mandated by ANSI Z83. Figure 15 shows the corrected NO_x values were between 4 and 6 ppm for the entire range of testing showing a slight decrease at the higher Wobbe values, except for S1 which was less than 1 ppm. Hydrocarbons in Figure 16 varied during testing but most of the values were less than 10 ppm indicating that complete combustion was occurring.

Based on the results in the figures and despite some small changes in performance and differences in the transient behavior of the burner, Fryer1 was able to operate of the entire range of test gases without increases in emissions to be out of compliance with the standards set in ANSI Z83. Fryer 1 showed a decrease in CO and NO_x emissions as Wobbe Number was

increased. However, if lower Btu gases are used as fuel, this appliance shows elevated levels of CO and unburned hydrocarbons. GTI is still working with Frymaster to determine how to address the differences in the transient behavior of the burner.

Results for Griddle

The griddle tested was the Vulcan 36RRG-1, Figure 18, with a faceplate firing rate of 82,500 BTU/hr.



Figure 18. Griddle

The burner is a tube style located under the griddle surface with a blue flame. A clear view of the burner was not available, but Figure 19 is an image through the viewing port showing the pilot.



Figure 19. Griddle Pilot Flame

Data was acquired using a flue gas sampling tube with evenly spaced sampling ports and thermocouples positioned in the flue along the back of the unit and two thermocouples on metal disks (Figure 20) on the surface of the griddle. The plates simulate a typical heating load being applied to the surface.



Figure 20. Metal Disks on Griddle Surface

Testing and Results

The Griddle was tested from a cold start with the thermostat set to 350°F. Data was continuously collected until the burners began to cycle. Figure 21 and Figure 22 give the transient profiles for the temperatures and emissions of the Griddle using test gas A2. The temperature profile shows a rapid increase in flue temperatures and a steady increase in the surface temperatures until the burner began to cycle at just past 8 minutes on the chart. These profiles are typical in shape and performance of the other test gases.

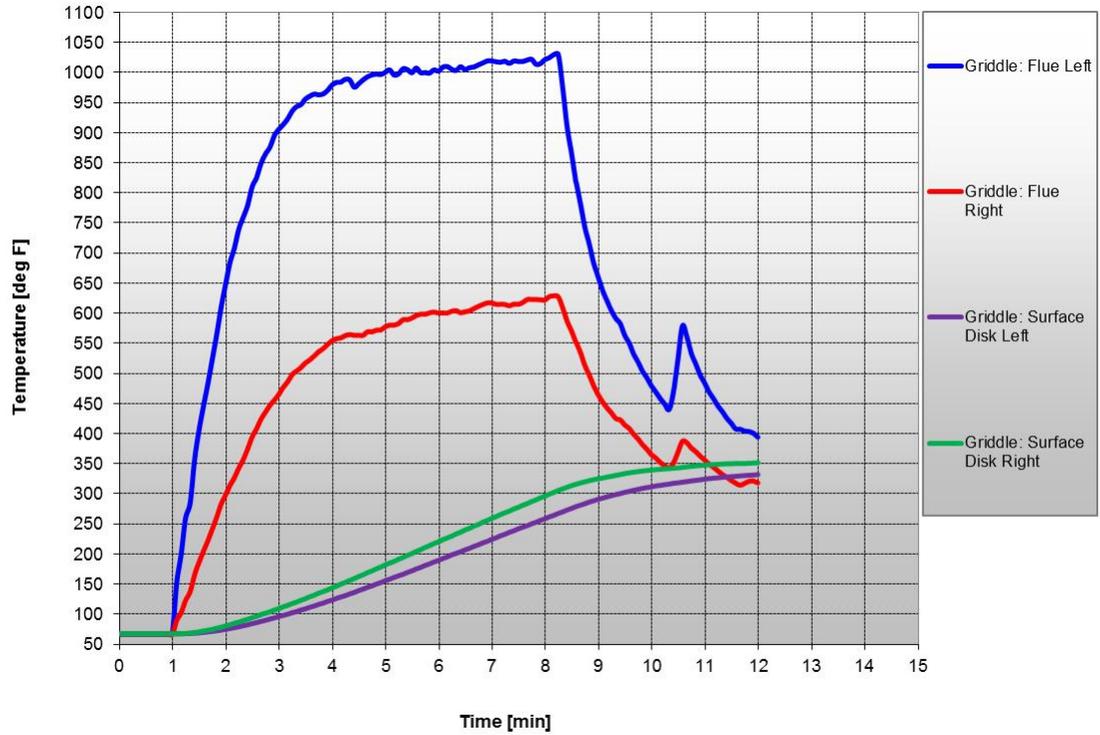


Figure 21. Transient Temperature Profile for Griddle

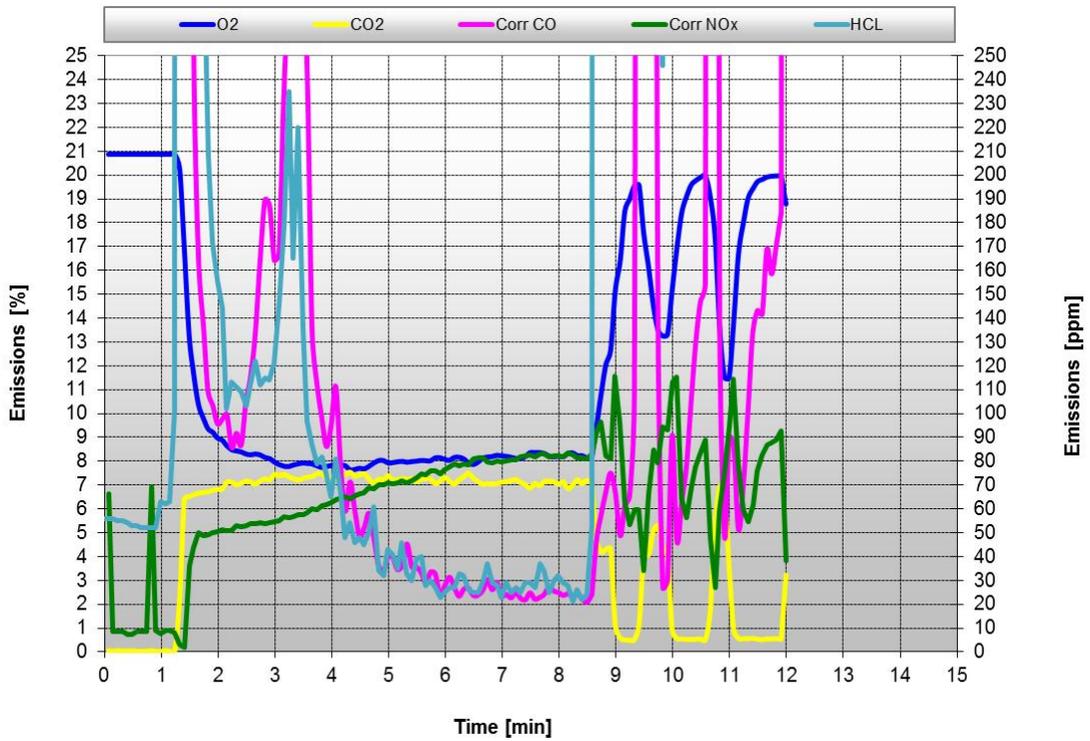


Figure 22. Transient Emissions Profile for Griddle

In order to compare specific performance characteristics of the Griddle for the different test gases on a single chart, experimental values for each test gas were taken as the average for the last minute before the burner began to cycle. These values should be similar to the values used in ANSI Z83.11 for determining the performance of the appliance. Below are figures for Firing Rate, Carbon Monoxide emissions (CO), Nitrogen Oxide emissions (NOx) and Total Hydrocarbon as a function of a Wobbe ratio. The Wobbe ratio for each data point is the Wobbe value for the test gas divided by the Wobbe value for test A2, which was chosen as the baseline gas to data calculations. The CO and NOx emissions values are corrected to 0% oxygen or to an air free value thus standardizing the values to remove dilution due to variations in excess air in the flue. Total Hydrocarbon is a measurement in ppm (parts per million) of the total amount of hydrocarbons or fuel that was not consumed in the combustion process. For processes with complete combustion, the Total Hydrocarbon should be near 0 ppm.

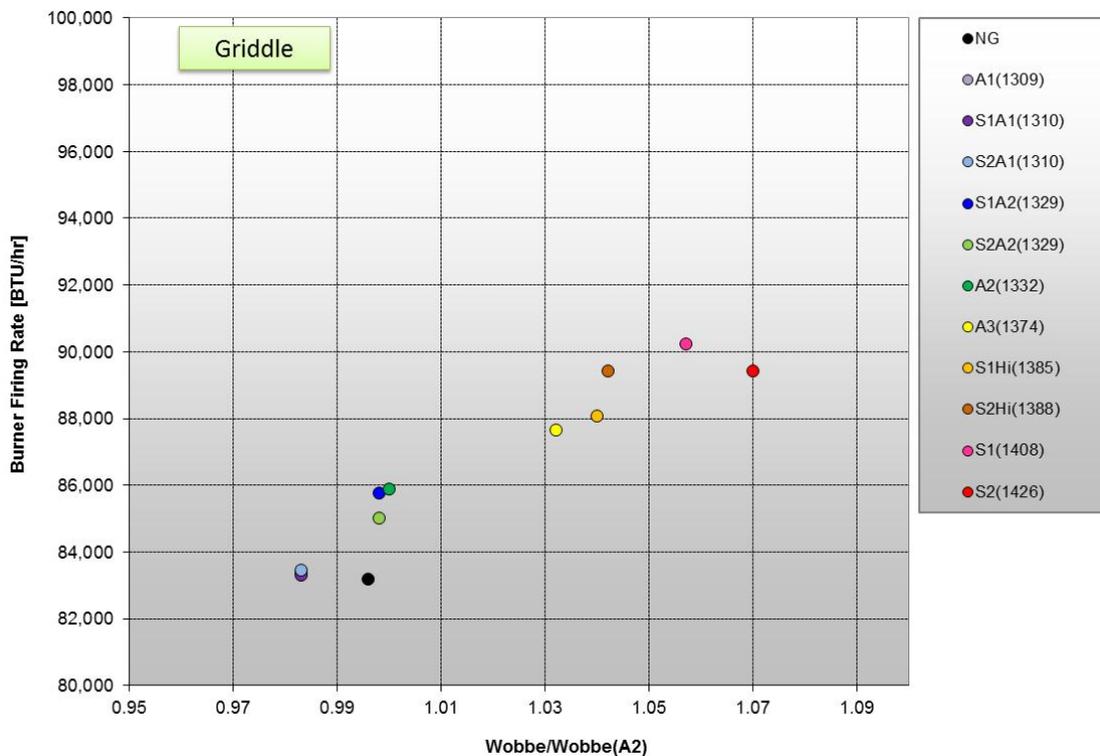


Figure 23. Griddle Firing Rate vs. Wobbe Ratio

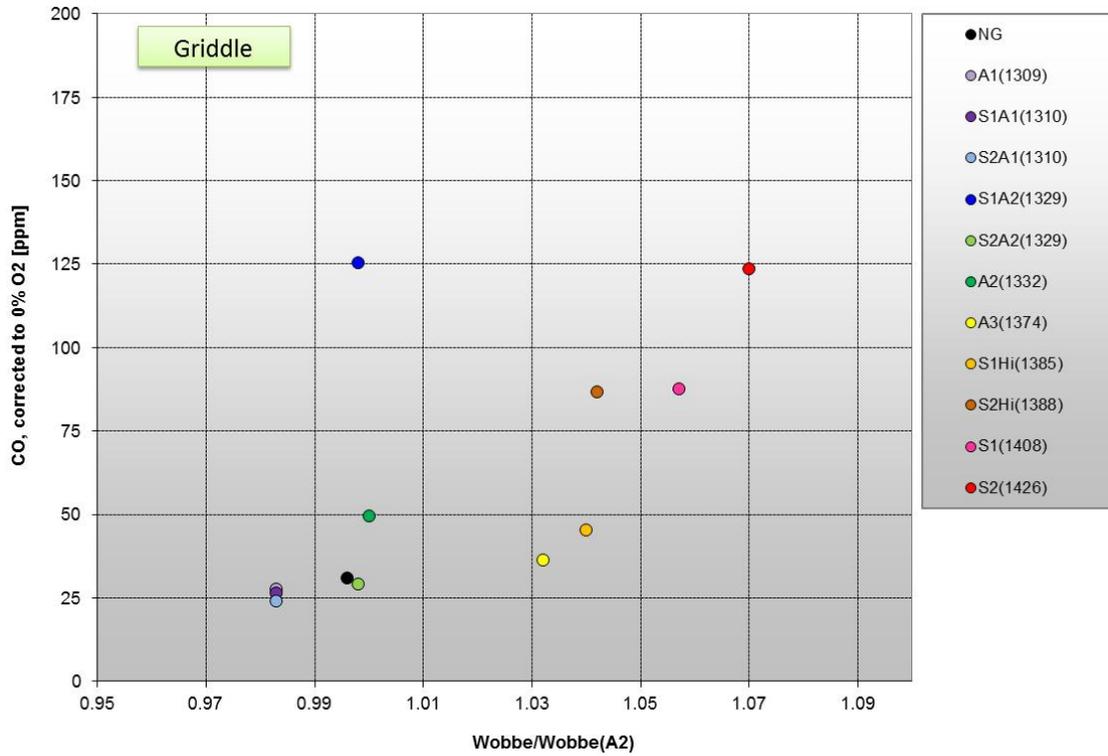


Figure 24. Griddle CO Emission vs. Wobbe Ratio

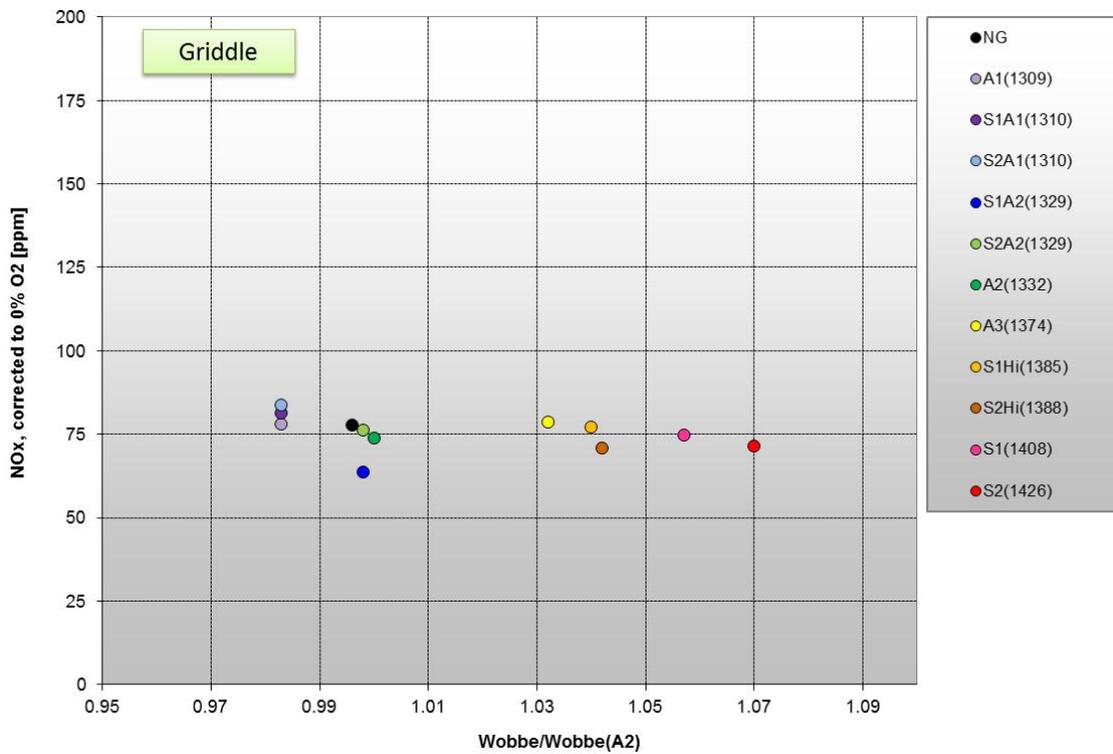


Figure 25. Griddle NOx Emission vs. Wobbe Ratio

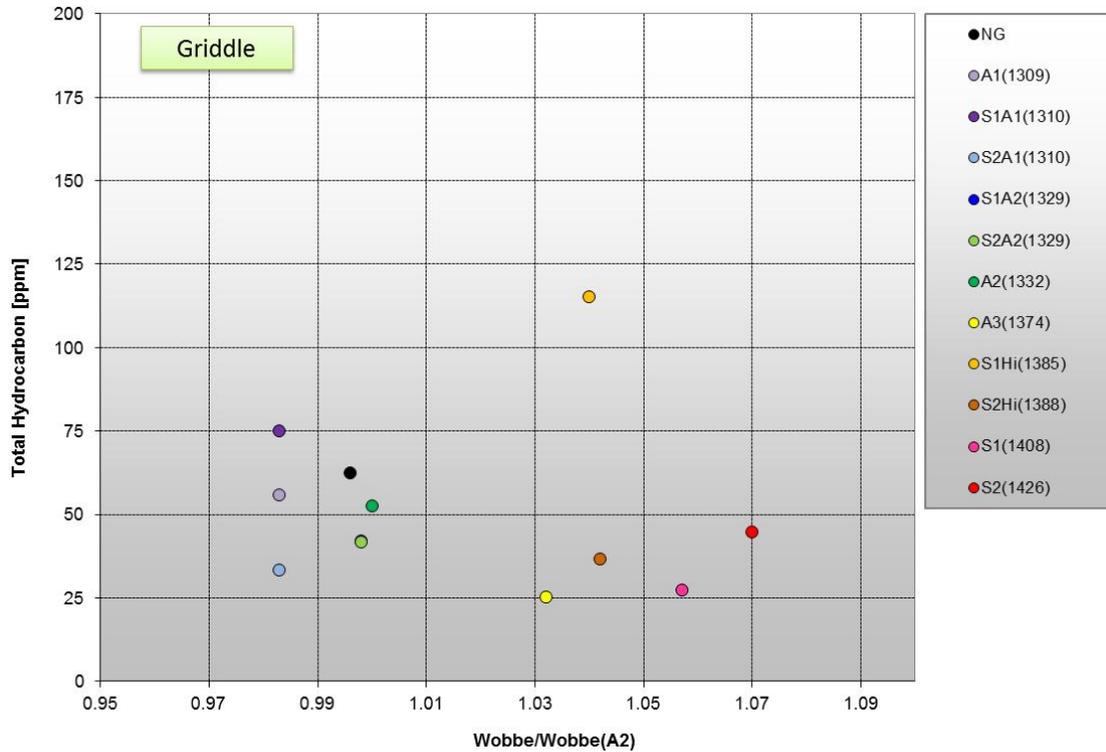


Figure 26. Total Hydrocarbon Emission vs. Wobbe Ratio

Analysis and Conclusions

As 17 shows, the emissions results were relatively steady for the final minute before the burner began to cycle. The firing rate for the griddle burner steadily increased from about 83,000 to 90,000 for the range of the Wobbe ratio, Figure 23. The scatter in the data is consistent with the accuracy of the total gas usage measured using the gas flow meter. CO data also exhibited a steady increase over the range of Wobbe ratio, Figure 24, with one outlier value for S1A2. For most of the testing with the griddle, the CO values tended to slowly change, but spikes in CO values were observed in some cases. In order to alleviate the spikes, the CO data was taken as an average value of the final minute of testing, however; for S1A2, the value was atypically higher than for the other data points and thus considered to be inconsistent with the other data points. All of the values for CO were well under the 800 ppm, corrected limited mandated by ANSI Z83. Figure 25 shows that the corrected NO_x values remained constant at around 75 ppm for the entire range of testing. The only data with a large amount of scatter was the Total Hydrocarbons in Figure 26. The values stayed between 25 and 125, with all but one value below 75 ppm, which suggests that complete combustion was occurring with some issues.

These values would follow the observance of the flame through the view port shown in Figure, where the flame behind the pilot was observed to have some minor yellowing during testing.

Based on the results in the figures and despite some small changes in performance, the griddle was able to operate over the entire range of test gases without increases in emissions to be out of compliance with the standards set in ANSI Z83. CO increased significantly with increased Wobbe Number. NO_x remained unchanged over the range of Wobbe Number tested. Total unburned hydrocarbons decreased as Wobbe Number increased. The large increase in CO for higher Wobbe Number gas is a concern for this cooking appliance.

Results for Convection Oven

The convection oven tested was the Blodgett DGF100, Figure 27, with faceplate firing rate of 55,000 BTU/hr.



Figure 27. Convection Oven

The unit uses a dual tube burner system that provides both indirect and direct heating to the cooking chamber. This means products of combustion are mixed with the cooking air that is circulated through the oven. Flame images were not taken because a clear view of the burner was not available.

Data was acquired using a gas sampling tube inserted through the flue in the back with the sample point located at the three round vent openings (Figure 28) located on the top and in the front of the cooking chamber.

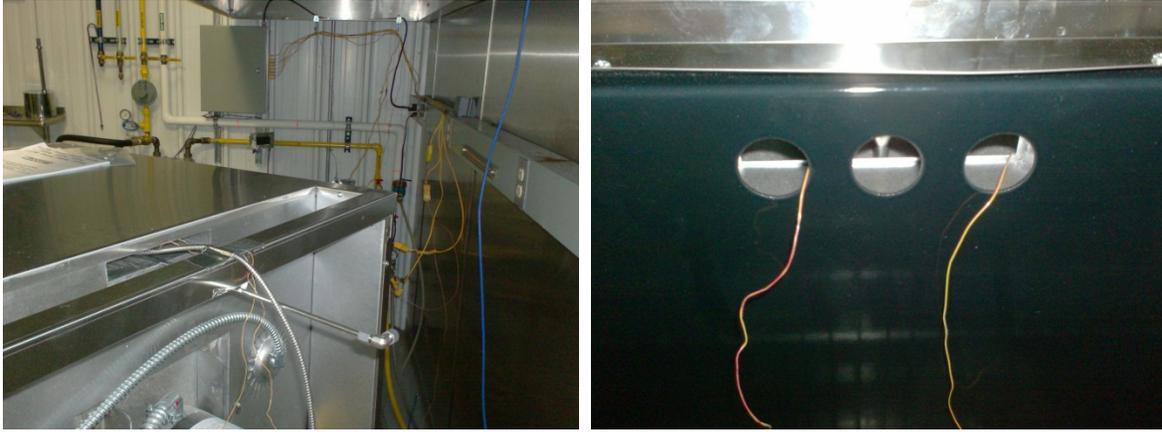


Figure 28. Flue and Vent Openings in Convection Oven Cooking Chamber

Thermocouples were also placed at the entrance of the vent openings and inside the cooking chamber.

Testing and Results

The Convection Oven was tested from a cold start with the thermostat set to 350 °F. Data was continuously collected until the burners had cycled three times, but for comparison in this study was taken before the first off cycle of the system. Figures 29 and 30 give the transient profiles for the temperatures and emissions of the Convection Oven using test gas A2.

The temperature profile shows a rapid increase in flue and chamber temperatures until the burner began to cycle at just past 14 minutes on the chart. These profiles are typical in shape and performance for the other test gases.

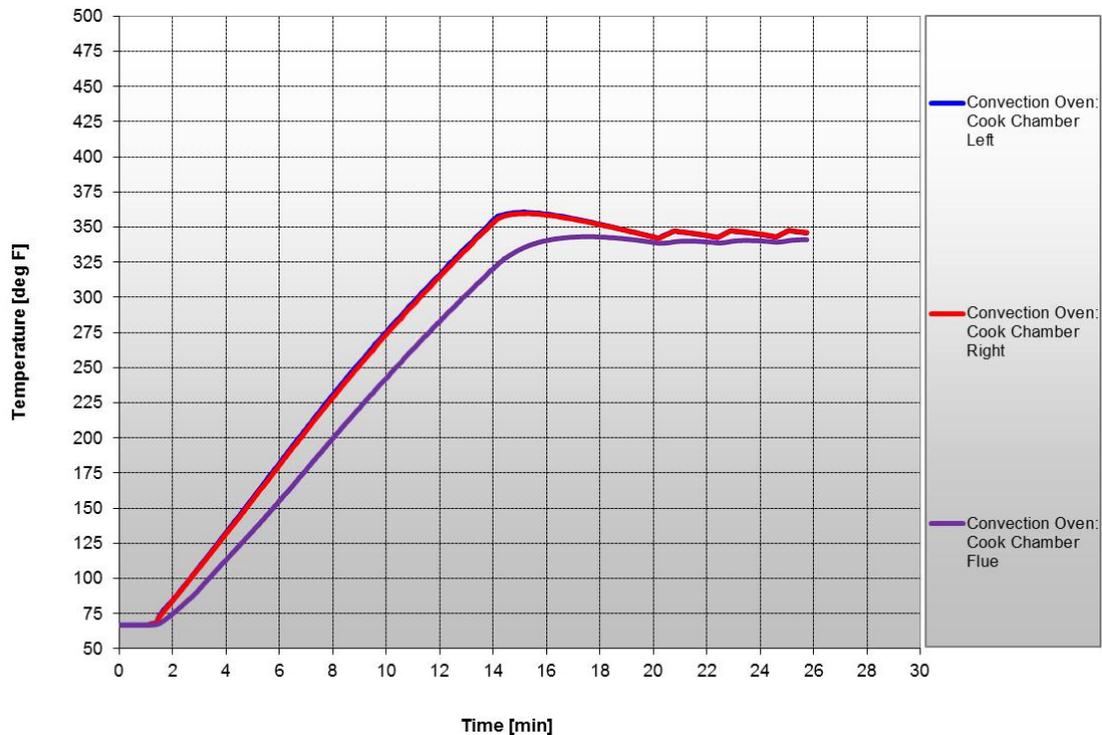


Figure 29. Transient Temperature Profile for Convection Oven

The Convection Oven had an unusual emissions profile when compared to the other appliances. As Figure 30 shows, the corrected values for the NO_x and CO were steadily increasing as the oven was heating up and the O₂ values were steadily decreasing. After the initial spike associated with most gas-fired appliances, the CO value began to decrease until the 8 minute mark and then begin to steadily increase. The value was still well below the 800 ppm required by ANSI Z83. The reason the system never reaches a true steady state is that the oven's direct heating systems mixes the flue gases with the air in the oven. As the burner runs, the percentage of the flue gases in the total volume of gases in the oven increases compared with the air in the oven. This process results in a lowering of O₂. The data was checked to confirm there is an increase in the actual amount of CO and NO_x during the test and that the corrected values of NO_x and CO were not increasing strictly due to the decrease in O₂ present¹. This behavior was observed for all the gases tested.

¹ Corrected emissions values are a direct function of the % of O₂ in the sample, thus an increase in O₂ would also increase the corrected value.

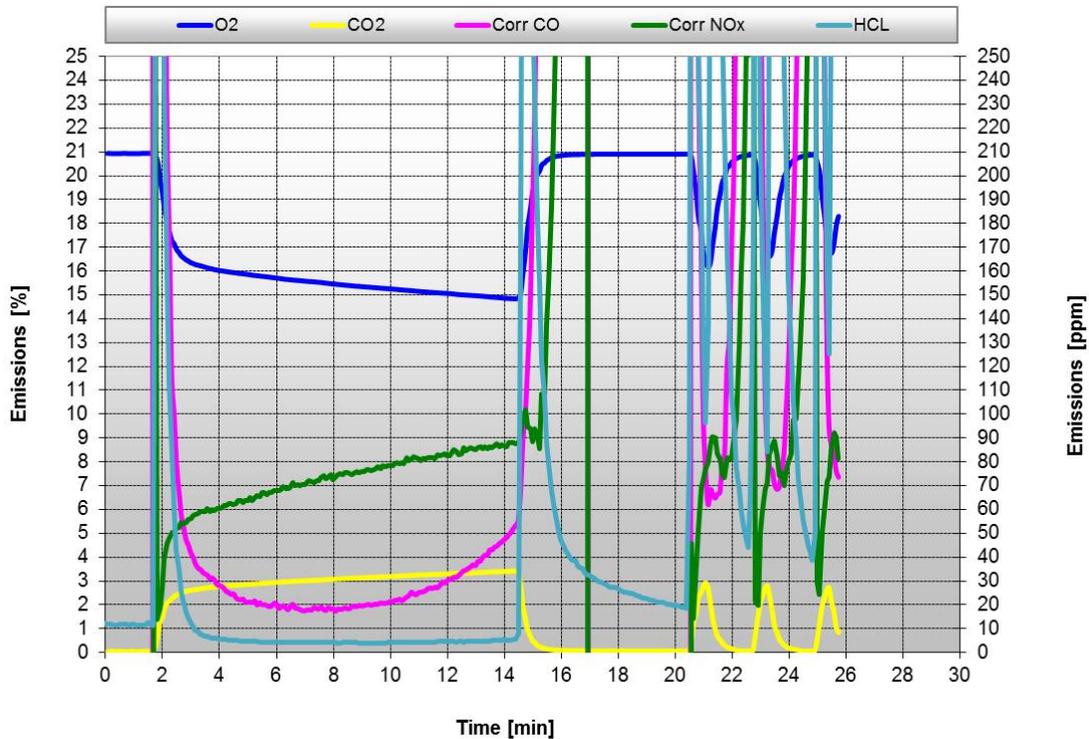


Figure 30. Transient Emissions Profile for Convection Oven

In order to compare specific performance characteristics of the Convection Oven for the different test gases on a single chart, experimental values for each test gas were taken as the average for the last minute before the burner began to cycle. These values should be similar to the values used in ANSI Z83.11 for determining the performance of the appliance. Below are figures for Firing Rate, Carbon Monoxide emissions (CO), Nitrogen Oxide emissions (NO_x) and Total Hydrocarbon as a function of a Wobbe ratio. The Wobbe ratio for each data point is the Wobbe value for the test gas divided by the Wobbe value for test A2, which was chosen as the baseline gas to data calculations. The CO and NO_x emissions values are corrected to 0% oxygen or to an air free value thus standardizing the values to remove dilution due to variations in excess air in the flue. Total Hydrocarbon is a measurement in ppm (parts per million) of the total amount of hydrocarbons or fuel that was not consumed in the combustion process. For a process with complete combustion, the Total Hydrocarbon should be near 0 ppm.

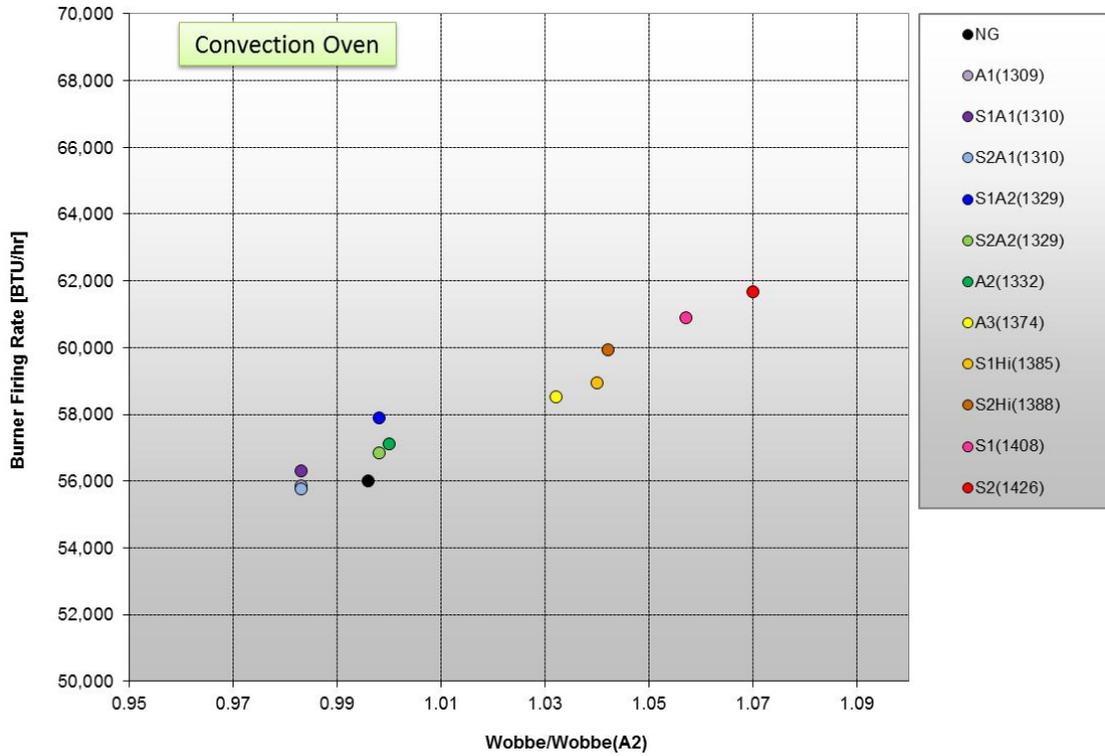


Figure 31. Convection Oven Firing Rate vs. Wobbe Ratio

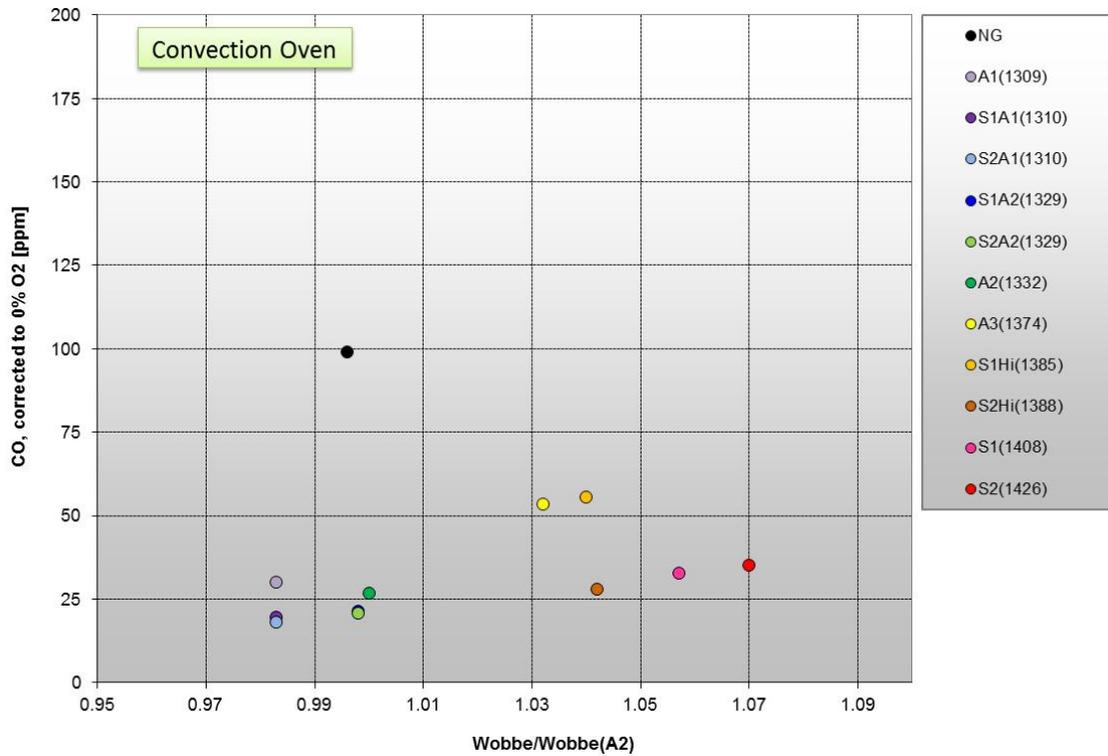


Figure 32. Convection Oven CO Emission vs. Wobbe Ratio

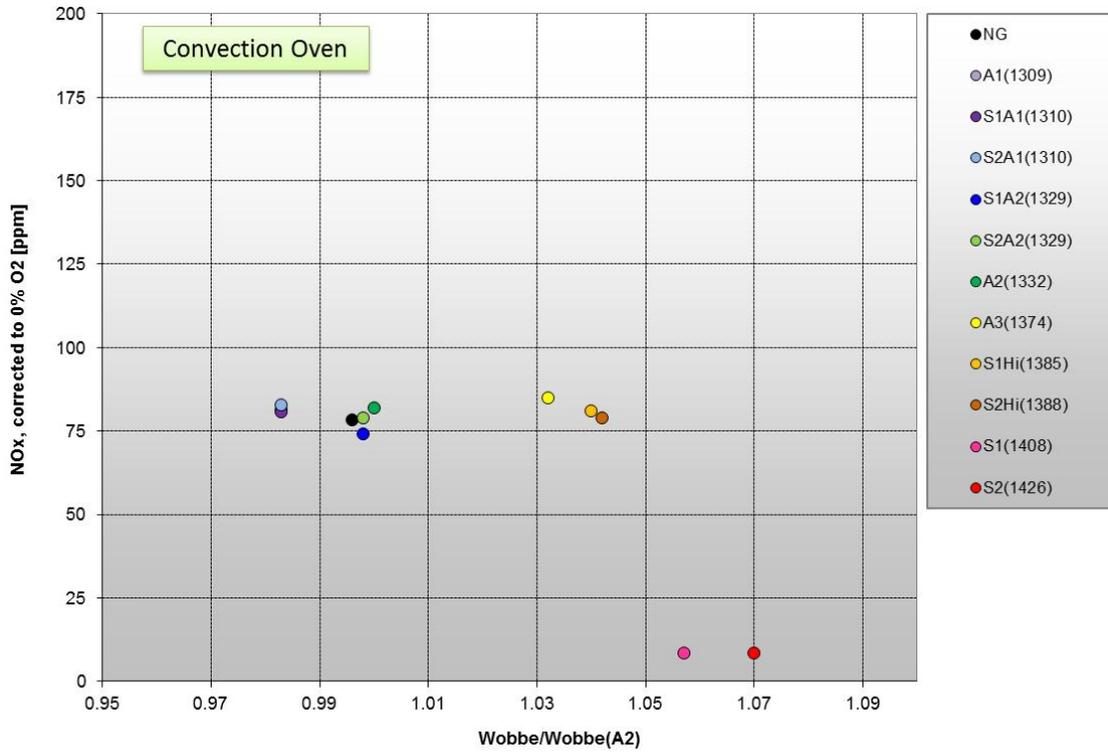


Figure 33. Convection Oven NOx Emission vs. Wobbe Ratio

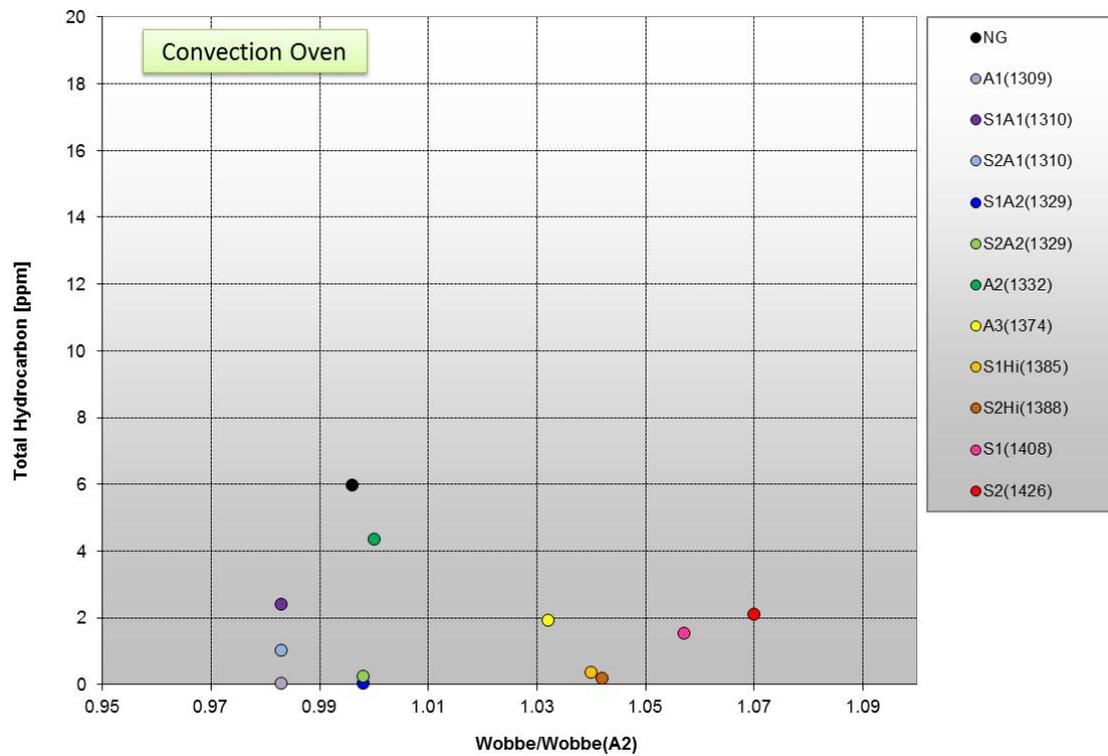


Figure 34. Convection Oven Total Hydrocarbon Emission vs. Wobbe Ratio

Analysis and Conclusions

As previously discussed and shown in Figure 30, the emissions results were changing for the final minute before the burner began to cycle. However, the average values measured over the last minute still show trends in the burner performance as a function of changing the content of the fuel gas. The firing rate for the oven burner steadily increased from about 55,000 to 62,000 for the range of the Wobbe ratio, Figure 31. The scatter in the data is consistent with the accuracy of the total gas usage measured using the gas flow meter. CO data also exhibited a slight increase for the higher Wobbe ratios, Figure 32, with one outlier value for NG or the house natural gas at GTI. For most of the testing with the Convection Oven, CO values tended to stay between 20 and 60 ppm, but spikes in CO values were observed in some cases. To alleviate the spikes, the CO data was taken as an average value of the final minute of testing, however; for NG, the value was atypically higher than for the other data points and thus inconsistent with the rest of the data. All CO values were well under 800 ppm, the corrected limit mandated by ANSI Z83. Figure 33 shows that the corrected NO_x values remained constant at around 75 ppm for the entire range of testing except for a sudden decrease for testing with S1 and S2, the highest Wobbe valued gases. This drop to about 10 ppm was unusual, but consistent with a retest of these data points. Total hydrocarbons in Figure 34 stayed consistently less than 6 ppm indicating complete combustion was occurring.

Based on the results in the figures and despite some small changes in performance, the convection oven showed a small increase in CO with increasing Wobben Number but was able to operate of the entire range of test gases without an increase in emissions to be out of compliance with the standards set in ANSI Z83.

Results for Oven

The Oven tested was the Garland G36-6R, Figure 35, with faceplate firing rate of 38,000 BTU/hr.



Figure 35. Oven

The unit uses tube burners with drilled ports. Air is entrained with the natural gas at the flared end of the burner with an adjustable air shutter, as shown in Figure 36. The burner heats the bottom of the cook chamber and flue gases flow through the chamber and out the flue in the

back of the unit. Flue samples were taken at the opening in the back of the unit where the flue products pass out and exit the oven cooking chamber.



Figure 36. Oven Burner

Testing and Results

The Oven was tested from a cold start until the unit's burner began to cycle at the thermostat set temperature of 350 °F. Figures 37 and 38 and give the transient profiles for the temperatures and emissions of the Oven using test gas A2.

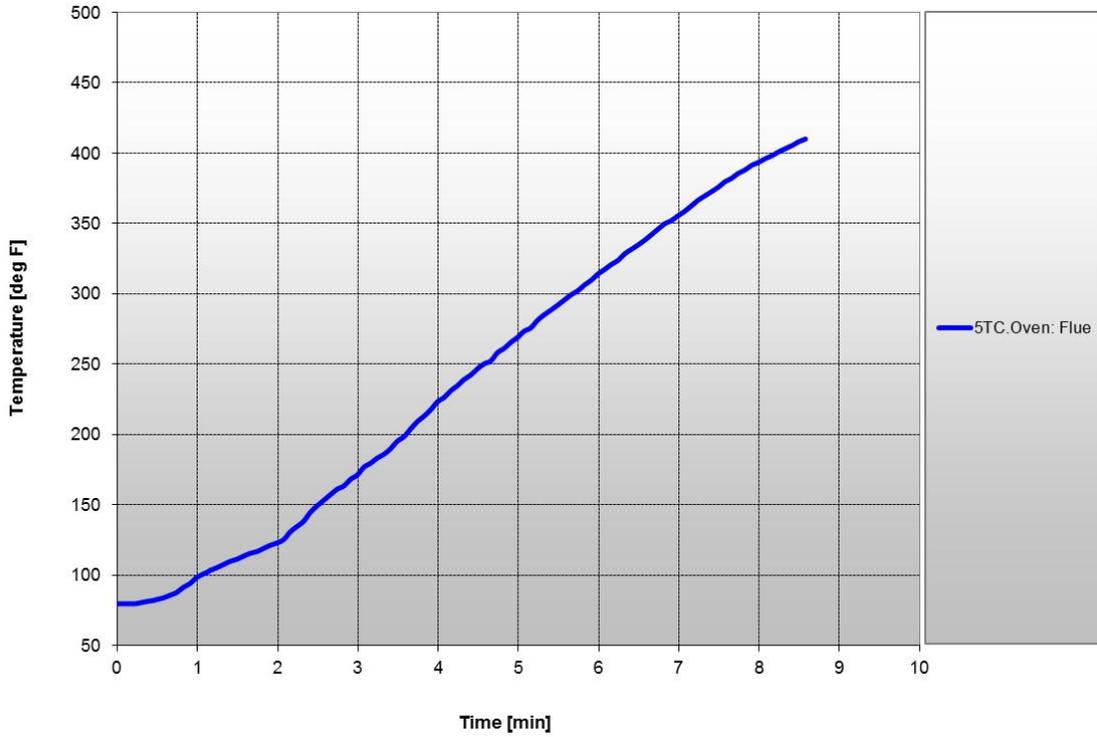


Figure 37. Transient Temperature Profile for Oven

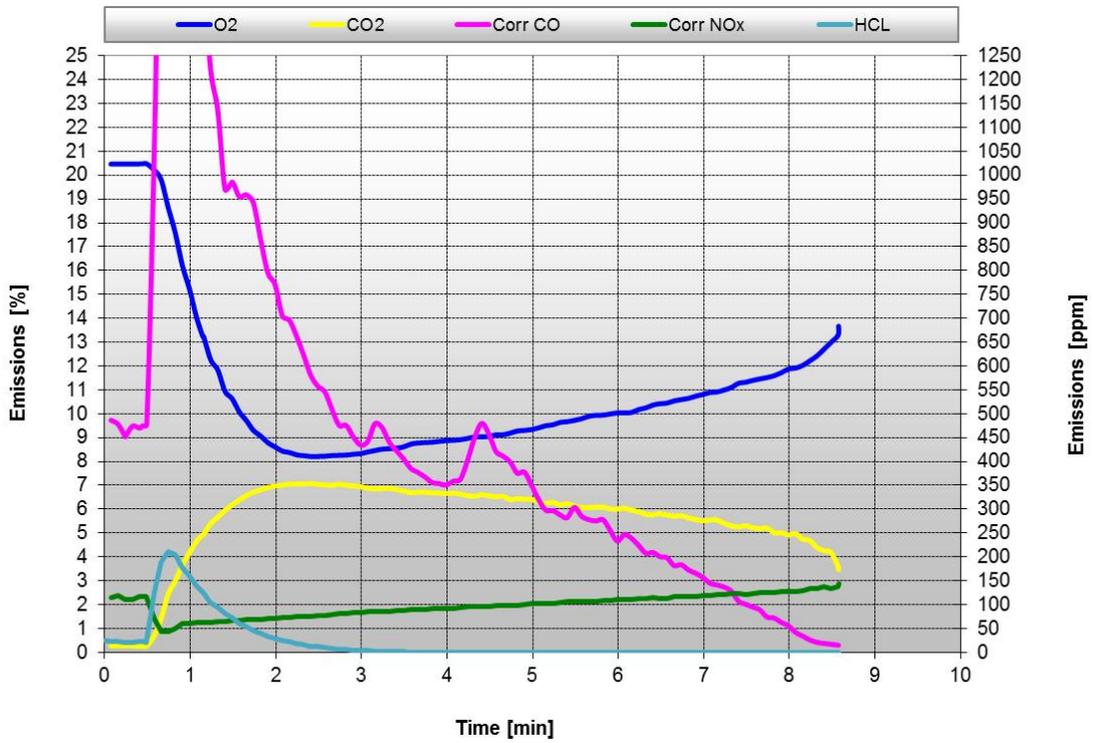


Figure 38. Transient Emissions Profile for Oven

The temperature profile shows a steady increase in flue temperature for the entire test. This profile is typical in shape and performance of the other test gases.

As Figure 38 shows, the Oven had steady changes in emissions values over the entire timeframe of the test. The values for O₂ and NO_x slowly increased while CO₂ and UHC slowly decreased. After the initial spike associated with most gas-fired appliances, the corrected CO value dramatically decreased to less than 30 ppm by the end of the test. This behavior was observed for all the gases tested, but the final values varied for different test gases.

In order to compare specific performance characteristics of the Oven for the different test gases on a single chart, experimental values for each test gas was taken as the average for the last minute before the burner began to cycle. These values should be similar to the values used in ANSI Z83.11 for determining the performance of the appliance. Below are figures for Firing Rate, Carbon Monoxide emissions (CO), Nitrogen Oxide emissions (NO_x) and Total Hydrocarbon as a function of a Wobbe ratio. The Wobbe ratio for each data point is the Wobbe value for the test gas divided by the Wobbe value for test A2, which was chosen as the baseline gas to data calculations. The CO and NO_x emissions values are corrected to 0% oxygen or to an air free value thus standardizing the values to remove dilution due to variations in excess air in the flue. Total Hydrocarbon is a measurement in ppm (parts per million) of the total amount of hydrocarbons or fuel that was not consumed in the combustion process. For a process with complete combustion, the Total Hydrocarbon should be near 0 ppm.

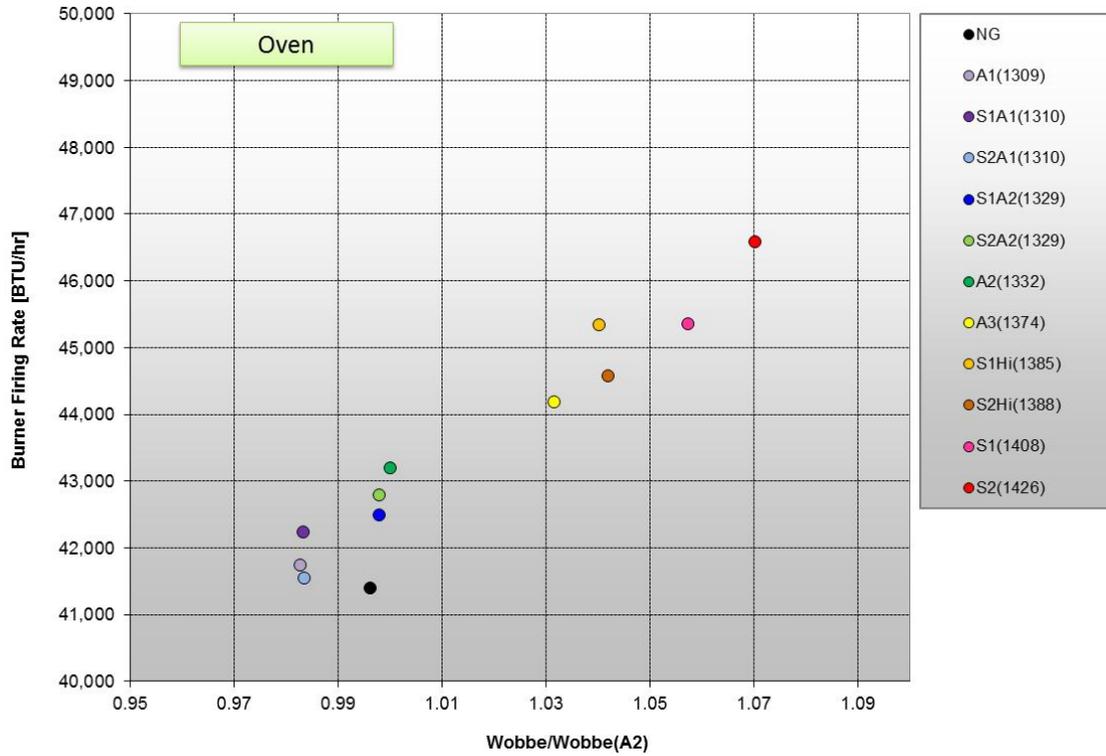


Figure 39. Oven Firing Rate vs. Wobbe Ratio

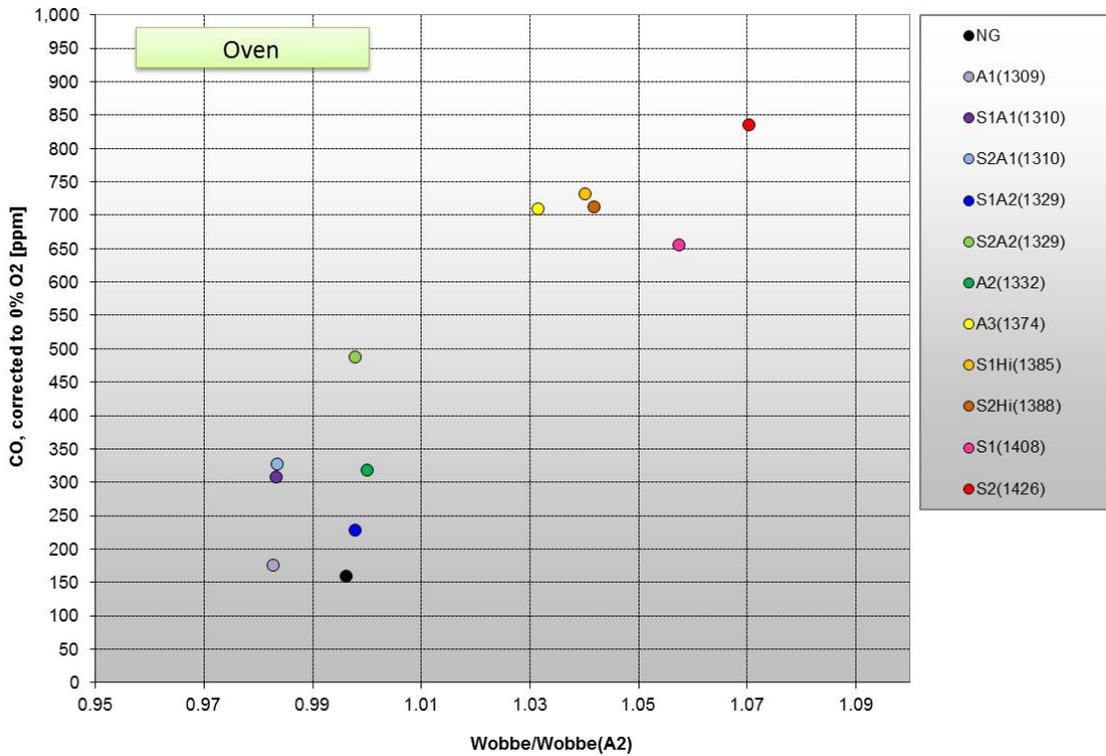


Figure 40. Oven CO Emission vs. Wobbe Ratio

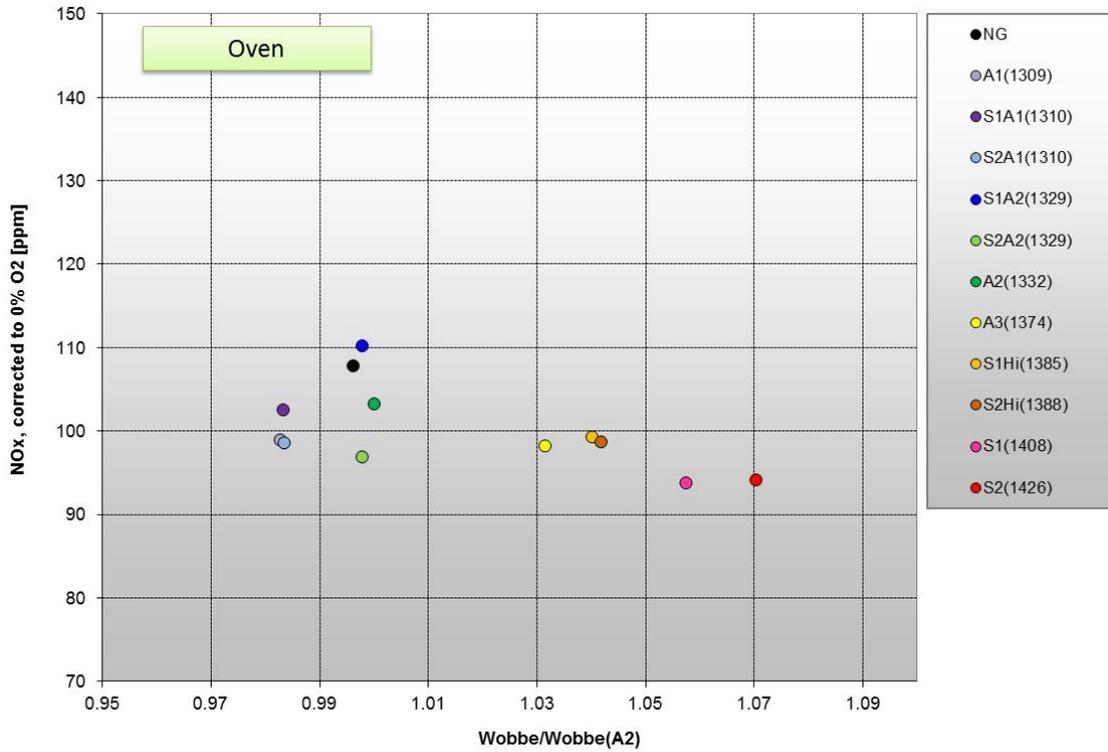


Figure 41. Oven NOx Emission vs. Wobbe Ratio

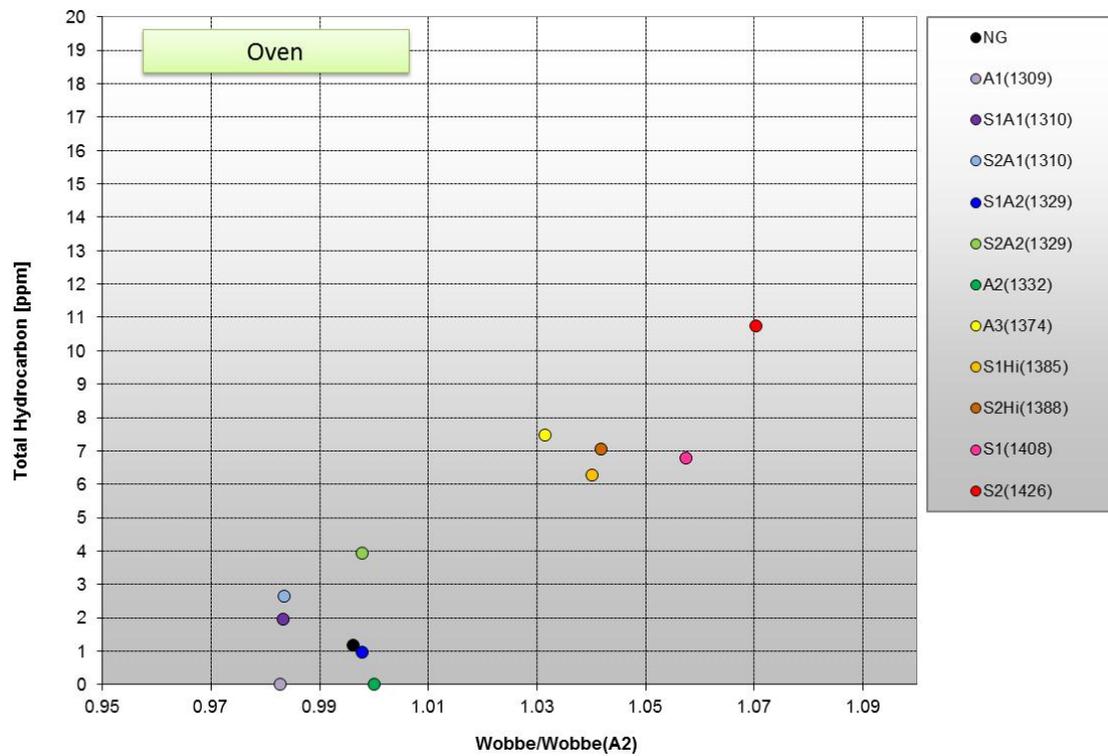


Figure 42. Oven Total Hydrocarbon Emission vs. Wobbe Ratio

Visual Data

The Oven offered a very limited view of the flame during testing. For each test gas, images and videos were taken of the flame. Figure 43 shows some images taken of the Oven flame for A1 and S2A1 test gases.

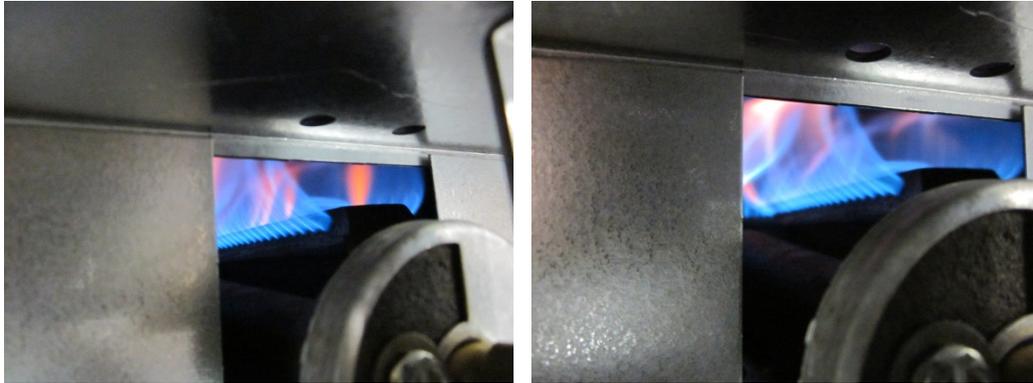


Figure 43. Oven Flame Images (A1 and S2A1)

The images and the videos taken show that the flame exhibited some yellowing with a slight increase in flame volume flame finger size for the higher Wobbe gases.

Analysis and Conclusions

The results for the Oven burner showed that increasing the Wobbe number of the fuel led to significant changes in terms of burner performance. The firing rate for the oven burner steadily increased from about 41,500 to just below 47,000 for the range of the Wobbe ratio, Figure 39. The scatter in the data is consistent with the accuracy of the total gas usage measured using the gas flow meter.

The corrected CO results in Figure 40 show that the burner has significant issues at the higher Wobbe gases. The corrected CO value increased from around 200 ppm to over 800 ppm for S2. This value is greater than the corrected limit of 800 ppm allowed by ANSI Z83 for combustion testing for ovens. This behavior has been recorded for other ovens of similar design. As the heat content increases in the fuel, the finger shaped flames elongated and began to impinge on the bottom of the oven chamber. This quenches the flame resulting in increased CO production. The resulting CO levels depend on the gas, the burner design and the spacing and shape of the oven's bottom surface.

In some burner systems, the same mechanism that results in increased CO can result in lower NO_x production. This appears to be the case for this oven. As Figure 41 shows, the corrected NO_x decreased slightly from between 100 to 110 ppm to less than 95 ppm at the higher Wobbe values. Flame quenching generally evens out the temperature variations in the flame and gives a lower peak flame temperature, both of which give lower NO_x emissions. The Total Hydrocarbons in Figure 42 exhibits behavior commonly associated with a burner system with

increasing CO production. Elongated flames that are being quenched tend to not fully complete the combustion process leading to unburned hydrocarbons. The figure shows that UHC values steadily increased from values of less than 3 ppm to over 10 ppm. This change is not overly concerning in terms of the burner performance, but it does show that the higher heat content fuel is affecting the burner.

Based on the results in the figures, the Oven was able to operate for most of the range of test gases without increases in emissions to be out of compliance with the standards set in ANSI Z83. However, the test gases with a Wobbe greater than 1374, the CO emissions increase to a level that goes from being a concern to the point of being out of compliance.

Results for Range Top

The range top tested was the Garland G36-6R, Figure 44, with a faceplate firing rate of 33,000 BTU/hr.



Figure 44. Range Top

The unit uses a cast iron burner with drilled ports (Starfire-Pro 2) that provides direct heating to the bottom of the pot. The flue products mix with the air around the pot and are exhausted from the work space via the kitchen hood above the unit. Figure 45 shows the burner off and on with the test pot sitting on the grates above the burner.

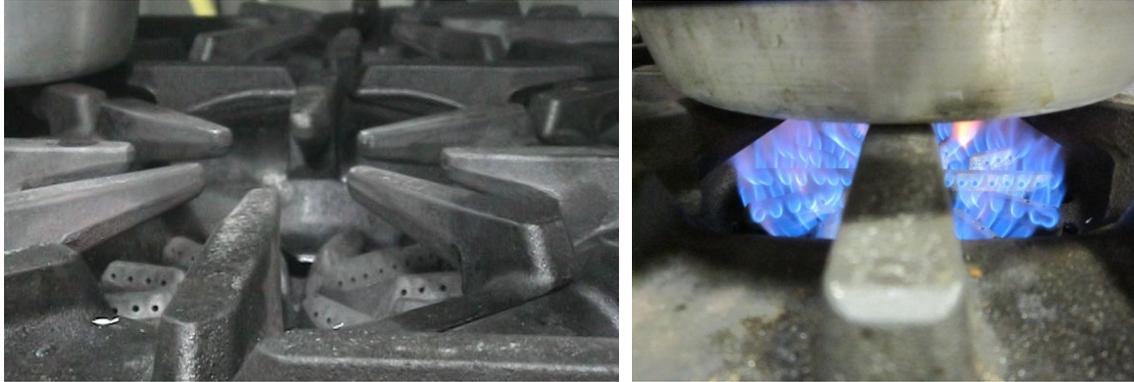


Figure 45. Range Top Burner

Previous range top testing showed that collection of meaningful flue samples from a range top can be difficult because of the mixing of the flue gases with air around the pot. The excess secondary air results in the flue sample being so diluted that the accuracy of the measured emissions values is too low for comparison with different gases. In previous range top interchangeability studies at GTI, a special capture hood was built and is shown in Figure 46. The hood is placed over the testing pot with the lip of the hood high enough above the grates to allow secondary air to get to the flames but low enough to prevent the flue sample from becoming too diluted. The two tubes in the image are sample lines on each side of the hood. Two thermocouples are mounted on the hood surface to measure flue temperatures. This method is different from the combustion test methods of ANSI Z83, but this approach has been shown to be more effective for conducting an interchangeability study.

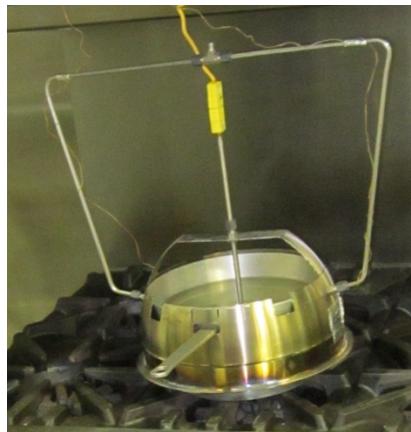


Figure 46. Range Gas Sampling Hood

Testing and Results

The Range Top was tested from a cold start with the test pot holding 8 pounds of room temperature water. The pot was set on the middle front burner, turned to high. Data was

continuously collected until the water reached 212 °F. Figure 47 and Figure 48 give the transient profiles for the temperatures and emissions of the Range using test gas A2.

The temperature profile shows an asymptotic increase in flue temperature and a steady increase in water temperature until the water began boiling at about 12 minutes. These profiles are typical in shape and performance of the other test gases.

As Figure 48 shows, the Range Top had fairly steady emissions values by the end of the test. The values for O₂, CO₂ and corrected value for CO were steady while the corrected NO_x values were still slowly increasing. After the initial spike associated with most gas-fired appliances, the CO value began to decrease until the 6 minute mark when it became nearly constant at about 10 ppm. This behavior was observed for all the gases tested.

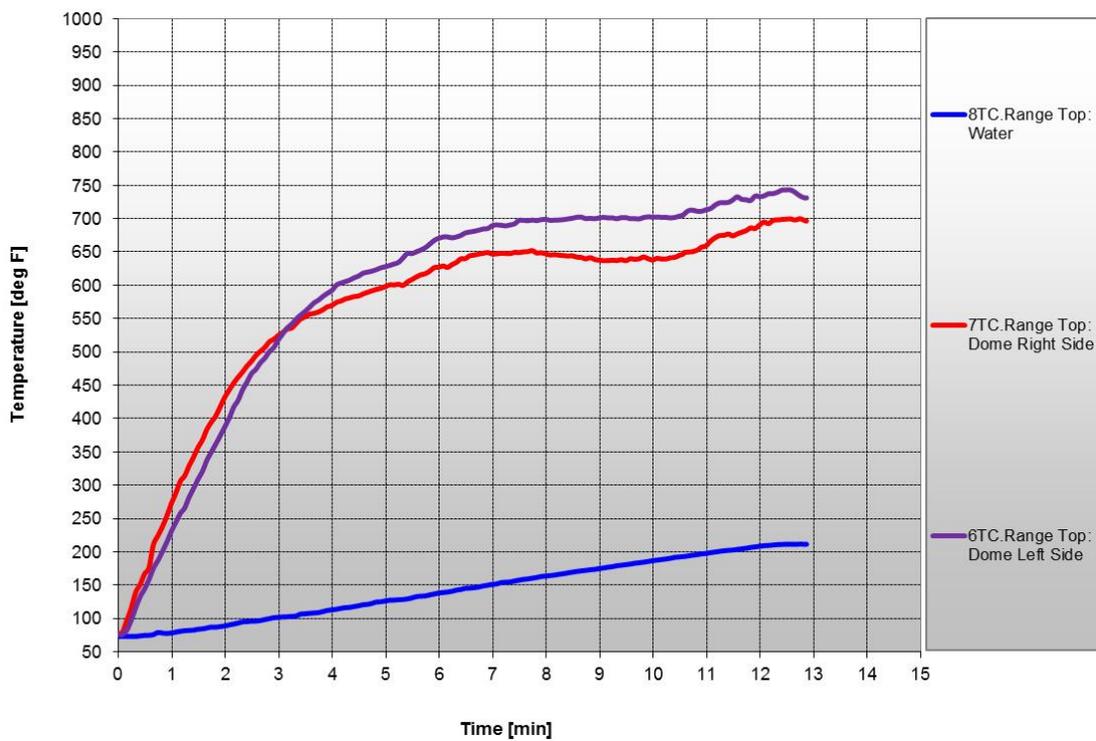


Figure 47. Transient Temperature Profile for Range Top

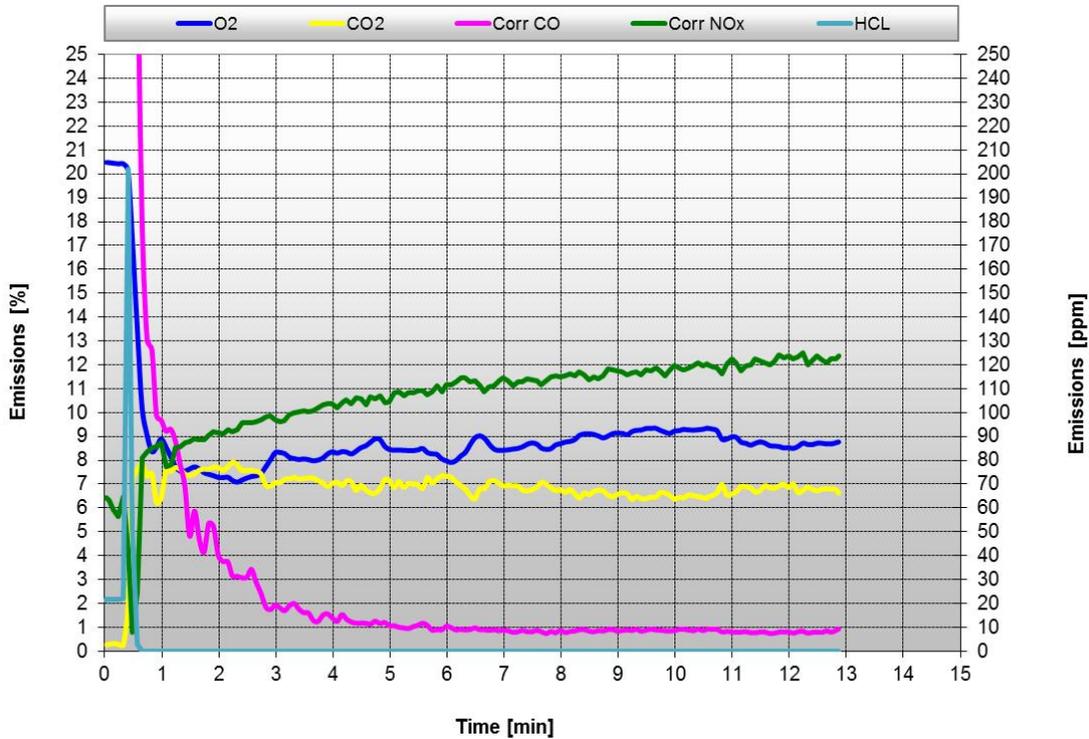


Figure 48. Transient Emissions Profile for Range Top

In order to compare specific performance characteristics of the Range Top for the different test gases on a single chart, experimental values for each test gas were taken as the average for the last minute before the burner began to cycle. These values should be similar to the values used in ANSI Z83.11 for determining the performance of the appliance. Below are figures for Firing Rate, Carbon Monoxide emissions (CO), Nitrogen Oxide emissions (NO_x) and Total Hydrocarbon as a function of a Wobbe ratio. The Wobbe ratio for each data point is the Wobbe value for the test gas divided by the Wobbe value for test A2, which was chosen as the baseline gas for data calculations. The CO and NO_x emissions values are corrected to 0% oxygen or to an air free value thus standardizing the values to remove dilution due to variations in excess air in the flue. Total Hydrocarbon is a measurement in ppm (parts per million) of the total amount of hydrocarbons or fuel that was not consumed in the combustion process. For a process with complete combustion, the Total Hydrocarbon should be near 0 ppm.

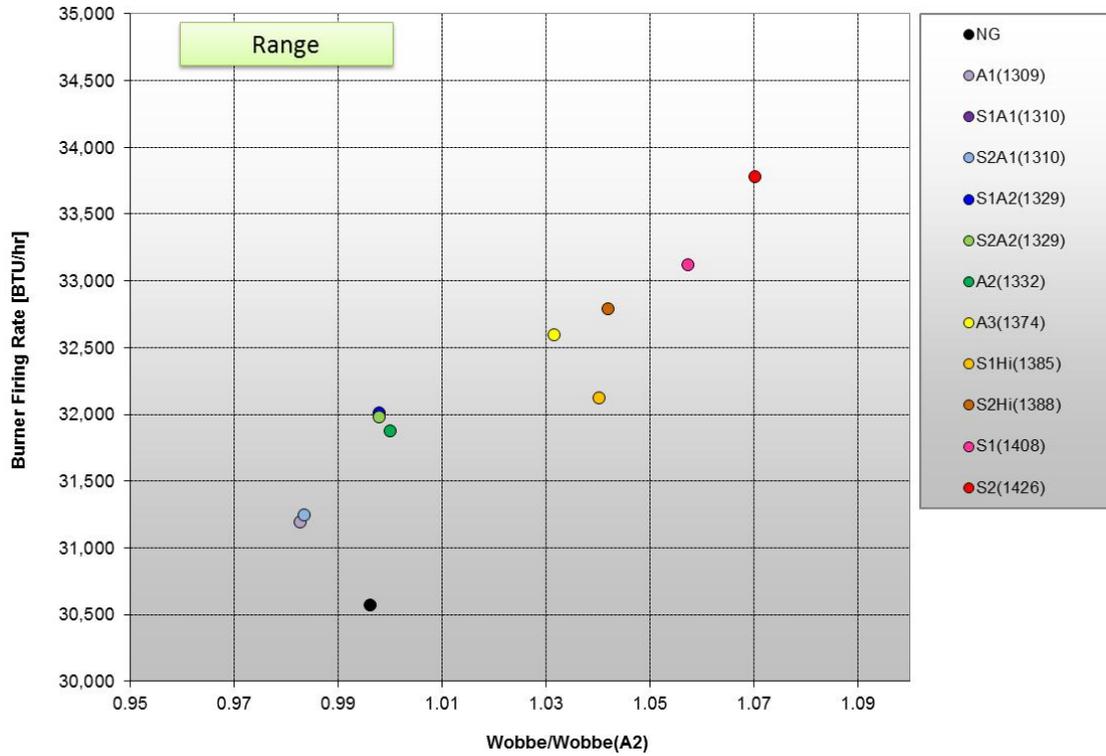


Figure 49. Range Top Firing Rate vs. Wobbe Ratio

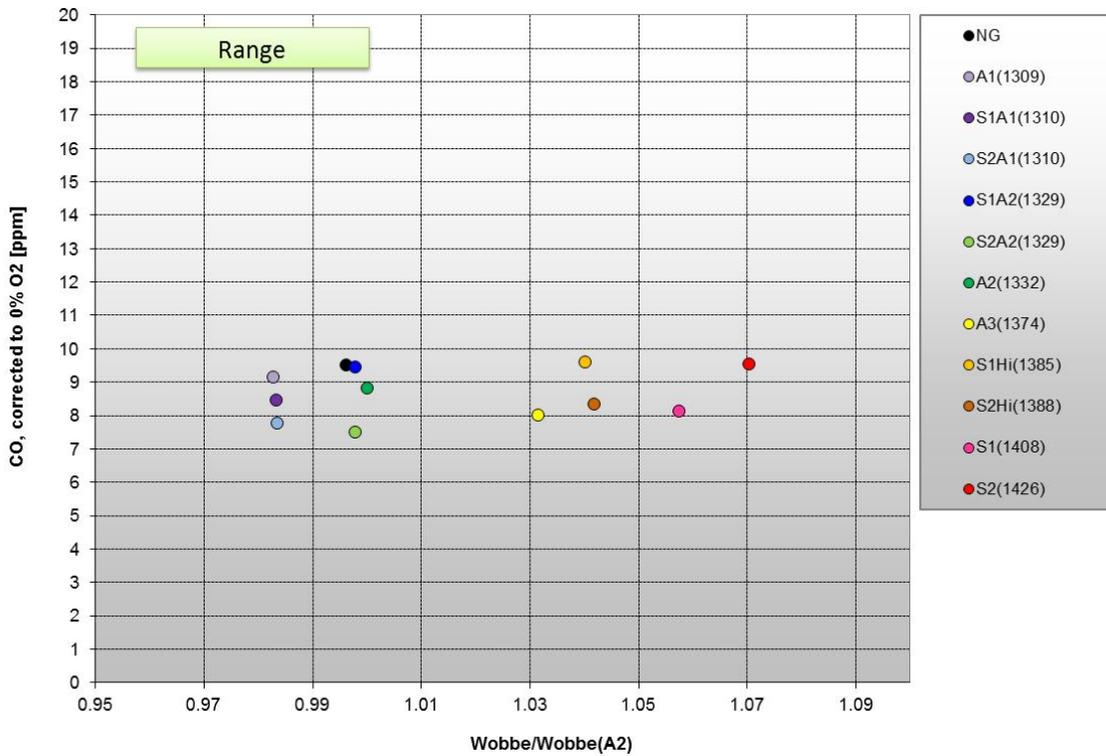


Figure 50. Range Top CO Emission vs. Wobbe Ratio

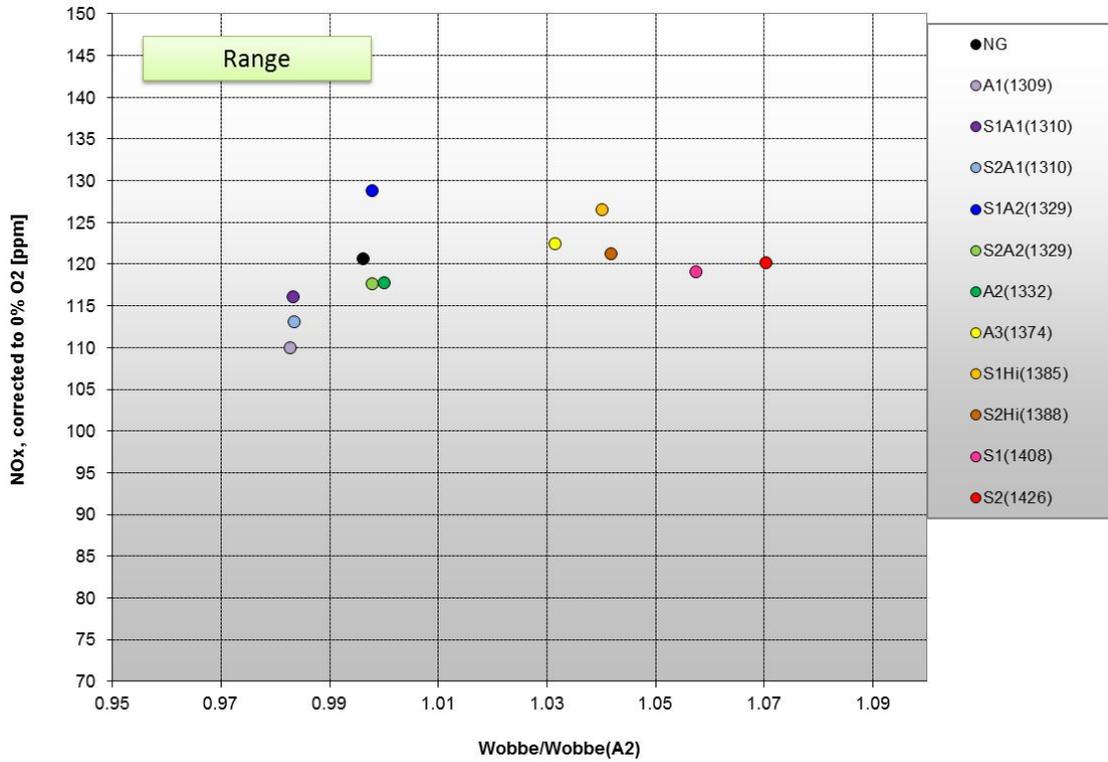


Figure 51. Range Top NOx Emission vs. Wobbe Ratio

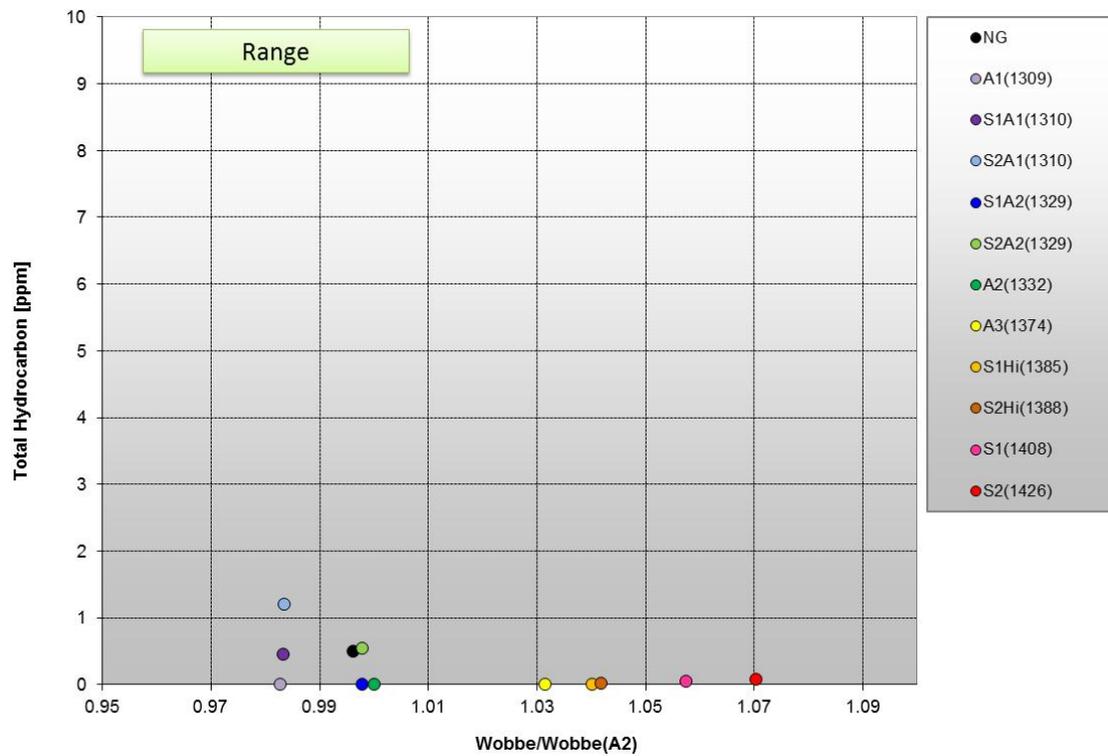


Figure 52. Range Top Total Hydrocarbon Emission vs. Wobbe Ratio

Visual Data

The Range Top offered the best view of the flame during testing. For each test gas, images and videos were taken of the flame. Previous interchangeability testing has shown that yellowing of this type flame is usually, but not always, associated with increases in CO production. Figure 53 shows some images taken of the Range Top flame for four different test gases.

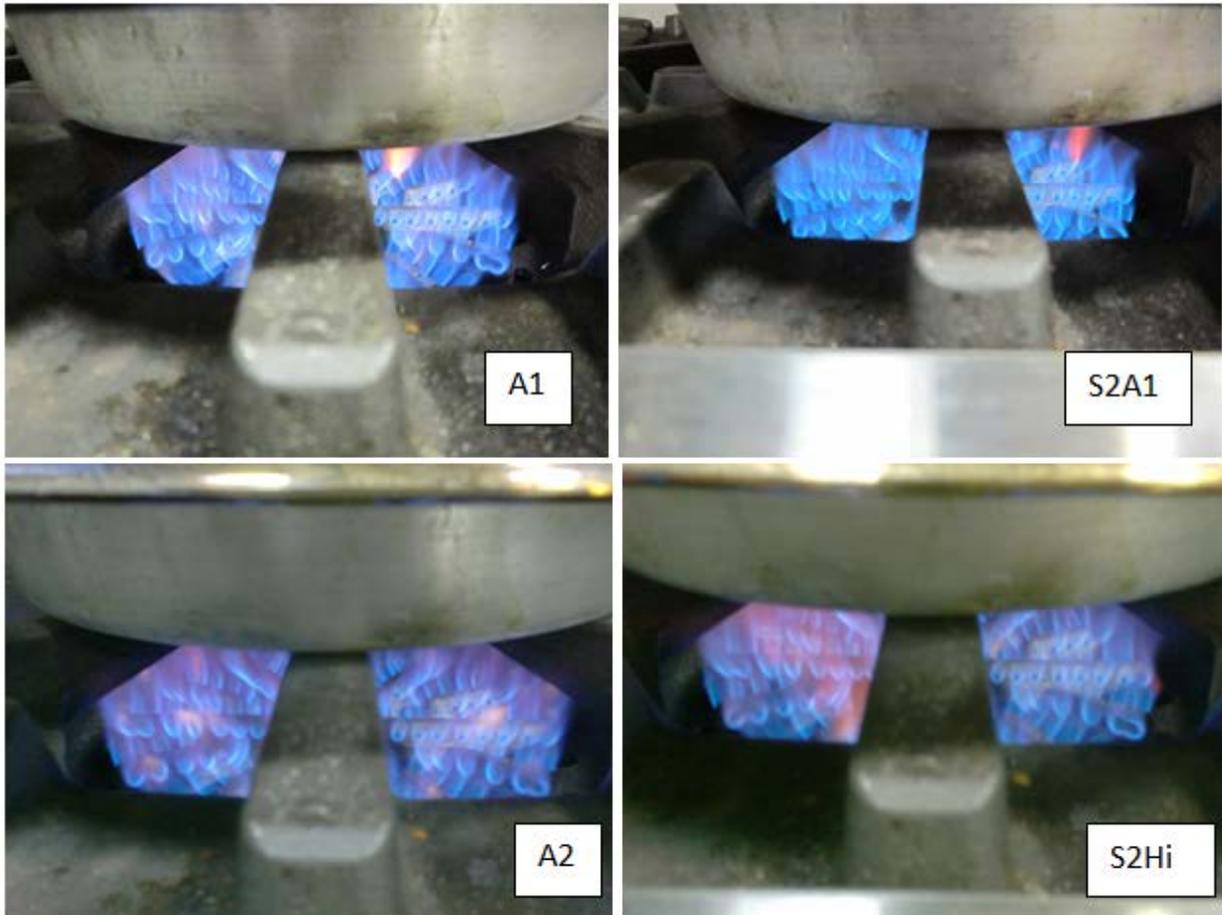


Figure 53. Range Top Flame Images

The images and the videos taken for the same test gases confirm that the flame showed some yellowing with a slight increase in flame volume and flame finger length for the higher Wobbe gases. Some increase in the yellowing was also observed for the pilot flames as shown in Figure 54.

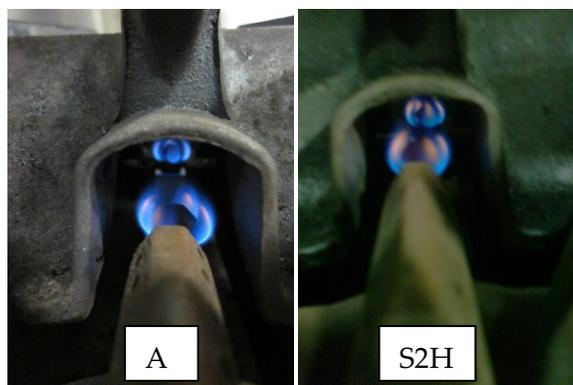


Figure 54. Range Top Pilot Lights

Analysis and Conclusions

The results for the Range Top burner showed that increasing the Wobbe number of the fuel led to some changes in terms of burner performance and appearance. The firing rate for the oven burner steadily increased from about 32,000 to just below 34,000 for the range of the Wobbe ratio, Figure 49, with one the GTI house natural gas value being in error. The scatter in the data is consistent with the accuracy of the total gas usage measured using the gas flow meter. CO remained constant within values of 7 and 10 ppm for the range of Wobbe ratios, Figure 50. All of the values for CO were well under the 800 ppm, corrected limited mandated by ANSI Z83. Figure 51 shows a slight increase for the corrected NO_x, but with the values staying between 110 and 130 ppm for all of the gases tested. The Total Hydrocarbons in Figure 52 stayed consistently less than 2 ppm indicating that complete combustion was occurring.

The yellowing of the flames in Figure 54 could suggest that the burner was not completing the combustion process for the higher Wobbe gases; however, the CO and Total Hydrocarbon values indicate otherwise. This result suggests that increasing the heat content of the gas did give longer and yellower flames, but sufficient secondary air was available to complete the combustion process. This result has been observed for other range type burners by GTI.

Based on the results in the figures and despite some small changes in performance, the Range Top was able to operate over the entire range of test gases without increases in emissions to be out of compliance with the standards set in ANSI Z83.

Results for Fryer2

One of the two fryers tested (Fryer2) was a Pitco SG14R, Figure 55, with a faceplate firing rate of 122,000 BTU/hr.



Figure 55. Fryer2

The burner is the Soltice burner that is an atmospheric burner with a mesh face. The burner is oriented such that the gas is fed from the orifices above the burner face. Figure 56 shows the burners and pilot during testing.

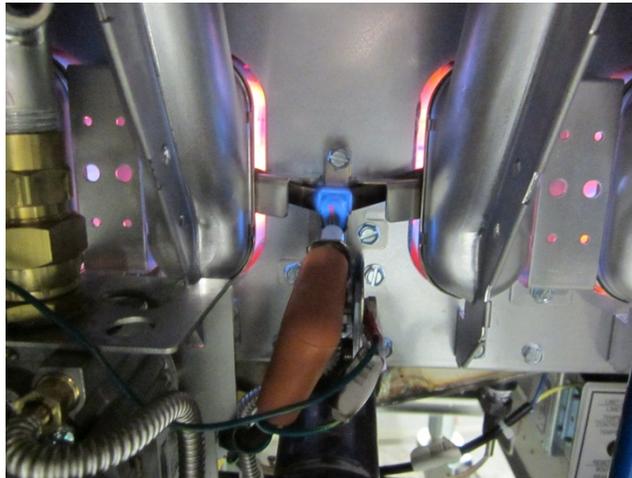


Figure 56. Fryer2 Burner System

Data was acquired using a flue gas sampling tube with evenly spaced sampling ports and thermocouples positioned in the flue along the back of the unit as shown in Figure 57. Water temperature was also recorded in the middle of the vat.

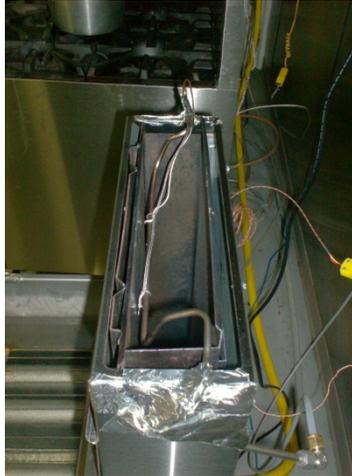


Figure 57. Flue Sample for Fryer2

Testing and Results

Fryer2 was tested from a cold start with the thermostat set to 350 °F with water in the vat filled to the max fill line. Data was continuously collected until water temperature reached 212 °F. Figure 58 and Figure 59 give the transient profiles for the temperatures and emissions of the fryer using test gas A2. The temperature profile shows a rapid increase in flue temperatures and a steady increase in the water temperature until it reaches boiling at just past 9 minutes on the chart. These profiles are typical in shape and performance of the other test gases.

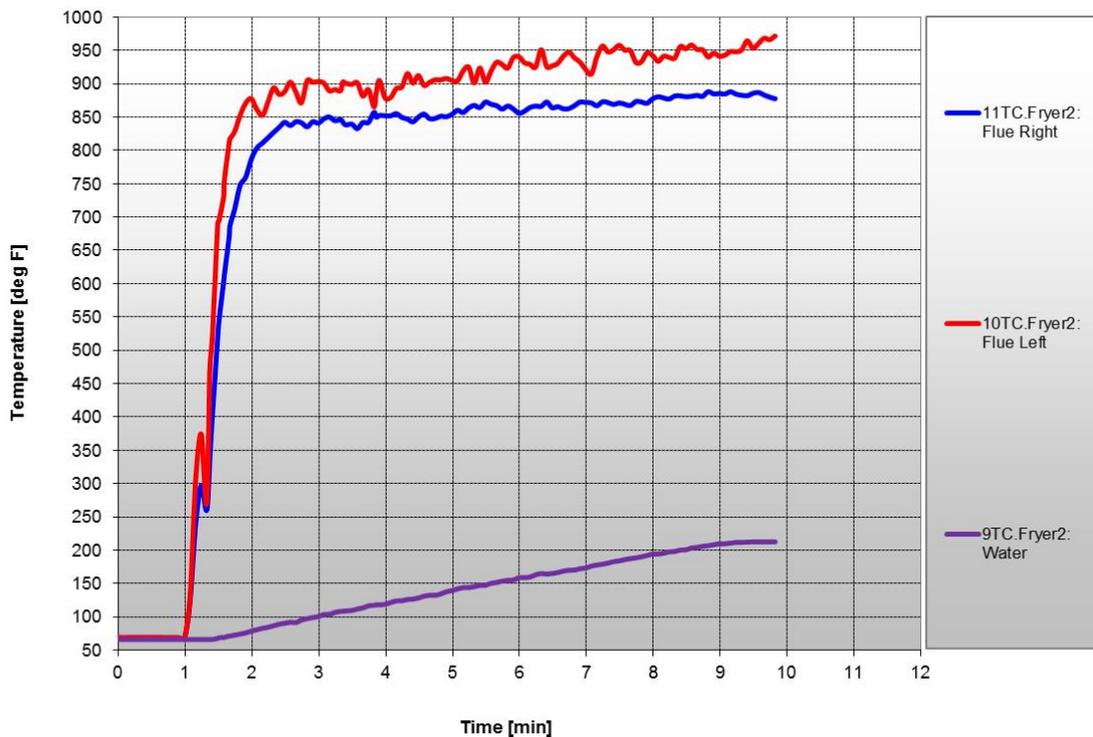


Figure 58. Transient Temperature Profile for Fryer2

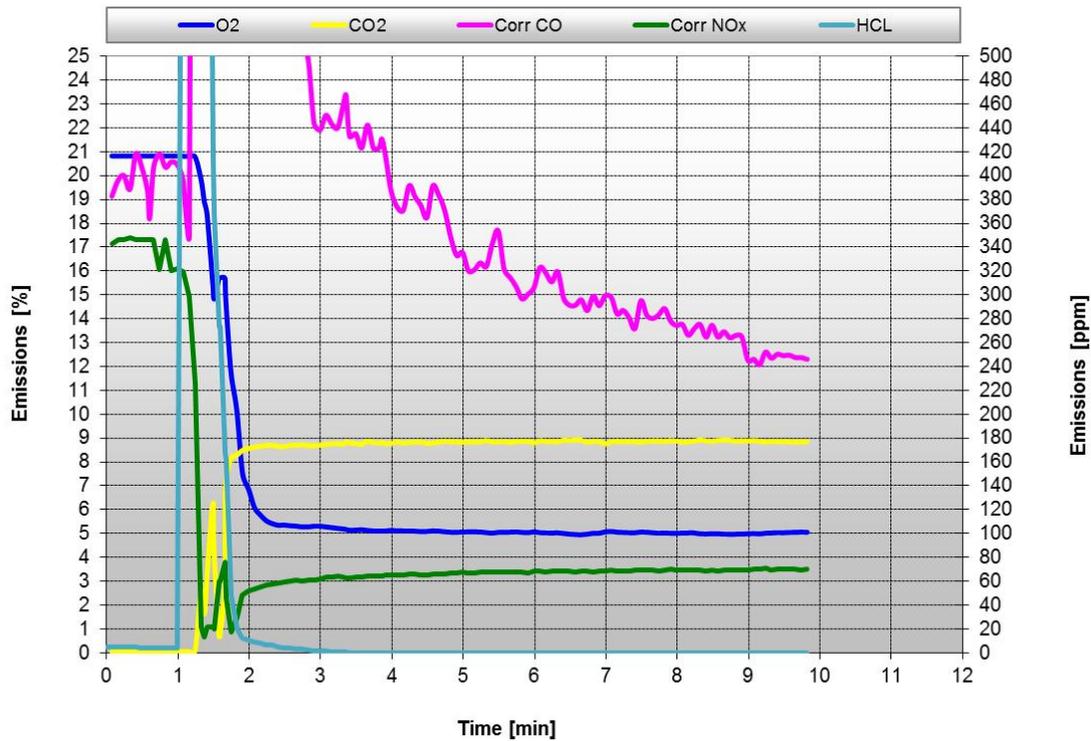


Figure 59. Transient Emissions Profile for Fryer2

After the initial CO spike associated with most gas-fired appliances, the correct CO value steadily decreased as the unit warmed up while the other emissions values reached steady state.

In order to compare specific performance characteristics of the fryer for the different test gases on a single chart, experimental values for each test gas were taken as the average for the last minute before the end of the test. These values should be similar to the values used in ANSI Z83.11 for determining the performance of the appliance. Below are figures for Firing Rate, Carbon Monoxide emissions (CO), Nitrogen Oxide emissions (NO_x) and Total Hydrocarbon as a function of a Wobbe ratio. The Wobbe ratio for each data point is the Wobbe value for the test gas divided by the Wobbe value for test A2, which was chosen as the baseline gas for data calculations. The CO and NO_x emissions values are corrected to 0% oxygen or to an air free value thus standardizing the values to remove dilution due to variations in excess air in the flue. Total Hydrocarbon is a measurement in ppm (parts per million) of the total amount of hydrocarbons or fuel that was not consumed in the combustion process. For a process with complete combustion, the Total Hydrocarbon should be near 0 ppm.

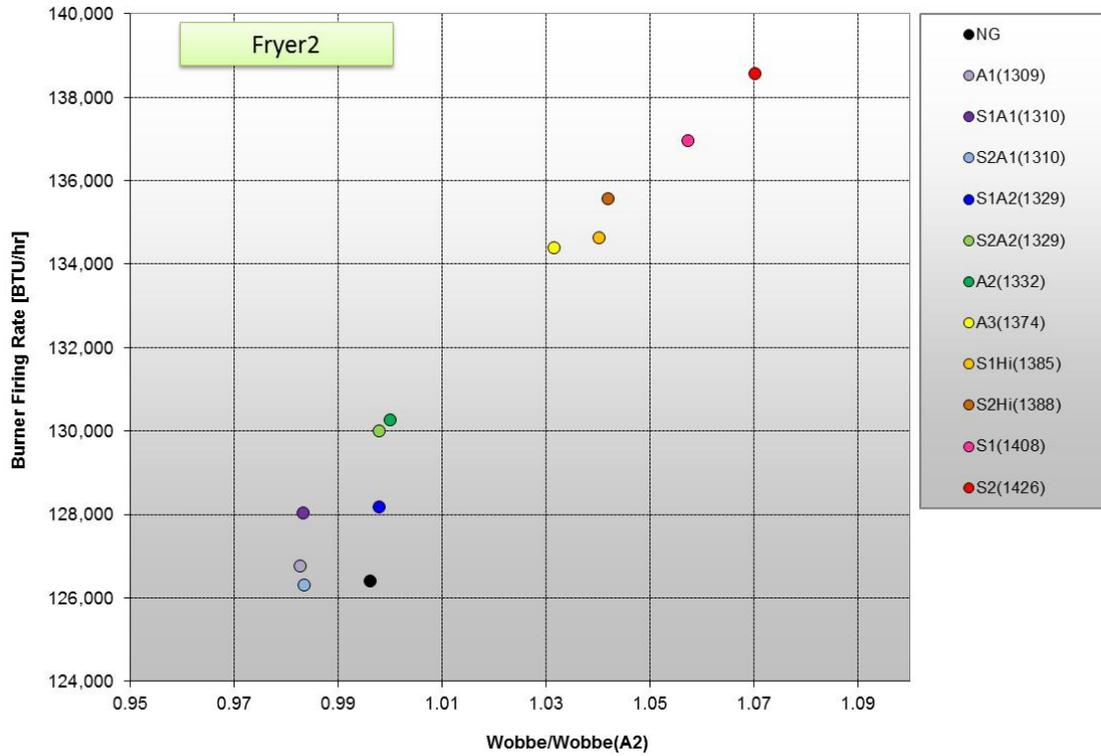


Figure 60. Fryer2 Firing Rate vs. Wobbe Ratio

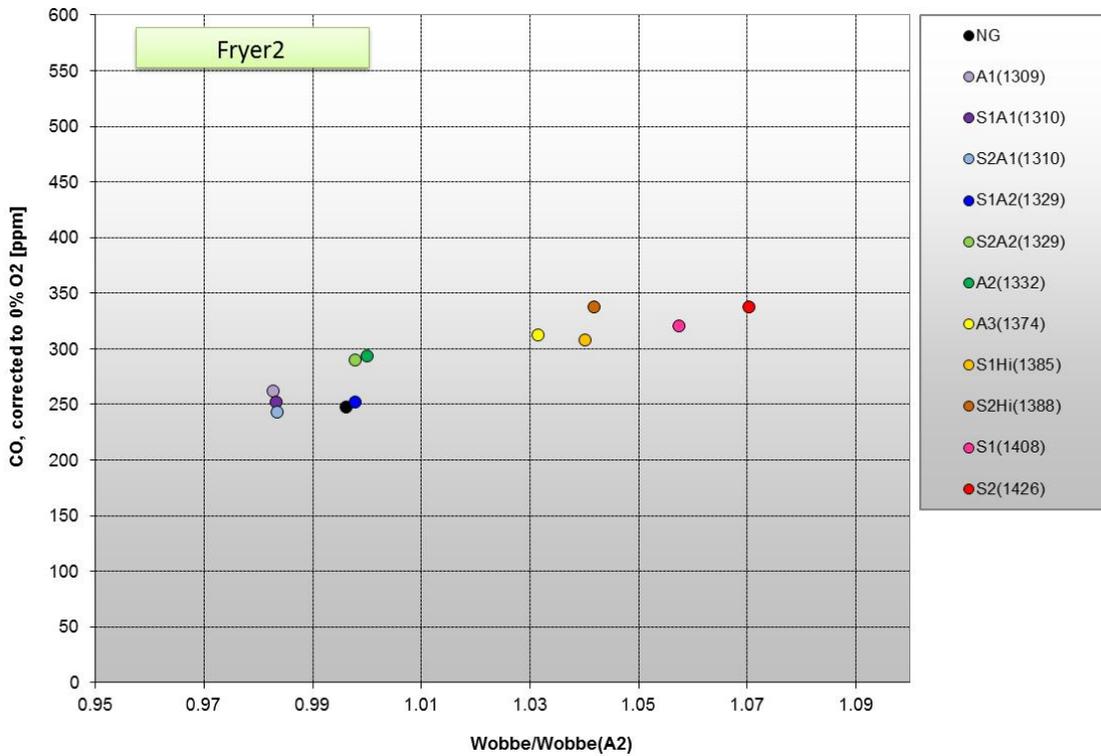


Figure 61. Fryer2 CO Emission vs. Wobbe Ratio

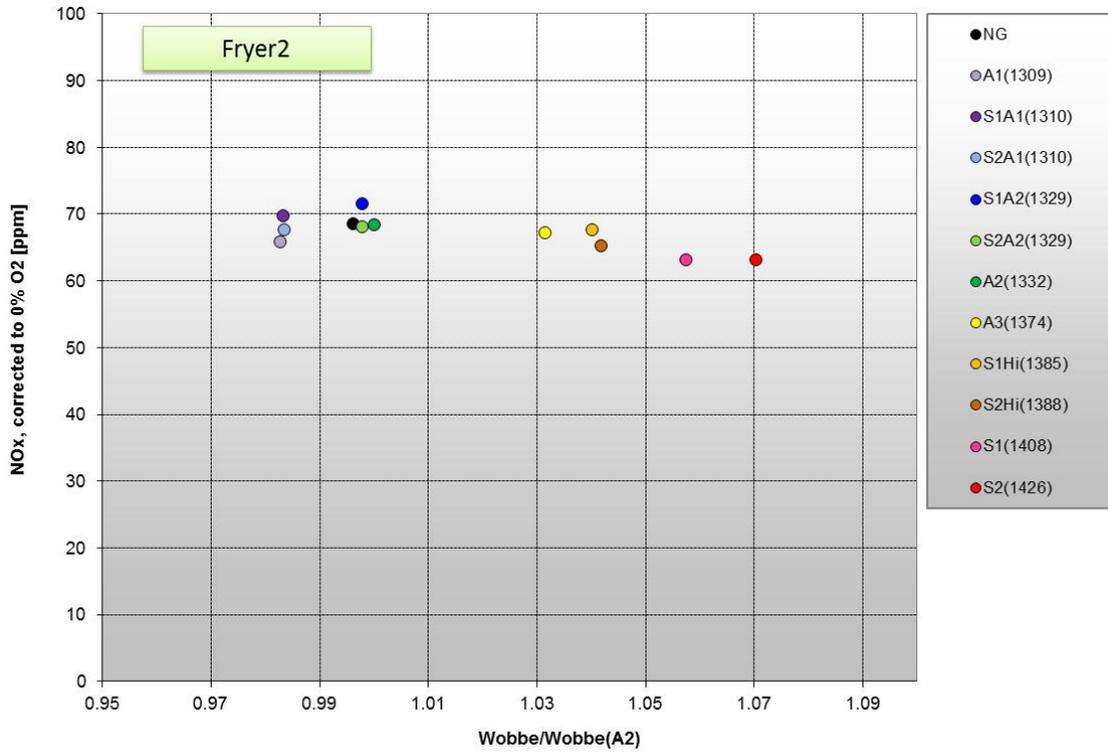


Figure 62. Fryer2 NOx Emission vs. Wobbe Ratio

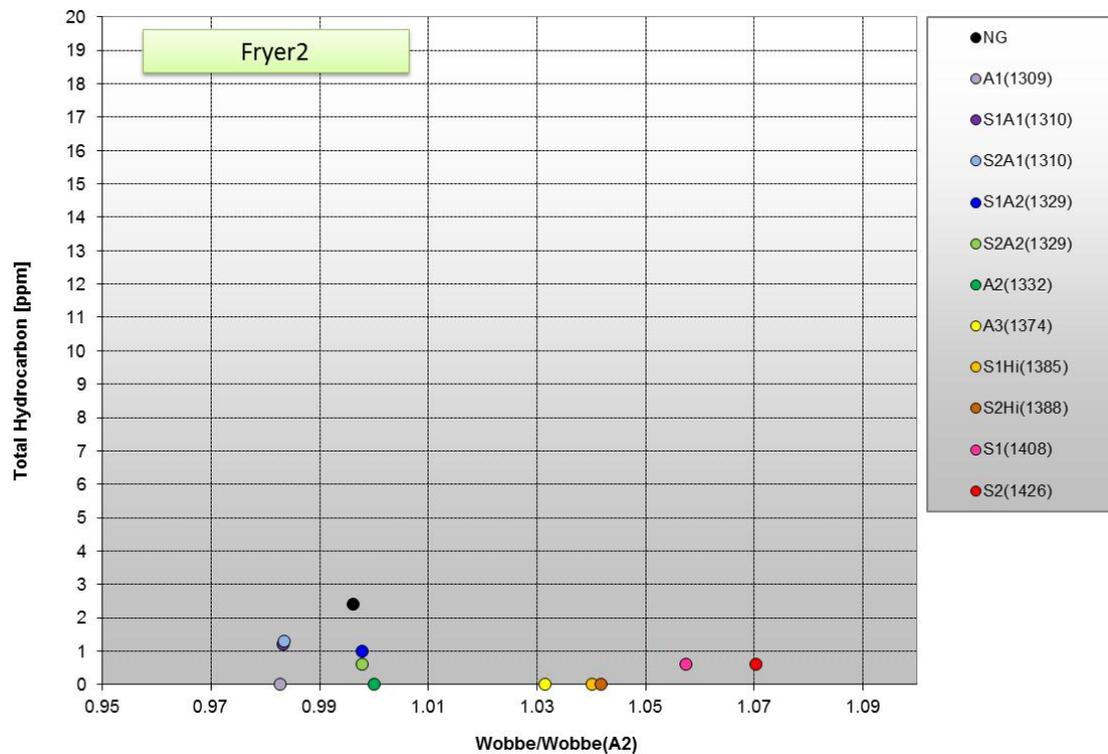


Figure 63. Fryer2 Total Hydrocarbon Emission vs. Wobbe Ratio

Visual Data

Fryer2 offered a limited view of the flame during testing, but some images were still taken. Figure 64 shows images taken of the fryer flame for two different test gases, A1 and S1Hi.

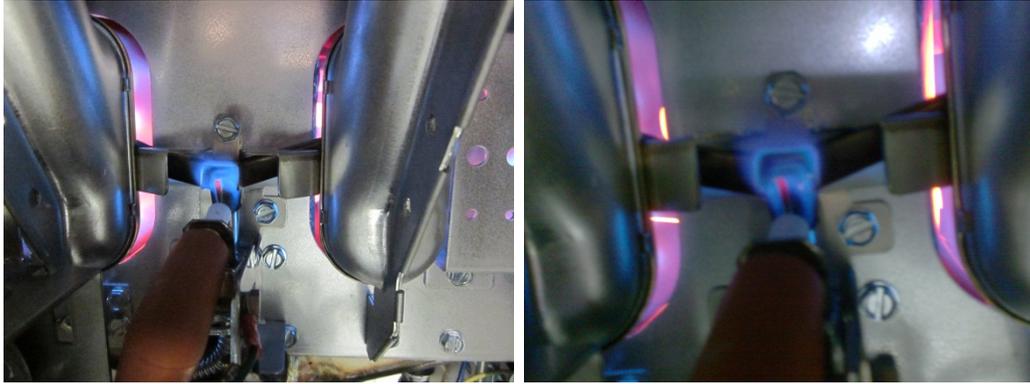


Figure 64. Fryer2 Flame Images (A1 and S1Hi)

The images and the videos taken did not show any significant changes in flame appearance for the entire set of gases tested.

Analysis and Conclusions

As Figure 59 shows, the emissions results were relatively steady for the final minute before the burner began to cycle, except for the corrected CO, which was slowly decreasing. The firing rate for the fryer burner steadily increased from about 126,000 to 139,000 for the range of the Wobbe ratio, Figure 60. The scatter in the data is consistent with the accuracy of the total gas usage measured using the gas flow meter. CO data also exhibited a near linear increase over the range of Wobbe ratio, Figure 61, starting at close to 250 ppm and increasing to a maximum of near 350 ppm. All of the values for CO were well under the 800 ppm, corrected limit mandated by ANSI Z83. Figure 62 shows the corrected NO_x values were around 68 ppm for the entire range of testing showing a slight decrease at the higher Wobbe values. Hydrocarbons in Figure 63 stayed consistently at less than 3 ppm indicating that complete combustion was occurring. These results would agree with the lack of change in the flames' appearances in Figure 64.

Based on the results in the figures and despite some small changes in performance, Fryer2 was able to operate over the entire range of test gases without increases in emissions to be out of compliance with the standards set in ANSI Z83.

Results for Steamer

The Steamer tested was the Accutemp Evolution Steamer, Figure 65, with a faceplate firing rate of 60,000 BTU/hr.



Figure 65. Steamer

The stainless steel, powered blue flame burner produces steam from volume of water at the bottom of the cook chamber shown in Figure 66.



Figure 66. Steamer Cook Chamber

Water and cooking chamber temperatures were recorded as shown in Figure 66. Combustion data was acquired using a flue gas sampling tube with evenly spaced sampling ports and thermocouples positioned in the flue along the back of the unit, as shown in Figure 67.



Figure 67. Flue Sample for Steamer

Testing and Results

The Steamer was tested from a cold start with room temperature water and ran until the unit switched from “Preheat” to “Cook” mode. Figure 68 and Figure 69 give the transient profiles for the temperatures and emissions of the Steamer using test gas A2.

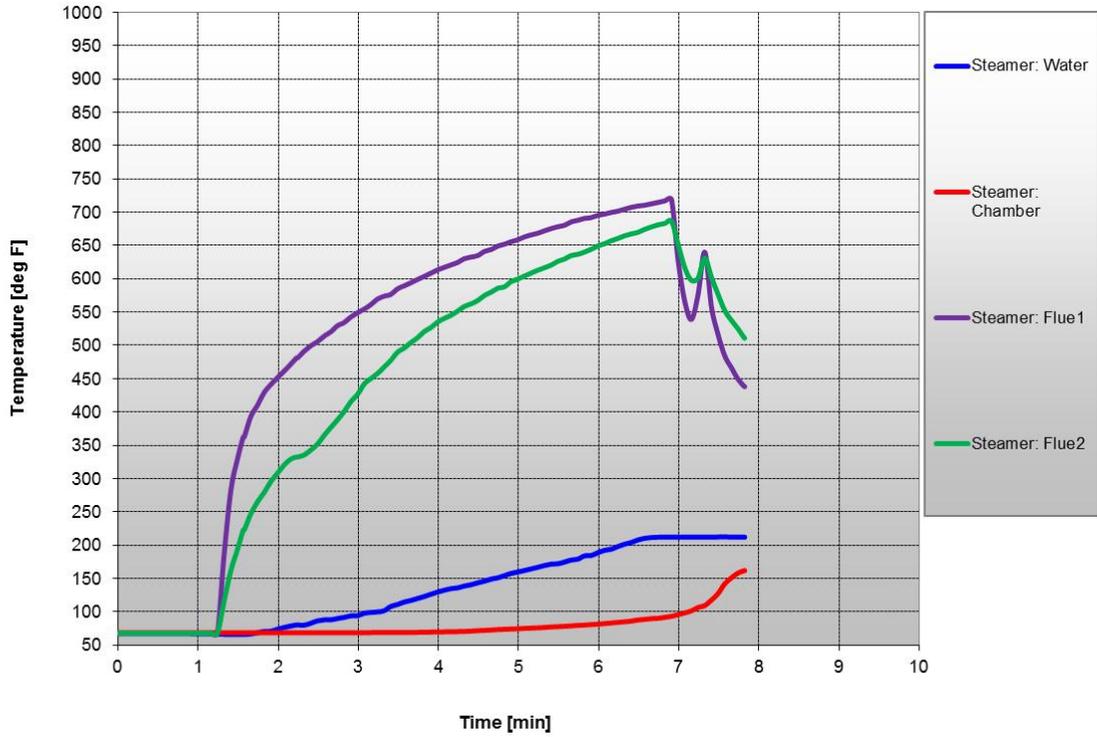


Figure 68. Transient Temperature Profile for Steamer

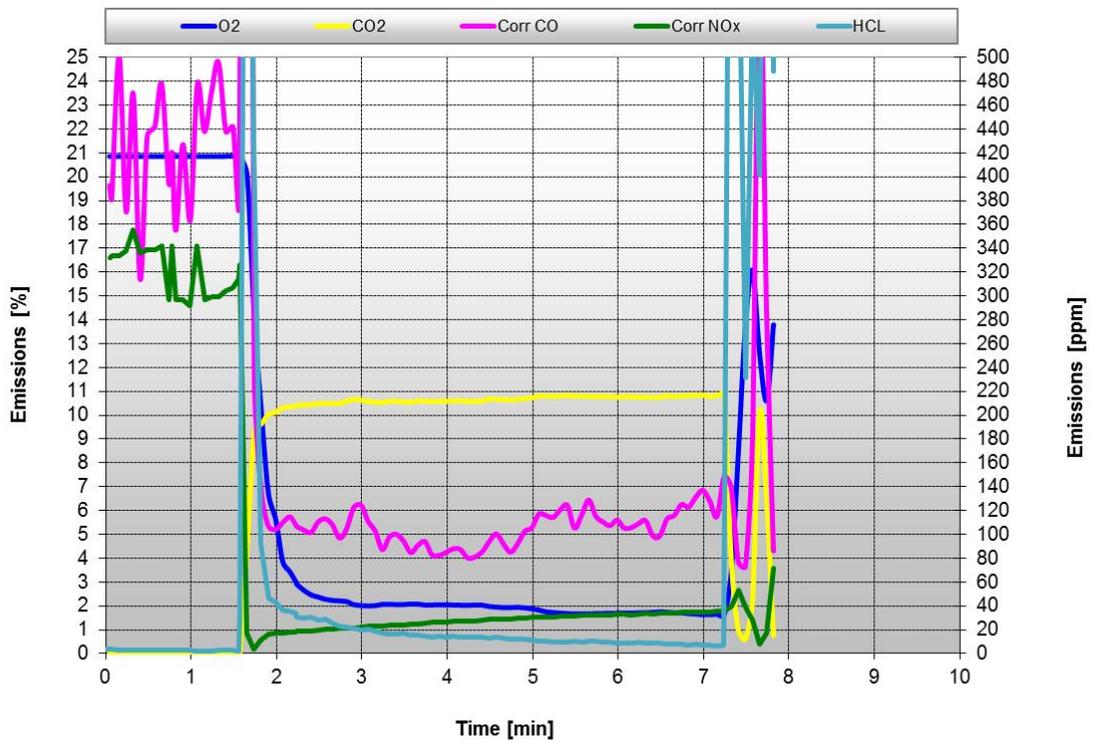


Figure 69. Transient Emissions Profile for Steamer

The burner begins to cycle (at about 7 minutes) before “Cook” mode is indicated (at about 8 minutes). The temperature profile shows a steady increase in flue and water temperature for the entire test. This profile is typical in shape and performance of the other test gases. As Figure 4 shows, the Steamer reached relatively steady emissions values by the end of the test. After the initial spike associated with most gas-fired appliances, the corrected CO varied some, but averaged about 120 ppm by the end of the test. This behavior for the emissions values was observed for all the gases tested, but the final values varied for different test gases, especially CO.

In order to compare specific performance characteristics of the Steamer for the different test gases on a single chart, experimental values for each test gas was taken as the average for the last minute before the burner began to cycle. These values should be similar to the values used in ANSI Z83.11 for determining the performance of the appliance. Below are figures for Firing Rate, Carbon Monoxide emissions (CO), Nitrogen Oxide emissions (NO_x) and Total Hydrocarbon as a function of a Wobbe ratio. The Wobbe ratio is the Wobbe value for the test gas divided by the Wobbe value for test A2, which was chosen as the baseline gas for data calculations. The CO and NO_x emissions values are corrected to 0% oxygen or to an air free value thus standardizing the values to remove dilution due to variations in excess air in the flue. Total Hydrocarbon is a measurement in ppm (parts per million) of the total amount of hydrocarbons or fuel that was not consumed in the combustion process. For a process with complete combustion, the Total Hydrocarbons should be near 0 ppm.

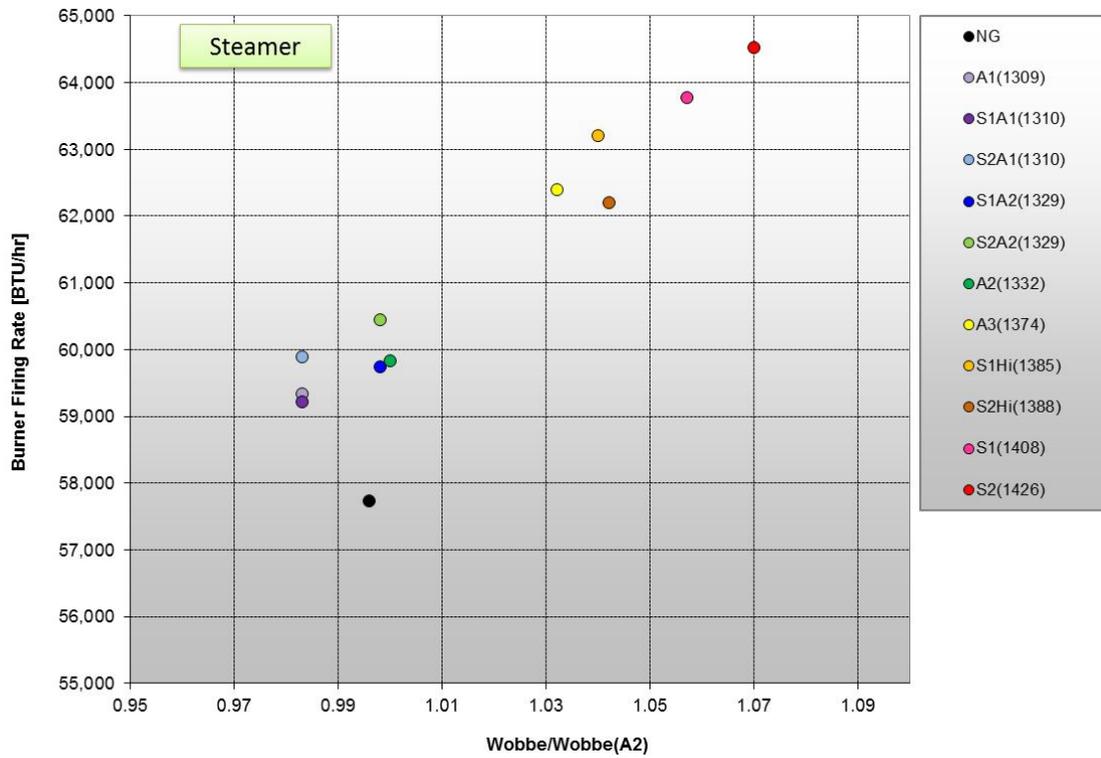


Figure 70. Steamer Firing Rate vs. Wobbe Ratio

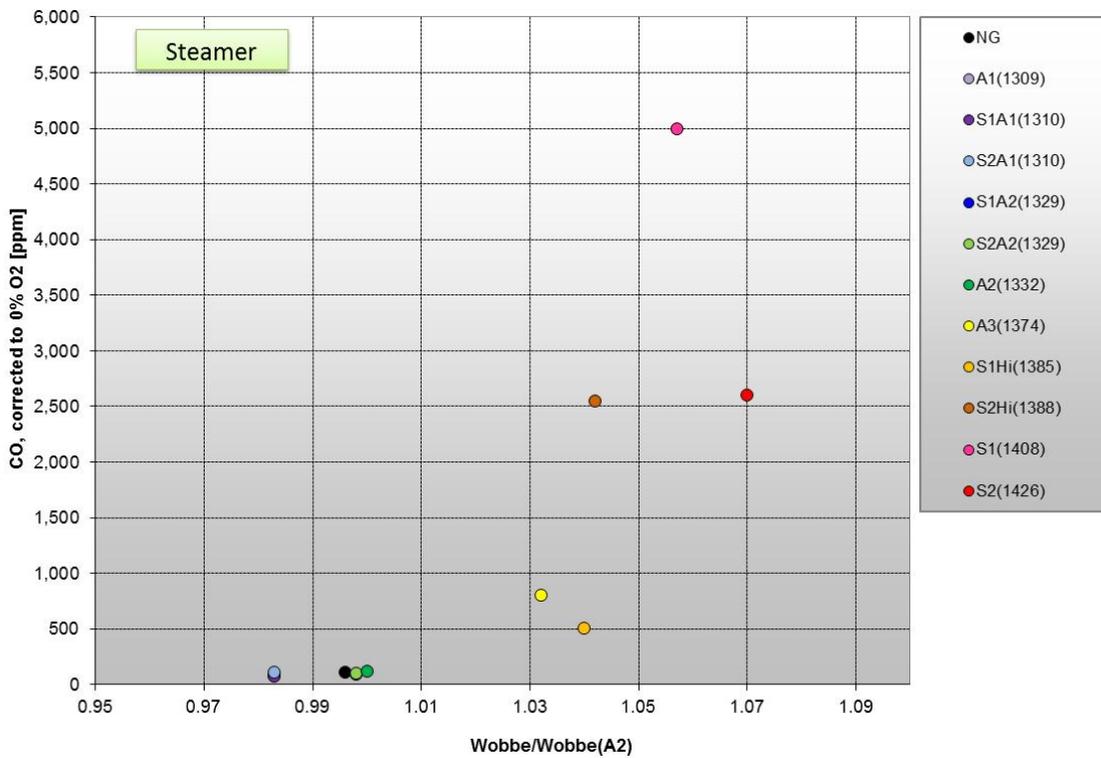


Figure 71. Steamer CO Emission vs. Wobbe Ratio

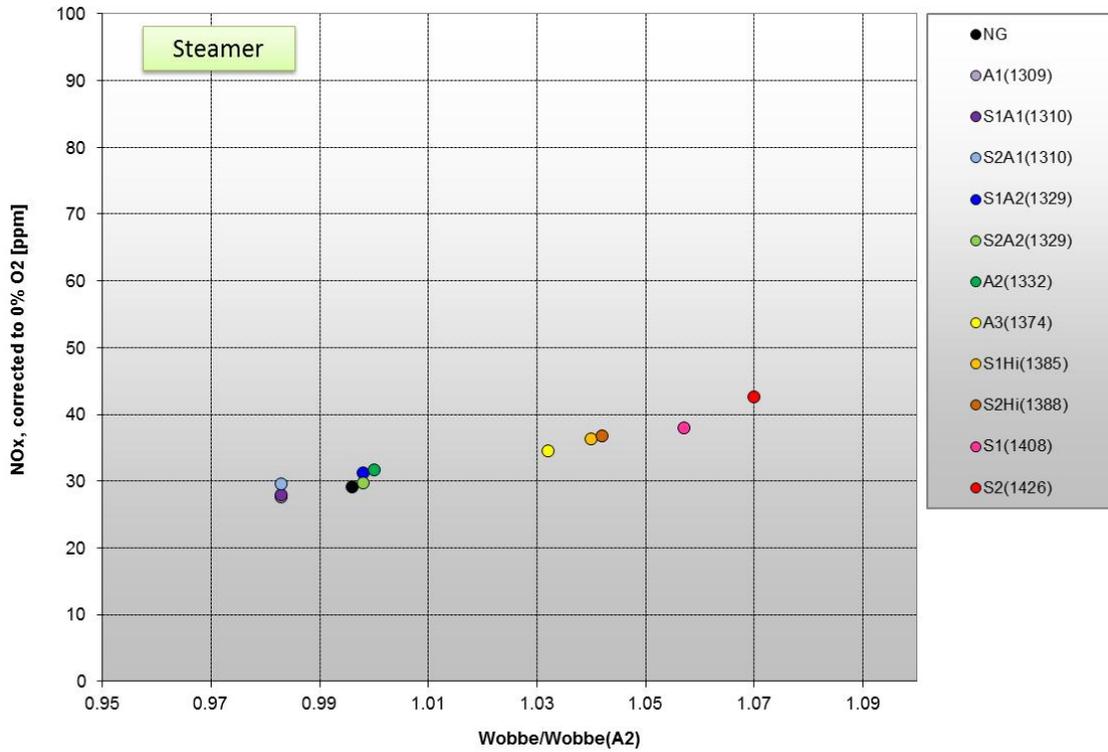


Figure 72. Steamer NOx Emission vs. Wobbe Ratio

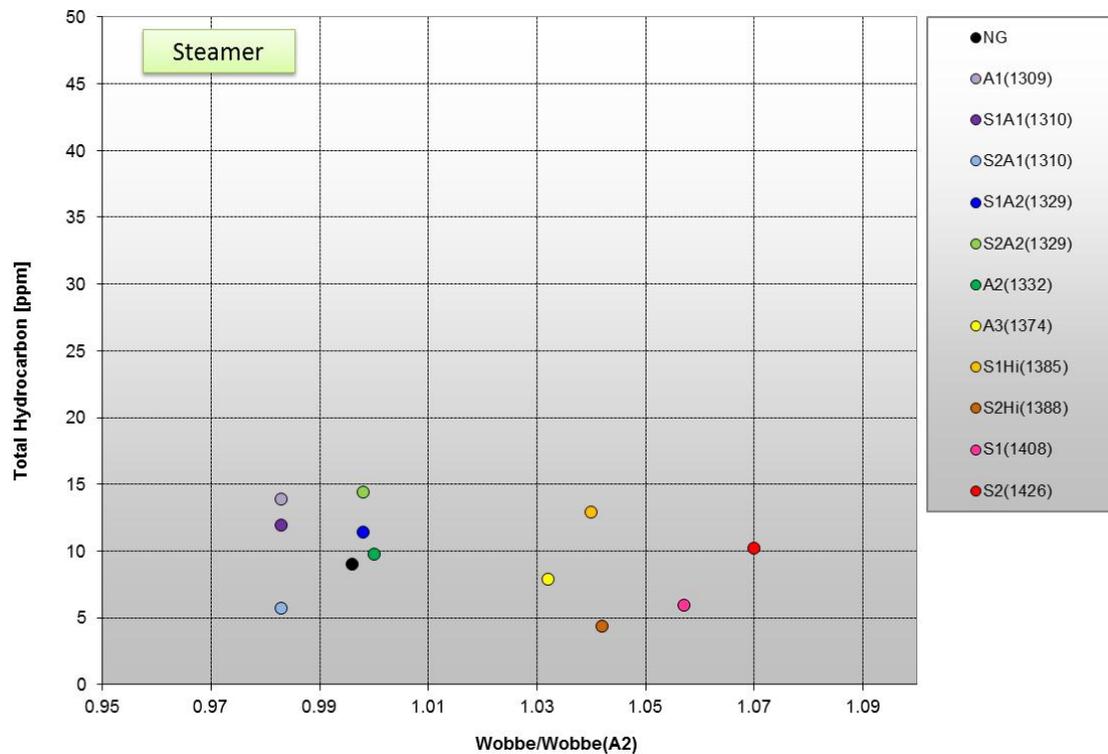


Figure 73. Steamer Total Hydrocarbon Emission vs. Wobbe Ratio

Analysis and Conclusions

The results for the Steamer showed that increasing the Wobbe number of the fuel led to significant changes in terms of burner performance. The firing rate for the burner steadily increased from about 59,000 to just over 64,000 for the range of the Wobbe ratio, Figure 70. The scatter in the data is consistent with the accuracy of the total gas usage measured using the gas flow meter, except the value for house natural gas (NG). It is expected a miscount of the pulses from the flowmeter occurred or the measured heat content was different from the sample that was taken a few days before testing.

The corrected CO results in Figure 71 show that the burner has significant issues at the higher Wobbe gases. The corrected CO value were consistently around 100 ppm for Wobbe less than 1350, but dramatically increased with increased Wobbe values. The CO increased to over 500 ppm for Wobbe equal to 1374 and 1385 and to over 2,000 ppm for Wobbe greater than 1388. Because of the calibration range used for the CO analyzers, the accuracy of values is very low over 2,000 ppm, but the values are definitely greater than the 800 ppm allowed by ANSI Z83 for combustion testing for steamers. The data suggests that the issue with the burner is not a quenching problem that has been observed with other tested appliances (see Oven), but an issue with available oxygen to complete combustion. Figure 69 shows that the percent oxygen in the flue is about 3% using fuels with heat content similar to typical natural gas. As the heat content of the fuel is increased, the amount of oxygen needed to complete combustion increases. If the oxygen is unavailable, the mechanism that converts CO to CO₂ in the combustion process is not completed and CO production increases.

The NO_x emissions were not as adversely affected. Figure 71 shows that the NO_x values increased from 30 ppm to just over 40 ppm. Figure 72 shows that the total hydrocarbons varied between 5 and 15 ppm for the entire range of fuels tested.

Based on the results in the figures, the Steamer was able to operate for range of test gases with Wobbe less than 1350 without increases in emissions to be out of compliance with the standards set in ANSI Z83. However, the test gases with a Wobbe greater than 1350, the CO emissions increased to levels that showed significant issues with the performance of the burner system and eventually performed to a level that would not be in compliance with standards established by ANSI.

Results for Braising Pan

The Braising Pan tested was the Groen BPM-40G, Figure 74, with a faceplate firing rate of 144,000 BTU/hr. The figure shows that the pan of the unit can be tilted for “pouring out” the product after cooking.



Figure 74. Braising Pan

The unit has a series of pierced port, tube burners under the bottom of the cooking pan. The hot flue gases travel from the burner, along the bottom surface of the pan and exit through a finned opening in the back of the unit shown in Figure 75. The burners are designed to be able brown or heat. Chili and soup are common items prepared with braising pans.



Figure 75. Braising Pan Burners



Figure 76. Braising Pan Flue Exit

Data was acquired using a flue gas sampling tube with thermocouples positioned in the flue shown in Figure 76. Water temperature was also recorded with a thermocouple positioned in the middle of the volume of water in the pan.

Testing and Results

The Braising Pan was tested from a cold start with 100 pounds of room temperature water and ran until the water temperature reached 180 °F. Figure 77 and Figure 78 give the transient profiles for the temperatures and emissions of the Braising Pan using test gas A2.

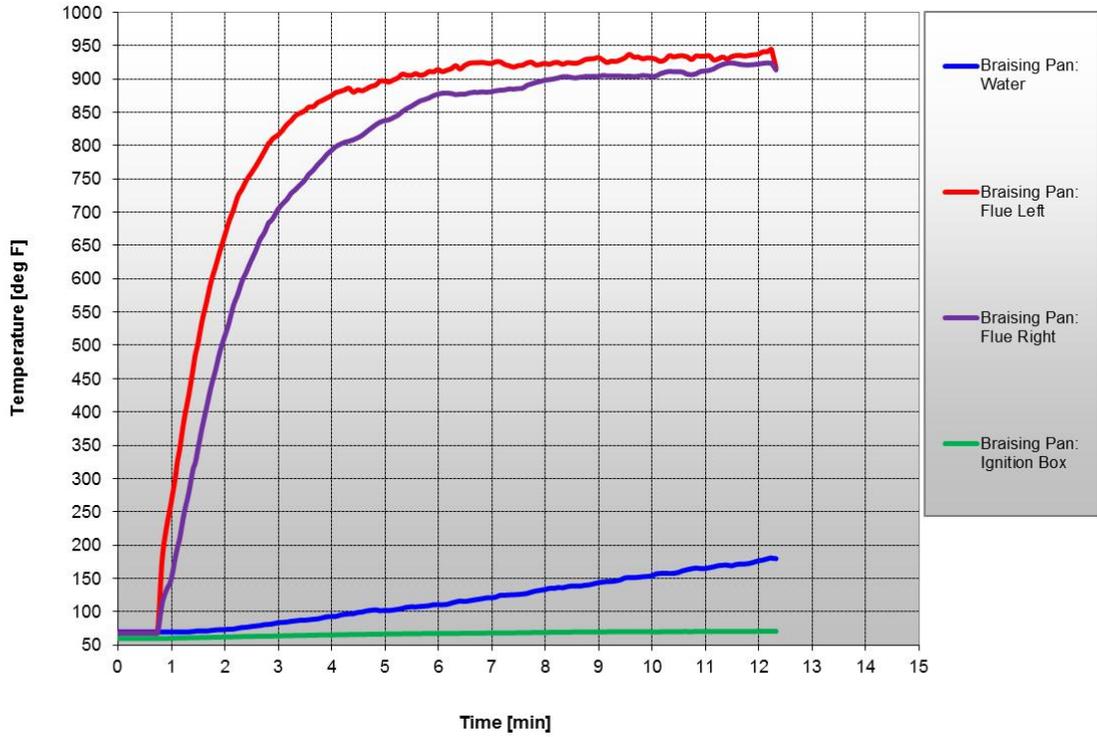


Figure 77. Transient Temperature Profile for Braising Pan

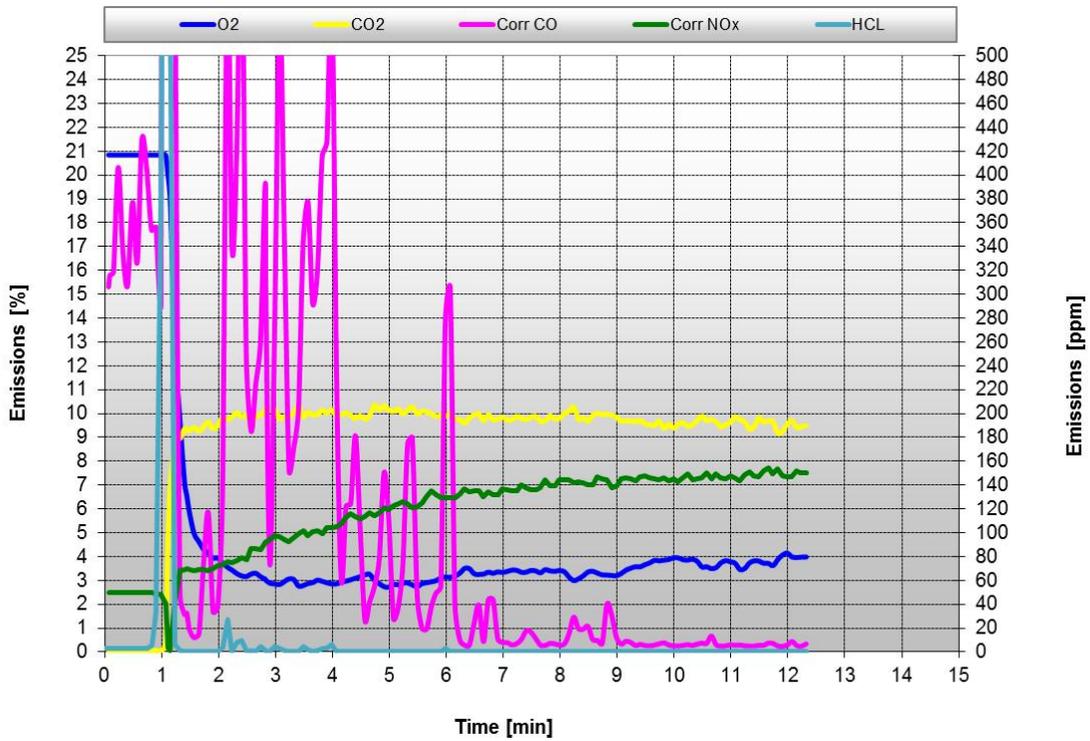


Figure 78. Transient Emissions Profile for Braising Pan

The temperature profile shows a rapid increase in flue temperature with a steady increase in water temperature for the entire test. This profile is typical in shape and performance of the other test gases.

As Figure 78 shows, the Braising Pan reached relatively steady emissions values by the end of the test. After the initial spike associated with most gas-fired appliances, the corrected CO leveled off to less than 10 ppm. The transient performance varied significantly for different test gases. The lower Wobbe gases were similar to Figure, while the for higher Wobbe gases CO values tended to vary during testing.

In order to compare specific performance characteristics of the Braising Pan for the different test gases on a single chart, experimental values for each test gas was taken as the average for the last minute before the burner began to cycle. These values should be similar to the values used in ANSI Z83.11 for determining the performance of the appliance. Below are figures for Firing Rate, Carbon Monoxide emissions (CO), Nitrogen Oxide emissions (NO_x) and Total Hydrocarbon as a function of a Wobbe ratio. The Wobbe ratio for each data point is the Wobbe value for the test gas divided by the Wobbe value for test A2, which was chosen as the baseline gas for data calculations. The CO and NO_x emissions values are corrected to 0% oxygen or to an air free value thus standardizing the values to remove dilution due to variations in excess air in the flue. Total Hydrocarbon is a measurement in ppm (parts per million) of the total amount of hydrocarbons or fuel that was not consumed in the combustion process. For a process with complete combustion, the Total Hydrocarbon should be near 0 ppm.

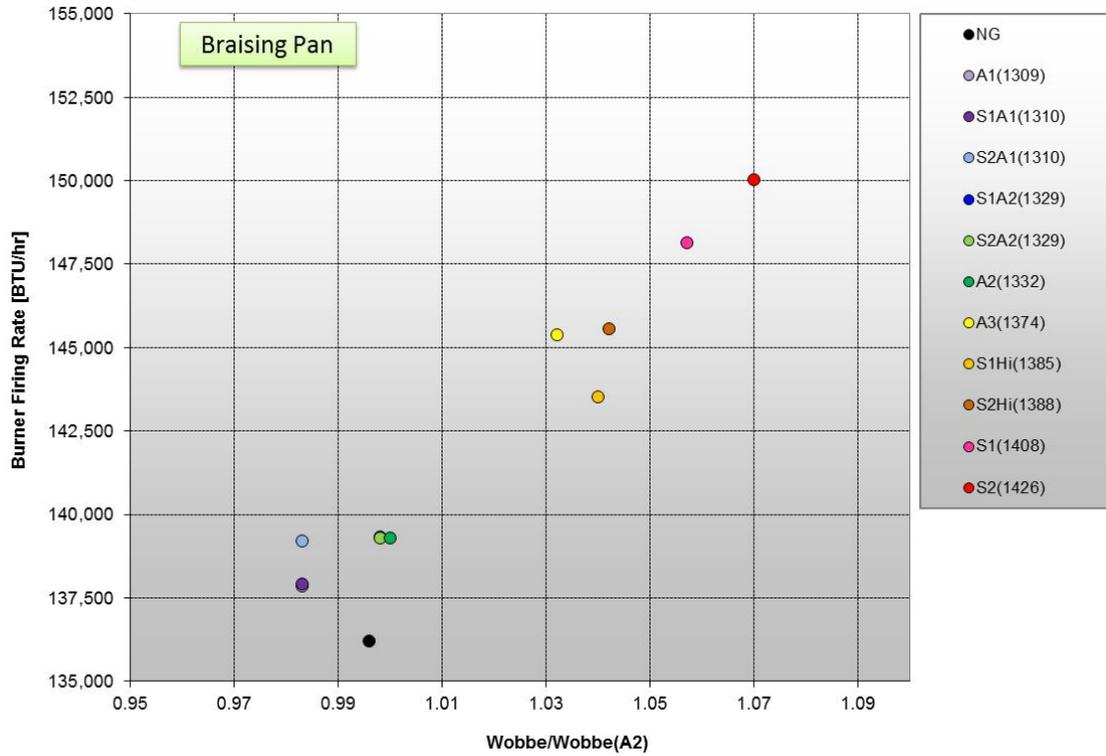


Figure 79. Braising Pan Firing Rate vs. Wobbe Ratio

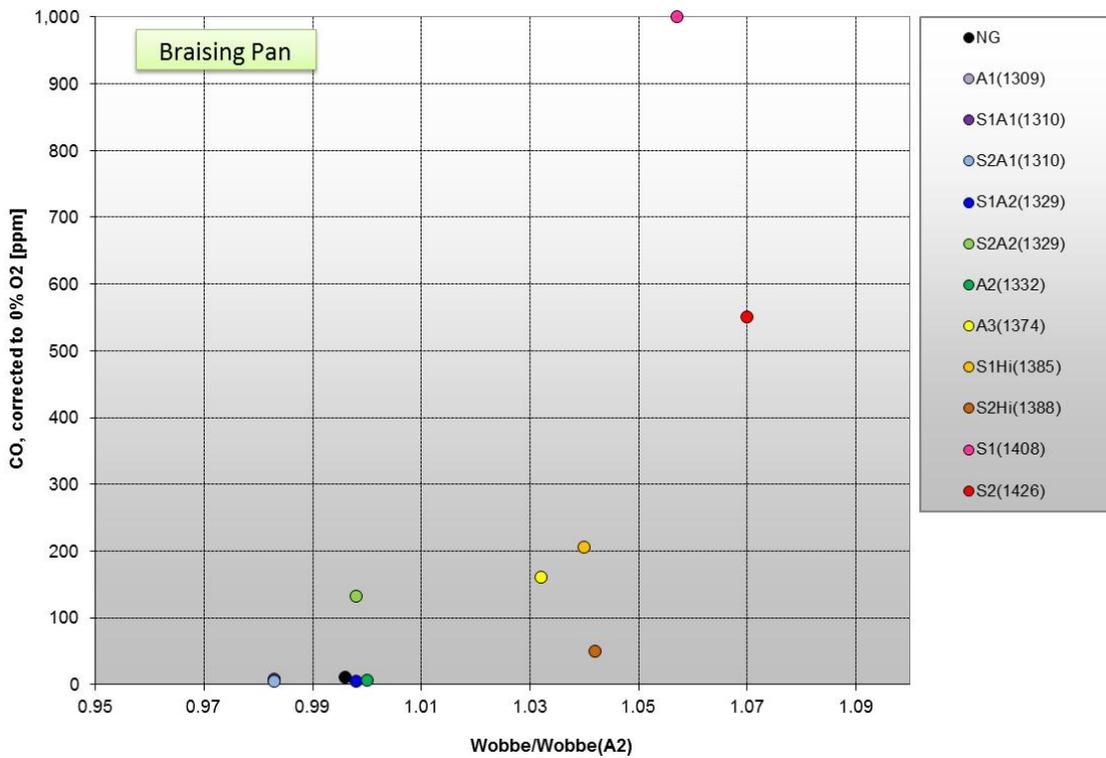


Figure 80. Braising Pan CO Emission vs. Wobbe Ratio

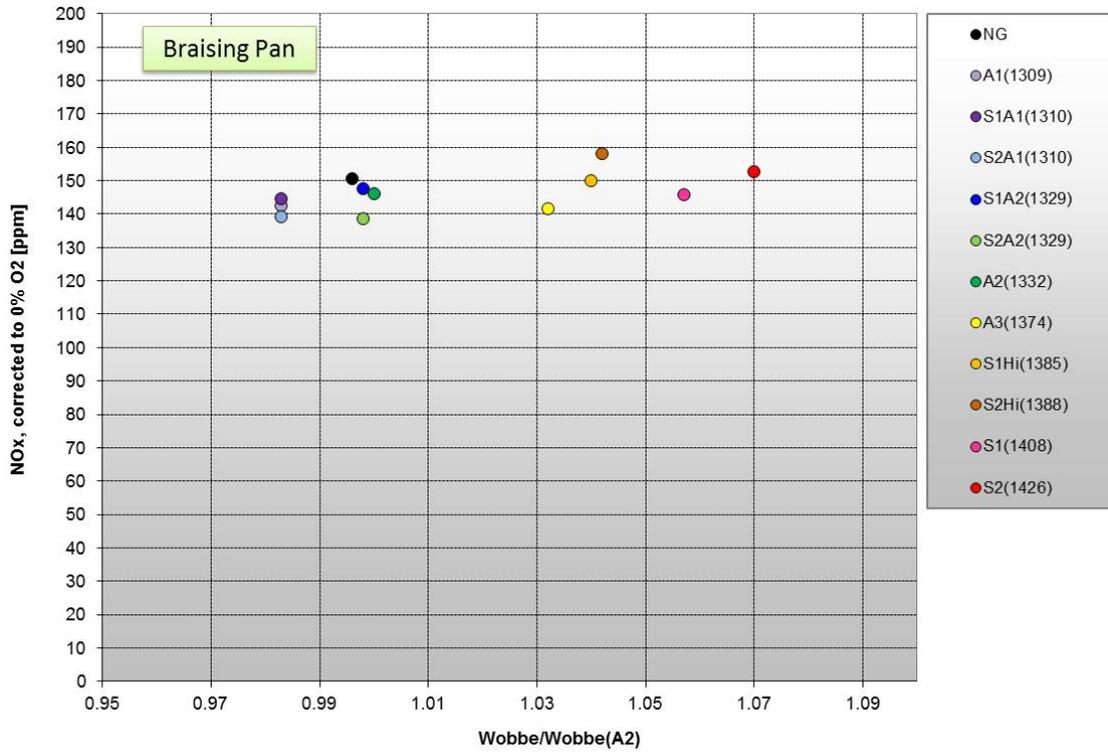


Figure 81. Braising Pan NOx Emission vs. Wobbe Ratio

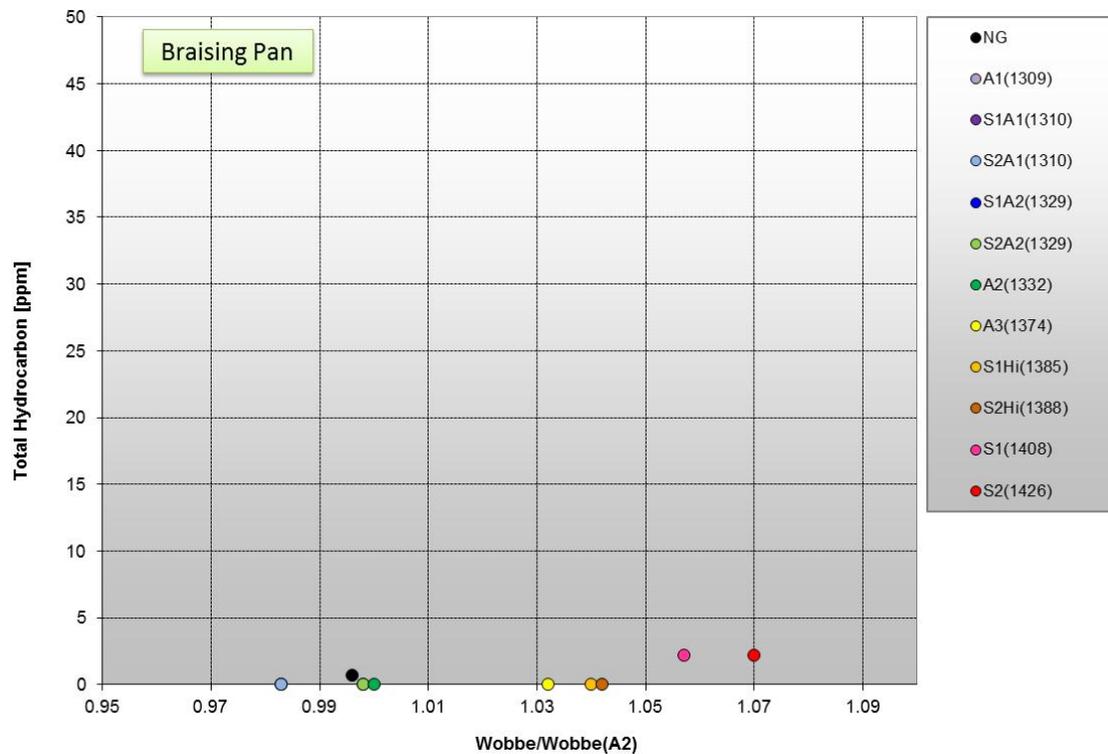


Figure 82. Braising Pan Total Hydrocarbon Emission vs. Wobbe Ratio

Visual Data

For several of the test gases, images and videos were taken of the flame from underneath the unit or through a view port on the front. As Figure 83 shows, the flames tended to yellow somewhat during testing. Visual inspection found that the percentage of the yellowing and the length of the flame were more for the higher Wobbe gases and substantially more for the test cases where the CO was the highest.



Figure 83. Braising Pan Flame Images

Analysis and Conclusions

The results for the Braising Pan showed that increasing the Wobbe number of the fuel had significant changes in terms of burner performance. The firing rate for the oven to steadily increase the fuel to the burner from about 137,000 to just about 150,000 over the range of the Wobbe ratio, Figure 79. The scatter in the data is consistent with the accuracy of the total gas usage measured using the gas flow meter, except the value for house natural gas (NG). It is expected a miscount of the pulses from the flowmeter occurred or the measured heat content was different from the sample that was taken a few days before testing.

The corrected CO results in Figure 80 show that the burner has significant issues when fired with the higher Wobbe gases. The corrected CO value consistently increased as Wobbe increased, rising to about 200 ppm for Wobbe of 1390. The CO emissions level dramatically increased for the two higher Wobbe value gases. The CO increased to consistently greater than 500 ppm for Wobbe greater than 1388. The transient data for each case showed that the corrected CO values never reached a steady state and would vary between 500 and 2,000 ppm. Because steady state data with values greater than 800 ppm, the performance of this unit would not comply with ANSI Z83 for combustion testing using the two higher Wobbe gases.

The data suggests that the issue with the burner is not a quenching problem that has been observed with other tested appliances (see Oven), but an issue with available oxygen to complete combustion. Figure 79 shows that the percent oxygen in the flue is about 4% using fuels with heat content similar to typical natural gas. As the heat content of the fuel is increased, the amount of oxygen needed to complete combustion increases. If the oxygen is

unavailable, the mechanism that converts CO to CO₂ in the combustion process is not completed and the CO production increases.

The NO_x emissions were not as adversely affected. Figure 81 shows that NO_x values increased only slightly, but consistently stayed between 135 and 160 ppm during the testing. Figure 82 shows that the total hydrocarbons may have increased a small amount for the high Wobbe gases but were less than 5 ppm for the entire range of fuels tested.

Based on the results in the figures, the Braising Pan was able to operate over range of test gases with Wobbe less than 1390 without increases in emissions to be out of compliance with the standards set in ANSI Z83. However, for the test gases with a Wobbe greater than 1390, the CO emissions increased to levels that showed significant issues with the performance of the burner system and eventually performed to a level that would not be in compliance with standards established by ANSI.

Results for Combi Oven

The Combi tested was the Cleveland Convotherm OGB-6.20 , Figure 84, with a faceplate firing rate of 75,700 and 68,200 BTU/hr for the oven and steam generator burners.



Figure 84. Combi Oven

The unit uses two combustion systems, for providing indirect heat to the air circulating through the cooking chamber and another for the steam generator. This means, unlike the Convection Oven tested in this study, products of combustion are not mixed with the cooking air that is circulated through the oven. Data are presented and discussed separately for the two combustion systems. Flame images were not taken because clear views of the burners were not available.

Data was acquired using a gas sampling tube inserted through the flues of the oven and steam generator on the top of the unit (Figure 85).



Figure 85. Flue Openings and Cooking Chamber in Combi

Thermocouples were also placed in the flues and inside the cooking chamber.

Testing and Results

The Combi was tested from a cold start with the thermostat set to 350°F. The unit was initially run in steam generator mode meaning only the steam generator burner was on. When the steam generator burner began to cycle, the unit was switched to hot air mode meaning only the oven burner would be operating. Data was continuously collected until the oven burner began to cycle. Figure 86 and Figure 87 give the transient profiles for the temperatures and emissions of the Combi using test gas A2. In the figures, the unit is in steam generator mode until 7 minutes when it is switched to hot air mode.

The temperature profile shows a rapid increase during steam generator mode for the flue temperature until the burner began to cycle at 7 minutes on the chart. After this point, the oven flue and chamber temperatures steadily increased for the remainder of the test. These profiles are typical in shape and performance of the other test gases.

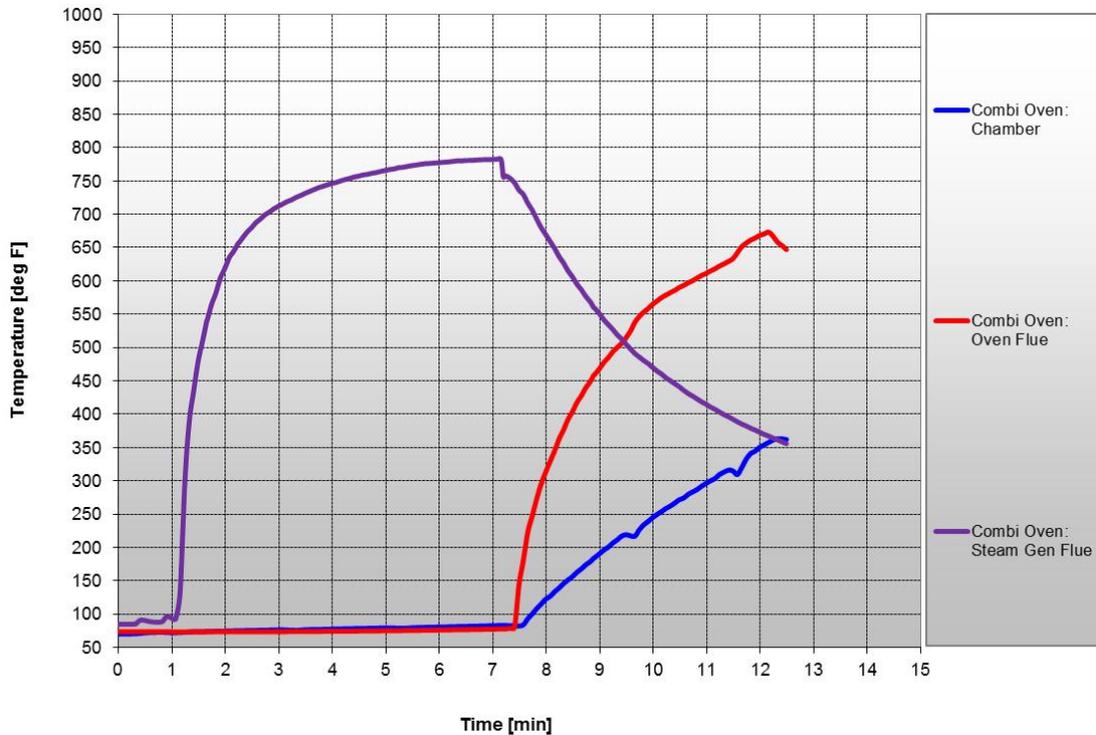


Figure 86. Transient Temperature Profile for Combi

The emissions profile for the Combi in Figure 87 is for the same timeframe for the different modes as for Figure. For the steam generator, all the emissions values reached steady values before the burner begin to cycle. Similarly, the emissions values for the oven burner reached steady values before cycling. The corrected CO values did slightly increase over time, but became relatively steady by the end of the test. For all modes of operation, the CO value was still well below the 800 ppm required by ANSI Z83. This behavior was observed for all the gases tested.

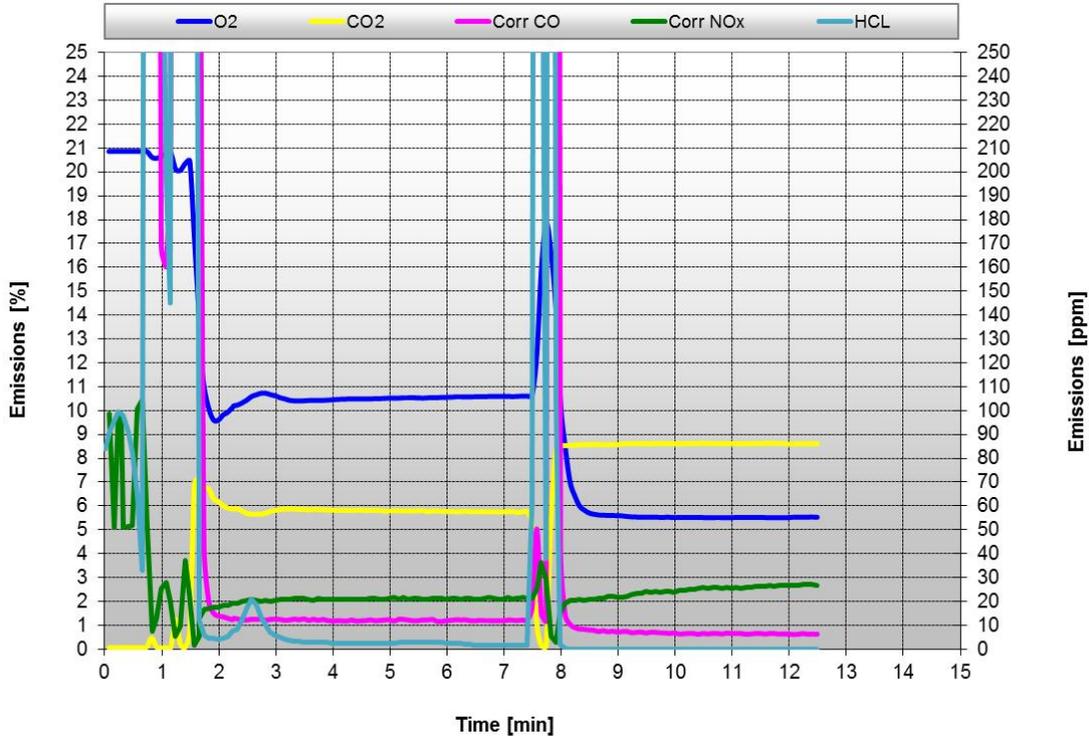


Figure 87. Transient Emissions Profile for Combi Oven

In order to compare specific performance characteristics of the Combi for the different test gases on a single chart, experimental values for each test gas were taken as the average for the last minute before the burner began to cycle. These values should be similar to the values used in ANSI Z83.11 for determining the performance of the appliance. Below are figures for Firing Rate, Carbon Monoxide emissions (CO), Nitrogen Oxide emissions (NO_x) and Total Hydrocarbon as a function of a Wobbe ratio. The Wobbe ratio for each data point is the Wobbe value for the test gas divided by the Wobbe value for test A2, which was chosen as the baseline gas for data calculations. The CO and NO_x emissions values are corrected to 0% oxygen or to an air free value thus standardizing the values to remove dilution due to variations in excess air in the flue. Total Hydrocarbon is a measurement in ppm (parts per million) of the total amount of hydrocarbons or fuel that was not consumed in the combustion process. For a process with complete combustion, the Total Hydrocarbon should be near 0 ppm.

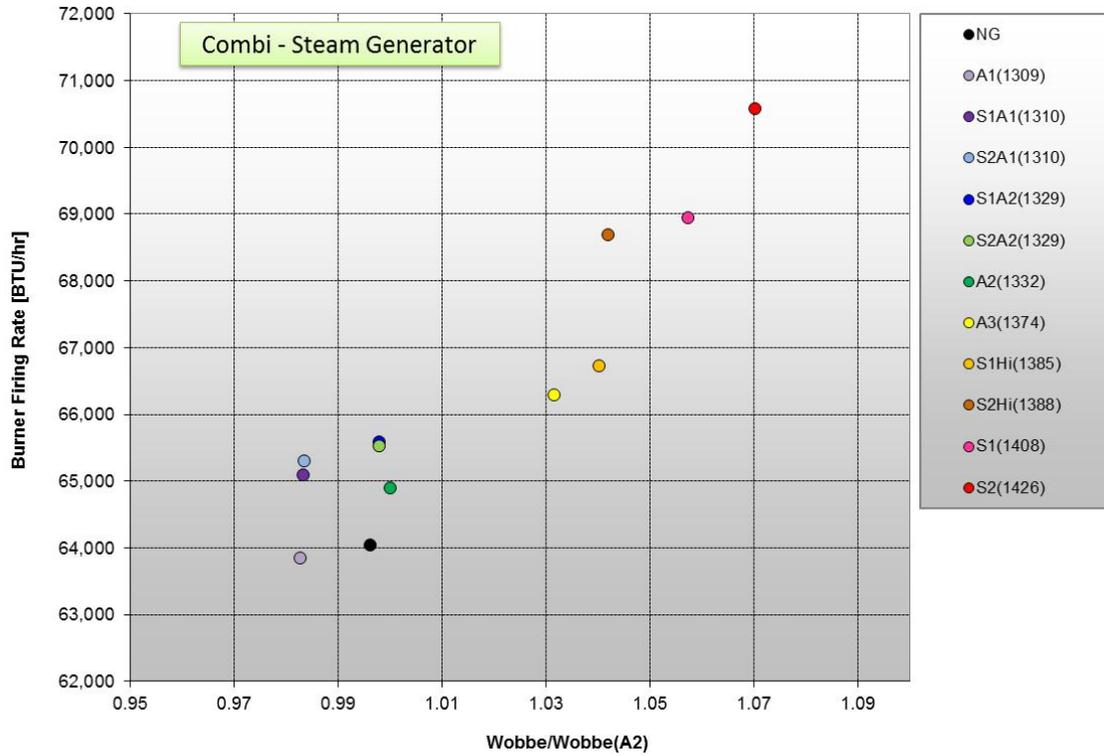


Figure 88. Combi Steam Generator Firing Rate vs. Wobbe Ratio

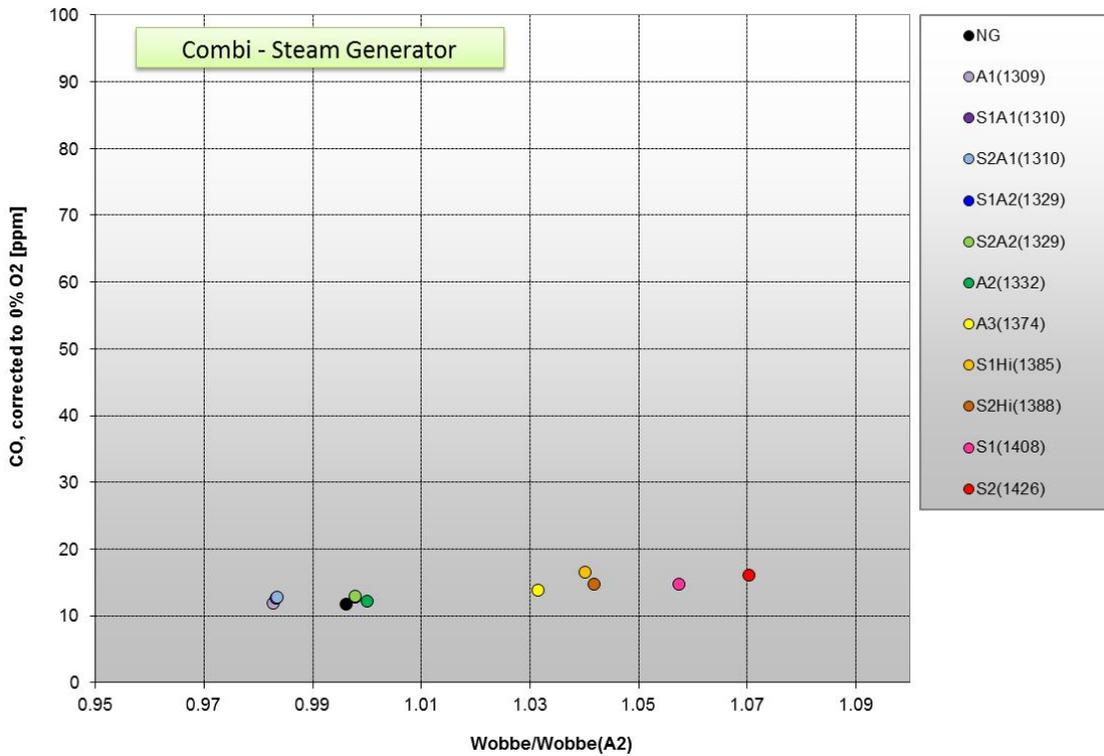


Figure 89. Combi Steam Generator CO Emission vs. Wobbe Ratio

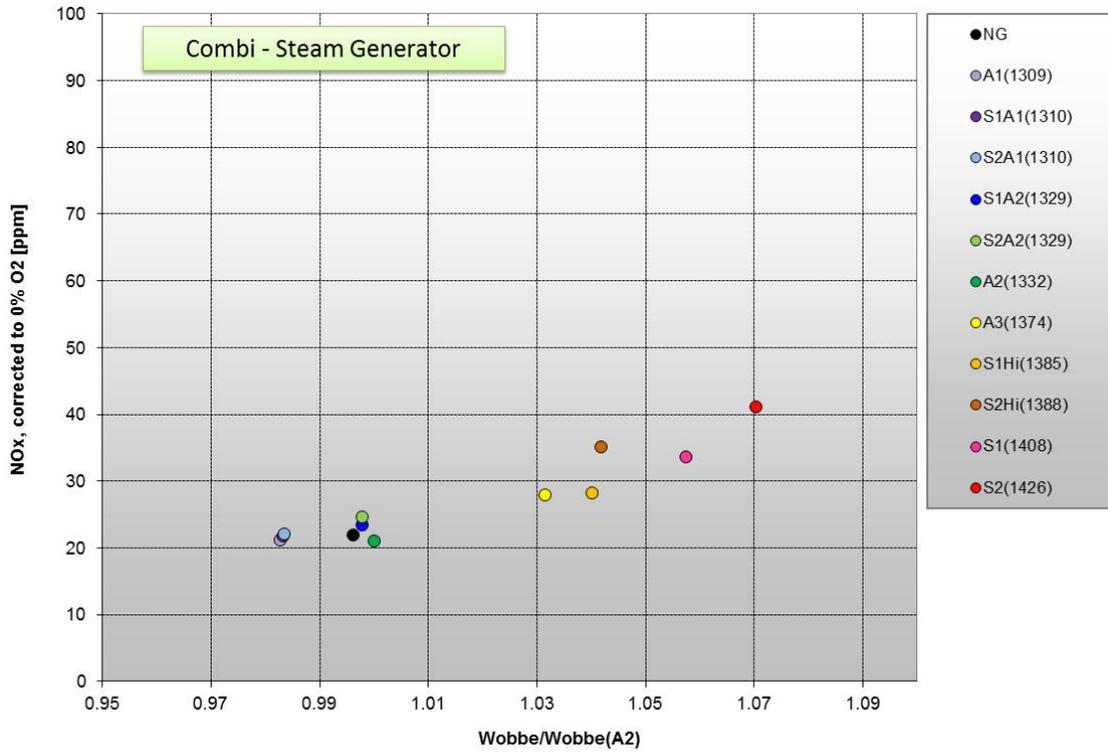


Figure 90. Combi Steam Generator NOx Emission vs. Wobbe Ratio

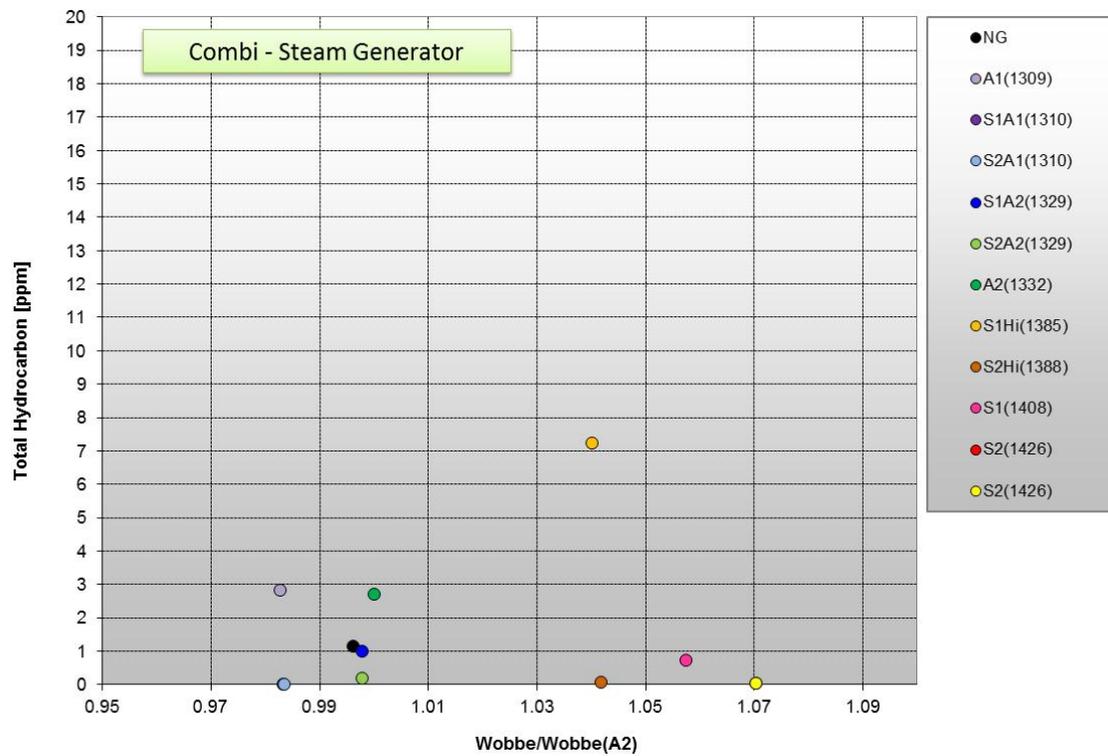


Figure 91. Combi Steam Generator Total Hydrocarbon Emission vs. Wobbe Ratio

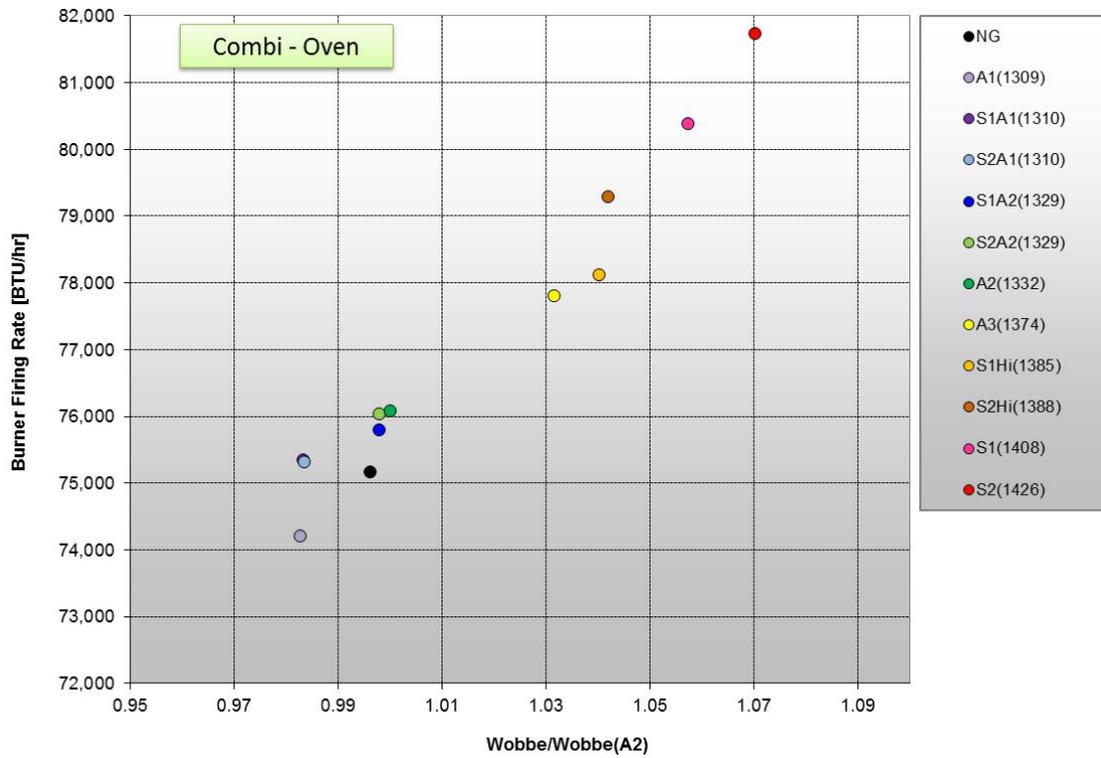


Figure 92. Combi Oven Firing Rate vs. Wobbe Ratio

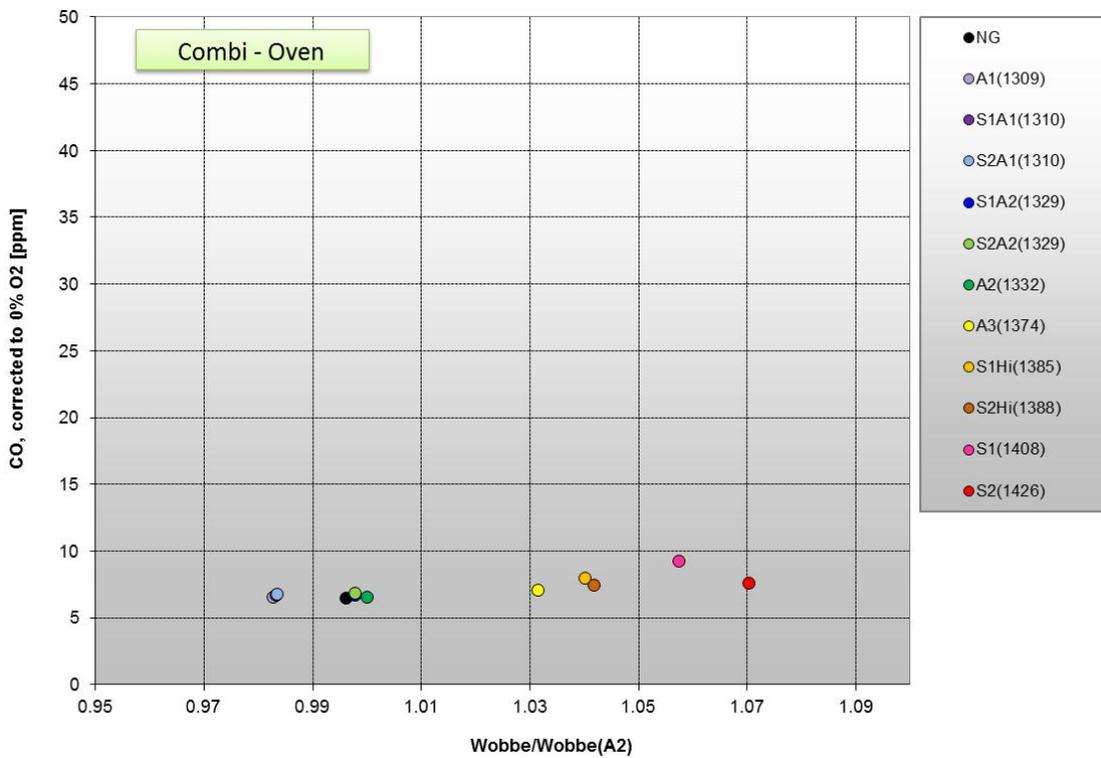


Figure 93. Combi Oven CO Emission vs. Wobbe Ratio

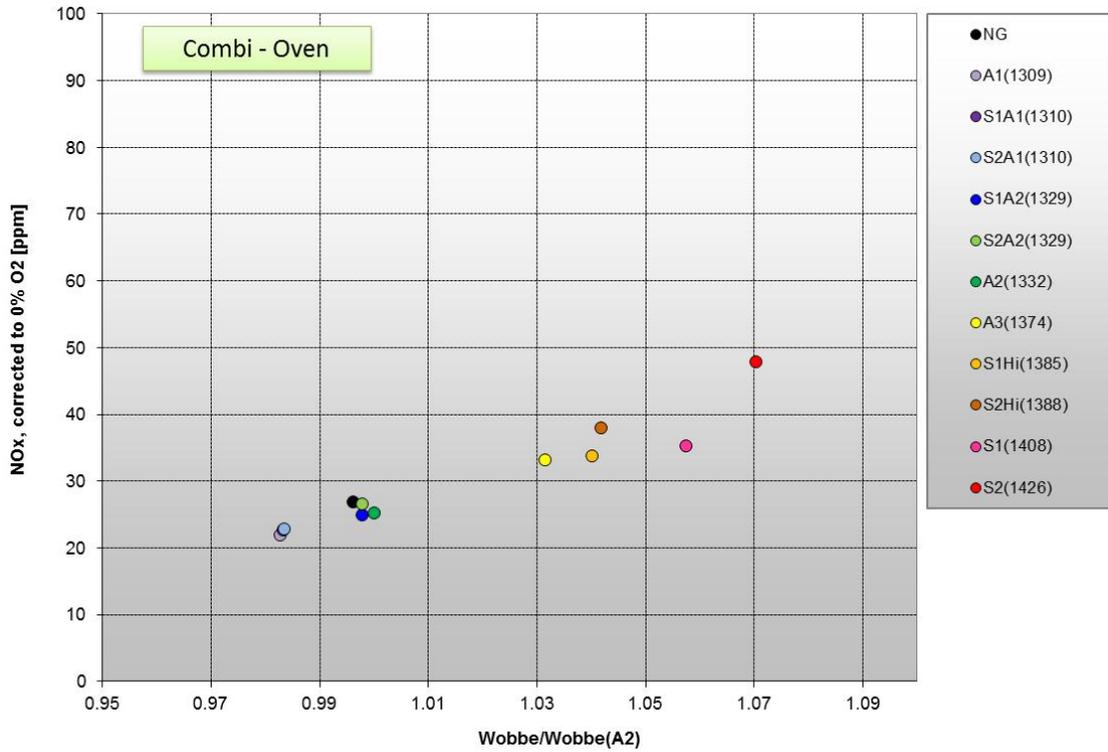


Figure 94. Combi Oven NOx Emission vs. Wobbe Ratio

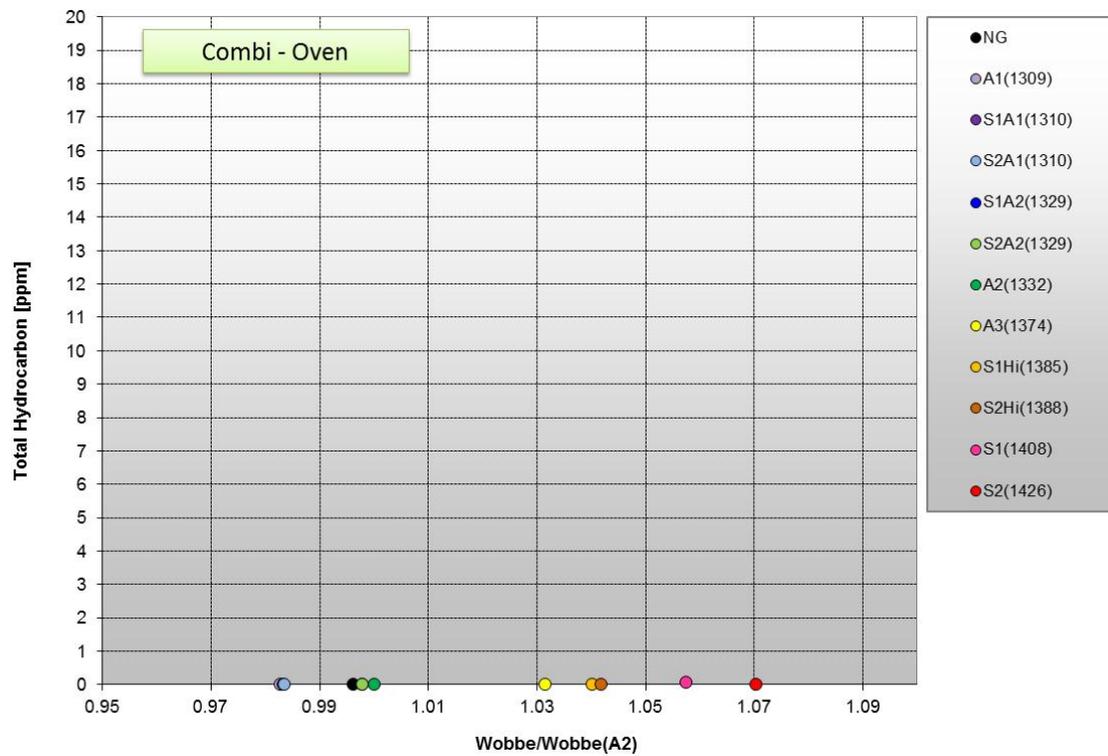


Figure 95. Combi Oven Total Hydrocarbon Emission vs. Wobbe Ratio

Analysis and Conclusions

For both the steam generator and the oven burner systems in the Combi, the performance values reached steady values before the burner cycled.

The firing rate for the steam generator steadily increased from about 64,000 to 70,500 BTU/hr for the range of the Wobbe ratio, Figure 88, and from about 74,000 to just under 82,000 BTU/hr for the oven burner, Figure 92. The scatter in the data is consistent with the accuracy of the total gas usage measured using the gas flow meter.

CO data also exhibited a slight increase for the higher Wobbe ratios, Figure 89 and Figure 93, with the values for the steam generator staying between 10 and 20 ppm and the values for the oven staying between 5 and 10 ppm. All of the values for CO were well under the 800 ppm, corrected limit mandated by ANSI Z83.

Figure 90 and Figure 94 show that the corrected NO_x values increased from about 20 to 40 ppm for the steam generator and 20 to 50 ppm for the oven for the highest Wobbe valued gases. The Total Hydrocarbons in Figure 91 and Figure 95 stayed consistently less than 8 ppm indicating that complete combustion was occurring, especially for the oven burner where the value were all close to 0.

Based on the results in the figures and despite some small changes in performance, both the steam generator and the oven burner in the Combi were able to operate over the entire range of test gases without increases in emissions to be out of compliance with the standards set in ANSI Z83.

Trace Hydrocarbons Sampling and Analysis

Concern was expressed regarding the possible presence of undesirably high levels of certain unburned hydrocarbons in the flue from the commercial foodservice equipment. The primary species of concern was formaldehyde, but other species of concern included acetaldehyde and acetone. These species could form during combustion in situations where combustion was not complete. Since the gas heating value and Wobbe number were increased in the substitute gases, the possibility existed that greater amounts of these species could form during the combustion process.

Samples were collected by GTI followed protocols specified by researchers at Lawrence Berkeley National Laboratory (LBNL). For each appliance,

- 1 Field Blank sample was collected
- 1 Background sample was then collected
- 2 samples per fuel (3 fuels) were collected
- A dilute flow with CO₂ at roughly 0.5-0.7% was used for sampling
- Testing involved appliance operation from cold start for 15 min or one cycle
- After sampling, the sample was capped and labeled (ring and pouch), put in an AL pouch, and then placed in a freezer until shipped overnight to LBNL for analysis

Collected samples were returned to LBNL and analyzed. Blind labeling was used to avoid any risk of sampling or reporting bias. Samples taken included blanks, backgrounds, and house natural gas operations of each appliance. Samples were taken for the baseline gas Adj2 (Wobbe of 1332) and for gas Sub1 at the high Btu condition matching Adj3 (Sub1Wobbe of 1375). All samples were collected during testing for CO and NO_x, and all samples were collected from the same flue collection points used for the monitoring the major emissions. Results from the HPLC analyses are presented in Figure 96 below.

Figure 96. HPLC Trace Hydrocarbon Data

Label	Appliance	Test Gas	Date	Time	Formaldehyde ng/μl	Acetaldehyde ng/μl	Acetone ng/μl
COBL	Convec. Oven	Blank	12/6/2010	8:55 AM	0.0055	0.0102	0.0090
COBK	Convec. Oven	Background	12/6/2010	9:00 AM	0.0794	0.8648	2.3638
CONG1	Convec. Oven	NG	12/6/2010	9:40 AM	3.4370	2.7213	4.5864
CONG2	Convec. Oven	NG	12/6/2010	4:30 PM	2.6178	1.8151	2.1586
COBK2	Convec. Oven	Background	12/7/2010	8:30 AM	0.0588	0.0343	0.1157
COBL2	Convec. Oven	Blank	12/7/2010	8:30 AM	0.0027	0.0098	0.0057
COA21	Convec. Oven	A2	12/7/2010	8:40 AM	2.6644	2.0595	3.7267
COA22	Convec. Oven	A2	12/7/2010	3:40 PM	1.3061	1.1721	1.6352
COBL3	Convec. Oven	Blank	12/8/2010	9:00 AM	0.0016	0.0033	-0.0182
COBK2	Convec. Oven	Background	12/8/2010	9:00 AM	0.0774	0.0521	0.1833
COS1H1	Convec. Oven	S1H1	12/8/2010	9:20 AM	3.3511	1.8883	2.7532
COS1H2	Convec. Oven	S1H1	12/8/2010	2:35 PM	1.6715	1.1549	1.8544
COBL4	Convec. Oven	Blank	12/9/2010	1:30 PM	0.0056	0.0124	0.0080
COBK4	Convec. Oven	Background	12/9/2010	1:30 PM	0.0907	0.0469	0.1673
CONG3	Convec. Oven	NG	12/9/2010	1:50 PM	5.8352	1.9061	9.0090
GNG1	Griddle	NG	12/6/2010	9:50 AM	4.5862	11.7359	3.0858
GNG2	Griddle	NG	12/6/2010	4:15 PM	0.4006	7.0768	2.0762
GA21	Griddle	A2	12/7/2010	9:15 AM	0.5887	12.0709	2.7102
GA22	Griddle	A2	12/7/2010	3:20 PM	0.2919	5.6516	1.5434
GS1H1	Griddle	S1H1	12/8/2010	9:50 AM	0.4165	6.7189	1.8631
GS1H2	Griddle	S1H1	12/8/2010	2:20 PM	0.5888	5.4604	1.5550
GNG2	Griddle	NG	12/9/2010	2:15 PM	1.8599	6.5481	0.6708
F1NG1	Fryer1	NG	12/6/2010	10:15 AM			

F1BK	Fryer1	Background	12/6/2010	3:35 PM	0.0818	0.0515	0.2213
F1NG2	Fryer1	NG	12/6/2010	3:50 PM			
F1A21	Fryer1	A2	12/7/2010	9:30 AM	25.2859	13.1394	0.5923
F1BK2	Fryer1	Background	12/7/2010	2:45 PM	0.0988	0.0478	0.1741
F1A22	Fryer1	A2	12/7/2010	3:00 PM	8.2504	8.6115	2.2107
F1S1H1	Fryer1	S1H1	12/8/2010	10:00 AM	7.0564	16.9977	0.9212
F1BK3	Fryer1	Background	12/8/2010	1:43 PM	0.0727	0.0398	0.2526
F1S1H2	Fryer1	S1H1	12/8/2010	2:20 PM	2.5566	8.1245	1.9682
F1NG3	Fryer1	NG	12/9/2010	2:30 PM	3.7735	6.9309	2.1503
0221BL	Blank	Blank	2/21/2011	3:05 PM	0.0000	0.0442	0.0510
0222BL	Blank	Blank	2/22/2011	9:09 AM	0.0000	0.0447	0.0503
0228BL	Blank	Blank	2/28/2011	8:30 AM	0.0344	0.0403	0.0483
412BL	Blank	BL	4/12/2011	9:10 AM			
0221BK	Background	Background	2/21/2011	3:05 PM	0.1509	0.1170	3.0449
0222BKA	Background	Background	2/22/2011	9:09 AM	0.1352	0.1361	1.2187
0222BKB	Background	Background	2/22/2011	2:58 PM	0.1500	0.1237	2.3080
0228BK	Background	Background	2/28/2011	8:30 AM	0.1473	0.1145	0.5932
0228BK2	Background	Background	2/28/2011	2:20 PM	0.1718	0.1403	3.7875
0301BK	Background	Background	3/1/2011	7:50 AM	0.1175	0.1010	0.2518
0301BL	Background	Background	3/1/2011	8:10 AM	0.0000	0.0475	0.0516
412BK	Background	BK	4/12/2011	9:10 AM			
BPNG1	Braising Pan	NG	2/21/2011	3:20 PM	0.2636	0.3799	0.2750
BPS1H1	Braising Pan	S1Hi	2/22/2011	10:04 AM	1.1941	1.3316	0.4452
BPS1H2	Braising Pan	S1Hi	2/22/2011	3:15 PM	0.1764	1.0199	0.9026
BPS1H3	Braising Pan	S1Hi	2/23/2011	8:30 AM	0.2918	0.9596	0.4966
BPA21	Braising Pan	A2	2/28/2011	8:45 AM	1.1919	2.0013	0.9708
BPA22	Braising Pan	A2	2/28/2011	2:50 PM	0.4453	1.3213	0.4719
BPNG2	Braising Pan	NG	3/1/2011	8:50 AM	0.2944	0.6940	0.4197
CBNG1	Combi Oven	NG	2/21/2011	3:41 PM	0.3436	0.3410	0.2445
CBS1H1	Combi Oven	S1Hi	2/22/2011	9:40 AM	0.5838	0.9395	0.5642
CBS1H2	Combi Oven	S1Hi	2/22/2011	3:30 PM	0.4283	0.1710	0.1711
CBA21	Combi Oven	A2	2/28/2011	9:00 AM	0.0913	0.8714	0.5765
CBA22	Combi Oven	A2	2/28/2011	3:10 PM	0.1852	0.4568	0.3563
CBNG2	Combi Oven	NG	3/1/2011	8:15 AM	0.1291	1.1898	1.3320

STNG1	Steamer	NG	2/21/2011	3:58 PM	0.2133	0.3398	0.2169
STS1H1	Steamer	S1Hi	2/22/2011	9:25 AM	0.3275	2.6120	4.3193
STS1H2	Steamer	S1Hi	2/22/2011	3:45 PM	0.1937	0.2626	0.1354
STA21	Steamer	A2	2/28/2011	9:20 AM	0.4952	0.5650	0.4800
STA22	Steamer	A2	2/28/2011	2:35 PM	0.3036	2.8945	2.7839
STNG2	Steamer	NG	3/1/2011	8:30 AM	0.8024	0.4479	0.3452
RGNG1	Range	NG	4/11/2011	1:35 PM			
RGNG2	Range	NG	4/11/2011	2:15 PM			
RGSH1	Range	S1Hi	4/11/2011	3:03 PM			
RGSH2	Range	S1Hi	4/11/2011	3:45 PM			
RGA21	Range	A2	4/12/2011	8:50 AM			
RGA22	Range	A2	4/12/2011	9:44 AM			
F2NG1	Fryer2	NG	4/11/2011	1:55 PM	17.1588	19.5995	1.2459
F2NG2	Fryer2	NG	4/11/2011	2:33 PM	8.5032	6.3300	1.9147
F2SH1	Fryer2	S1Hi	4/11/2011	3:23 PM			
F2SH2	Fryer2	S1Hi	4/11/2011	4:03 PM			
F2A21	Fryer2	A2	4/12/2011	8:25 AM			
F2A22	Fryer2	A2	4/12/2011	9:28 AM			

Trace hydrocarbon analyses found that formaldehyde, acetaldehyde, and acetone were produced in very low concentrations in all appliances under firing with all adjust and substitute gases. Because of the low concentrations measured, there is a large degree of scatter in the data. Comparison of measured values under appliance operating conditions relative to the blank and background samples found that small levels of all three species were produced by all appliances. There is no indication that any appliance produced significantly more of the three measured species than any other appliance. Also, there is no indication for any appliance that the level of the three species was different for the test gas with different heating values and Wobbe numbers.

The primary conclusions of the trace hydrocarbon species analyses are that:

All appliances produce formaldehyde, acetaldehyde, and acetone but at very low levels

- No appliance produced significantly more of the three hydrocarbon species than any other appliance
- There was no pattern found for any appliance between the amount of the three hydrocarbon species produced and the heat content or Wobbe number of the test gases

The data collected led to an inconclusive result regarding production of these three hydrocarbon species for different gas compositions.

**APPENDIX F:
Simulation-Based Estimates of
Indoor Exposures to Pollutants
From Natural Gas Cooking Burners**

NATURAL GAS IN CALIFORNIA:
ENVIRONMENTAL IMPACTS AND
DEVICE PERFORMANCE

**Simulation-Based Estimates of Indoor
Exposures to Pollutants from Natural Gas
Cooking Burners Task 14**

Prepared for:
California Energy Commission
Prepared by:
Lawrence Berkely National Laboratory



Jerry Brown
Governor

Task 14 Report

December 2011
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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Natural Gas Variability in California: Environmental Impacts and Device Performance: Simulation-Based Estimates of Indoor Exposures to Pollutants From Natural Gas Cooking Burners is an interim report for the Natural Gas Variability in California: Environmental Impacts and Device Performance (contract number 500-05-026) conducted by Lawrence Berkeley National Laboratory and the Gas Technology Institute. The information from this project contributes to Energy Research and Development Division's Energy-Related Environmental Research Program.

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ABSTRACT

Using liquefied natural gas for residential cooking burners can increase air pollutant emission rates relative to operating burners with conventional natural gas blends distributed in California. This study estimated the impacts of liquefied natural gas use on pollutant concentrations and exposures in California homes. A physics-based mass balance model was applied to calculate time-dependent concentrations of carbon monoxide, nitrogen dioxide and formaldehyde resulting from cooking burner use in homes. The model simulated pollutant emissions from cooking, pollutant entry from outdoors, dilution throughout the home, removal by ventilation, and other processes that affect exposure. Simulations were run for one week each in summer and winter for a representative sample of Southern California homes. Residence characteristics— including building age; floor area; number of children, adults, and seniors residents; and cooking frequency— were obtained from the *2003 Residential Appliance Saturation Survey* database. Ventilation rates, occupancy patterns, and burner use per meal were inferred from household characteristics. Researchers used cooking burner pollutant emission factors that were measured for cooking with natural gas or liquefied natural gas in controlled experiments conducted during an earlier phase of this study. The model tracked pollutant emissions from cooking burners, carbon monoxide and nitrogen dioxide entry from outdoors, indoor dilution, removal by surface deposition (nitrogen dioxide only) and removal by ventilation. Impacts were quantified per 1,000 homes to allow scaling to any liquefied natural gas distribution. Results indicate that cooking with conventional natural gas and without regular use of a kitchen exhaust fan can cause pollutant concentrations in homes that exceed health-based standards. For winter conditions in homes that cook with gas and do not use exhaust, the model estimated that 40-45 percent of residents are exposed to nitrogen dioxide at levels exceeding the federal one-hour outdoor standard, 4-6 percent are exposed to carbon monoxide in excess of the eight-hour outdoor standard, and 20-25 percent exceed the federal guideline level for acute formaldehyde exposure. The model estimated that with liquid natural gas these rates increase by about 3.5 percent for nitrogen dioxide, one percent for carbon monoxide and 1-2 percent for formaldehyde.

Keywords: Indoor air quality, gas appliances, carbon monoxide, formaldehyde, nitrogen dioxide, emissions, ventilation

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EXECUTIVE SUMMARY

Introduction

The California Energy Commission requested research to assess the potential device performance and air quality impacts of an anticipated increase in the use of liquefied natural gas (LNG) in California. Lawrence Berkeley National Laboratory (LBNL) and the Gas Technology Institute have worked together to assess these impacts, with LBNL focusing on residential appliances and air quality and Gas Technology Institute focusing on industrial burners.

Natural gas cooking burners—including cooktop, oven, and broiler burners—emit air pollutants that can affect residential indoor air quality, pollutant exposures, and related health risks. Recent experiments conducted by LBNL found that for some cooking burners the use of LNG in place of conventional natural gas led to an increase in emissions of three air pollutants that directly affect human health: carbon monoxide (CO), nitrogen dioxide (NO₂), and formaldehyde. Ultrafine particle concentrations—tracked by measurements of particle number concentrations—were influenced by operating conditions such as recent burner use and temperature setting for oven burners, but not discernibly by fuel properties.

The extent to which changes in emission factors impact pollutant exposures and health depends on many factors that vary across homes. These include the amount of cooking burner use, the size of the home into which emitted pollutants are diluted, the rate at which pollutants are removed via ventilation, the number of people in the home when cooking occurs, and the proximity effect, whereby anyone who is close to the source (such as the person using the burner) will be exposed to higher concentrations.

Project Purpose

The principal objective of this research was to quantitatively assess the impacts of LNG on residential pollutant concentrations and exposures associated with cooking burner use in California. The selected approach was intended to allow for quantitative assessment of the distribution of exposures across the population (that is, not just average levels).

Project Results

This study began by estimating the quantity of pollutants emitted from the use of conventional natural gas in cooking burners as well as the occupants' exposures to those emissions. The same analysis was then conducted for LNG use. These analyses were accomplished with a physics-based, data-supported simulation model designed to allow analysis at county, region, or statewide scales. The model built sample cohorts of homes from a database that was representative of the population of California homes. Time-resolved pollutant concentrations within each home were calculated using a physically based mass balance model that accounted for emissions, dilution, and deposition to surfaces and removal by air exchange. Parameters that affected these processes—including building characteristics and household cooking activity patterns—were drawn from several sources, including the *California Residential Appliance Saturation Survey*.

The study assessed the potential health impact of LNG through a set of quantitative exposure metrics. These included the distribution of concentrations in homes and among individual occupants averaged over periods of one hour to one week. These household and individual exposure concentrations were compared to acute and chronic health standards and guidelines and the rates at which the standards were exceeded were tracked. Because there were no formal standards to assess indoor exposures, the authors relied on ambient air quality standards set by the U.S. Environmental Protection Agency (U. S. EPA) and California EPA and on guidelines established by the Agency for Toxic Substances and Disease Registry and California’s Office of Environmental Health Hazard Assessment. Table ES-1 presents a summary of the standards and guidelines used as benchmarks against which calculated residential exposure concentrations were compared.

Table ES-1: Pollutant Standard and Guideline Concentrations for Various Exposure Periods

Pollutant	1-hr Average ^a (acute)	8-hr Average ^a (acute)	Annual Average ^a (chronic)	Agency ^b
CO	20 ppm (23 mg/m ³)	9 ppm (10 mg/m ³)	n/a	CAAQS (CARB)
	35 ppm (40 mg/m ³)	9 ppm (10 mg/m ³)	n/a	NAAQS (EPA)
NO ₂	180 ppb (339 µg/m ³)	n/a	30 ppb (57 µg/m ³) ^c	CAAQS (CARB)
	100 ppb (188 µg/m ³) ^d	n/a	53 ppb (100 µg/m ³)	NAAQS (EPA)
Formaldehyde (HCHO)	40 ppb (49 µg/m ³)	8 ppb (9.6 µg/m ³)	8 ppb (9.6 µg/m ³)	ATSDR
	45 ppb (55 µg/m ³)	7.3 ppb (9 µg/m ³)	7.3 ppb (9 µg/m ³)	OEHHA non-cancer REL

^a Units: ppm = parts per million; ppb = parts per billion; mg = milligrams; µ = micrograms; m³ = cubic meter

^b ATSDR = Agency for Toxic Substance and Disease Registry; CAAQS = California Ambient Air Quality Standards set by the California Air Resources Board (CARB), listed in the Table of Standards in Section 70200 of Title 17 of the California Code of Regulations; NAAQS = National Ambient Air Quality Standards set by the U.S. EPA (U.S. EPA, 1990); OEHHA = Office of Environmental Health Hazard Assessment; REL = Reference exposure level.

^c The California ambient air quality standard was enacted March 20, 2008.

^d The U.S. EPA NO₂ one-hr NAAQS was enacted February 9, 2010 and was effective as of April 12, 2010.

The model was configured to simulate one week of activity in the summer or winter using seasonally appropriate, county-resolved ambient air quality data. Both summer and winter scenarios used air exchange or ventilation rates assigned from building age-dependent and seasonally specified empirical distributions. These distributions were derived from available measurements that have been made in California homes and are identified in results tables as “Empirical.” The winter scenario was additionally simulated to consider air exchange solely by infiltration, which corresponded to minimal or no window opening or use of other mechanical exhaust fans. These scenarios are identified in results tables as “Infiltration.” The rate of air infiltration depended on the difference between outdoor and indoor temperature, winds, and the tightness or leakiness of the building. A value for building tightness was assigned to each

simulated residence based on building age and type, with different values for single detached homes and apartments.

The modeled residential exposure concentrations were linked with archetypal time-activity patterns of time spent at home for each individual in a given household. Simulations separately tracked pollutants emitted from the gas cooking burners and pollutants coming from outdoors. This separation allowed for an assessment of exposure concentrations resulting only from cooking burner emissions and for the combined effects of cooking burner emissions and pollutants entering from outdoors.

The model also took into account near-source, or proximity, effects on the exposures to the household member that was doing the cooking (the “cook”), and to young children (aged 0–5 years) in the household who were at home and assumed to be near the cooking adult. The proximity effect was expressed only for pollutants emitted from the burners. The effect of being near the cooking burners was calculated by multiplying the well-mixed concentration in the home by a proximity multiplier; this was applied only to the well-mixed concentration of pollutants emitted by the cooking burners. The authors selected multipliers based on a review of relevant published research. The baseline proximity multipliers were 2.0 for the adult cook and 1.5 for young children. One adult who was assigned as the “cook” was assumed in the model to be exposed to cooking burner pollutants at twice the level that persisted throughout the rest of the home during a cooking event. The nearby child was assumed to have exposure that was 50 percent higher during cooking. The cook and young children were exposed to pollutants from outdoors at the home average level in the model.

The model calculated exposure for both the cook and the child at the home average level once the cooking event ended. The values of these proximity multipliers were uncertain so the research team conducted a sensitivity analysis to assess the extent to which final results would vary if these multipliers were higher or lower than the estimated values of 2.0 and 1.5. The research team conducted runs to assess this sensitivity with proximity values set to twice the baseline values (4.0 for the cook, 3.0 for young children) or to 1.0; that is, with no higher exposure assumed for the person cooking or young children nearby. The model considered that everyone else in the home—excluding the cooking adult and children 0–5 years old—were exposed to the well-mixed pollutant concentration in the home. The exact magnitude of the effect is uncertain, but the near-source or proximity effect is known to occur and to be important to exposure. The inclusion of this effect and the analysis of uncertainty about its magnitude reflected a best effort to achieve accurate and transparent results.

Table ES-2 shows summary results for the calculated indoor pollutant concentrations resulting from gas cooking burner use in Southern California. Results are presented for CO, NO₂, and formaldehyde (HCHO) considering only emissions from cooking burners, and for CO and NO₂ considering both cooking burner emissions and entry from outdoors. Results are presented as the averages of the values calculated for 6,634 Southern California homes selected from the *Residential Appliance Saturation Survey* database. Results are presented for acute (highest one-hour concentration) and chronic (time-averaged over one week of simulations) durations and for the variations in season (winter, summer) and air exchange conditions (calculated based

on infiltration only or selected from an empirical distribution of measurements) as described above. In each cell, the first value shown is the average of the concentrations calculated for all the homes using emission factors measured for conventional natural gas; in parentheses is the change in the average concentration resulting from LNG use in all of the homes.

Total concentrations are also higher for the infiltration-only scenario as compared to empirical air exchange rate scenarios, owing to lower air exchange rates (in winter compared with summer, or with infiltration only compared to empirical distributions in winter) and thus slower removal of the pollutants emitted in residences by gas cooking burners.

In almost all cases, use of LNG is found to have a discernible but small impact on average pollutant concentrations in residences in almost all cases. On a relative basis, LNG use is predicted to change average concentrations by less than five percent in most cases and by less than 10 percent in almost all cases on a relative basis. Larger relative increases in indoor pollutant concentrations are seen only when the concentrations resulting from conventional natural gas combustion are very small.

Table ES-2: Model Predicted Indoor Pollutant Concentrations Averaged across a Cohort of 6,634 Southern California Homes from the 2003 Residential Appliance Saturation Survey Database.

Pollutant Metric	Season AER ^a	Summer	Winter	
		Empirical	Infiltration	Empirical
(a) Only gas cooking burners				
CO (ppm)				
Highest 1-hr		2.9 (+0.5)	5.1 (+0.9)	4.3 (+0.7)
1-week average		0.2 (+0.03)	0.9 (+0.1)	0.5 (+0.1)
NO₂ (µg/m³)				
Highest 1-hr		148 (+11)	207 (+16)	190 (+14)
1-week average		6.4 (+0.4)	10.8 (+0.8)	9.3 (+0.7)
HCHO (µg/m³)				
Highest 1-hr		23.2 (+0.7)	40.8 (+1.1)	33.9 (+1.0)
Highest 8-hr		6.9 (+0.2)	24.0 (+0.6)	14.9 (+0.5)
1-week average		1.6 (+0.1)	6.8 (+0.2)	3.7 (+0.2)
(b) Gas cooking burners and outdoors^b				
CO				
Highest 1-hr		3.2 (+0.5)	5.9 (+0.9)	5.1 (+0.8)
Highest 8-hr		1.1 (+0.2)	3.9 (+0.6)	2.9 (0.3)
1-week average		0.43 (+0.04)	1.70 (+0.15)	1.33 (+0.08)
NO₂ (µg/m³)				
Highest 1-hr		158 (+12)	215 (+16)	204 (+15)
Highest 8-hr		40.4 (+2.2)	55.2 (+3.3)	54.9 (+2.2)
1-week average		17.6 (+0.4)	17.0 (+0.9)	20.8 (+0.7)

Concentrations resulting: (a) solely from gas cooking burner emissions, and (b) from gas cooking burners plus entry from outdoors. Each column presents results for a scenario defined by season and home air exchange rate (AER) estimation method. The first number in each cell is the modeled value with conventional natural gas; in parentheses is the change resulting from LNG use. These results can be compared against the health-based benchmarks in Table ES-1.

^a Air exchange rate scenarios. For Empirical, an AER was assigned to each home from age- and seasonally-resolved distributions of measurements compiled from studies of California homes. The Infiltration-only scenario first assigned to each home an air tightness value based on the building age and type and then calculated air exchange with a validated physical model that assumed no window or fan use. See the text of the main report for additional details.

^b Results presented under (b) included pollutant emissions from the gas cooking burner, in addition to pollutants coming indoors from outdoors with ventilation air. Outdoor pollutant levels were derived from data collected at ambient air monitoring stations, resolved to a county level.

Table ES-3 provides analogous summary statistics for the 19,288 residents of the homes included in this modeling study, but presents only the contribution of gas cooking burners to exposure concentrations. Average concentrations are higher for individuals (as shown in Table ES-3) relative to values for homes (as shown in Table ES-2) owing to the proximity effect. There must be at least one adult close to the source each time a cooking burner was used and it was assumed this individual would be more highly exposed. The effect is larger for acute exposures and larger for NO₂ relative to the other two pollutants because the proximity multiplier is applied only for the duration of cooking, and thus more reflects the conditions extant before deposition to surfaces removes much of the emitted NO₂ from the air.

Table ES-3: Model Predicted Indoor Exposure Concentrations Attributable to Gas Cooking Burner Emissions Averaged across 19,288 Individuals Living in Southern California.

Pollutant and Metric	Season	Summer	Winter			
	AER ^a	Empirical	Infiltration	Empirical		
	F _{prox} ^b	(2, 1.5)	(2, 1.5)	(2, 1.5)	(4, 3)	(1, 1) ^c
CO (ppm)						
Highest 1-hr		3.5 (+0.6)	5.8 (+1.1)	4.9 (+0.6)	6.8 (+1.2)	4.2
1-week average		0.3 (+0.04)	0.9 (+0.1)	0.5 (+0.1)	0.5 (+0.1)	0.5
NO₂ (µg/m³)						
Highest 1-hr		183 (+14)	251 (+19)	231 (+18)	336 (+26)	185
1-week average		7.5 (+0.6)	12.1 (+0.9)	10.5 (+0.8)	13.8 (+1.0)	9.0
HCHO (µg/m³)						
Highest 1-hr		27.8 (+0.7)	46.5 (+0.8)	39.0 (+1.0)	54.2 (+1.4)	33.1
1-week average		1.8 (+0.1)	6.8 (+0.2)	3.8 (+0.1)	4.3 (+0.1)	3.6

The cohort was developed from data included in the 2003 Residential Appliance Saturation Survey database. The first number in each cell is the modeled value with conventional natural gas; in parentheses is the change resulting from LNG use. Each column presents results for a scenario defined by season, home air exchange rate estimation method, and assumed multipliers for higher exposures of the person cooking and nearby young children. These results can be compared against the health-based benchmarks in Table ES-1.

^a Air exchange rate (AER) scenarios. For Empirical, an AER was assigned to each home from age- and seasonally-resolved distributions of measurements compiled from studies of California homes. The Infiltration-only scenario first assigned to each home an air tightness value based on the building age and type and then calculated air exchange with a validated physical model that assumed no window or fan use. See text of main report for additional details.

^b Proximity effect multiplier. During cooking, household average concentrations were multiplied by the two values shown to estimate, respectively, the higher exposures of adult cook and 0- to 5-year-old children assumed to be in same room or near the cook. See the text for additional details.

^c Only the conventional natural gas scenario was modeled.

Table ES-3 also provides an estimate of the sensitivity of results to the specific values selected for proximity effect multipliers. The rightmost columns used the winter empirical air exchange scenario as a basis and show that variation in the proximity multiplier has a larger impact on average NO₂ concentrations than on average concentrations of other pollutants, as well as a larger impact on acute exposure metrics than on chronic exposure metrics. As noted above, the base and bounding values for proximity multipliers were developed from a review of relevant published data. The proximity effect and the correct multipliers to use will vary based on the layout of the home, occupant activities, and many other factors. The intent of the sensitivity analysis was to assess the extent to which uncertainty in the proximity multiplier affects overall results.

The effect of LNG on individual exposure concentrations is discernible and varies by pollutant, similar to the home air concentrations. Liquefied natural gas is found to increase average formaldehyde exposure concentrations by a few percent or less, to affect NO₂ concentrations by 5–10 percent, and to affect CO by as much as 20 percent relative to baseline natural gas, depending on the scenario.

Table ES-4 shows the frequency among 1,000 simulated individuals of being exposed to concentrations exceeding a relevant acute air quality standard or guideline, based solely on emissions from gas cooking burners. Results indicate exceedance rates of 2.6–5.5 percent for CO,

15–25 percent for formaldehyde, and 31–46 percent for NO₂ across scenarios when conventional natural gas use and base (best estimate) proximity multipliers are assumed. Exceedance rates increased by 0.5–1.2 percent for CO, 0.5–2.0 percent for formaldehyde and 3.2–3.4 percent for NO₂ in absolute percentages when LNG was used. These increases are discernible and vary from a roughly 20 percent relative increase for CO to roughly 10 percent or less relative increases for NO₂ and formaldehyde relative to exceedance rates for baseline natural gas. The rate of being exposed to pollutants at concentrations exceeding health-based standards and guidelines is therefore expected to increase but not change dramatically when LNG is used among those households that use natural gas cooking burners.

Table ES-4: Model-Predicted Rate at Which Southern California Residents Are Exposed in Their Homes to Pollutant Concentrations Exceeding an Acute Air Quality Standard or Guideline.

Pollutant and standard ^a	Season	Winter				
	AER ^b	Empirical	Infiltration	Empirical		
	F _{prox} ^c	(2, 1.5)	(2, 1.5)	(2, 1.5)	(4, 3)	(1, 1) ^d
CO 1-hr (CA)		26 (+5)	55 (+12)	43 (+9)	75 (+16)	33
NO ₂ 1-hr (U.S.)		312 (+32)	456 (+35)	416 (+34)	493 (+30)	334
HCHO 1-hr		147 (+5)	248 (+20)	210 (+13)	271 (+12)	181

The rate is the number of residents exposed above the standard per 1,000 residents living in homes that use gas cooking burners at least once per week. a Results are based solely on pollutant emissions from gas cooking burners, excluding all other sources. The first number in each cell is the modeled value with conventional natural gas; in parentheses is the change resulting from LNG use. Each column presents results for a scenario defined by season, home air exchange rate (AER), estimation method, and assumed multipliers (F_{prox}) for higher exposures of the person cooking and nearby young children.^c

^a From Table ES-1, CAAQS for CO (1 hour, 20 ppm); NAAQS for NO₂ (190 micrograms per cubic meter averaged over 1 hour); ATSDR HCHO guideline (49 micrograms per cubic meter over 1 hour).

^b Air exchange rate scenarios. For Empirical, an AER was assigned to each home from age- and seasonally resolved distributions of measurements compiled from studies of California homes. The Infiltration-only scenario first assigned to each home an air tightness value based on the building age and type and then calculated air exchange with a validated physical model that assumed no window or fan use. See the text of the main report for additional details.

^c Proximity effect multiplier. During cooking, household average concentrations multiplied by the two values shown to estimate, respectively, the higher exposures of adult cook and 0- to 5-year-old children assumed to be in same room or near the cook. See text for additional details.

^d Only the conventional natural gas scenario was modeled.

This study’s results show that exposure to pollutants emitted by natural gas cooking burners represents a substantial public health concern in California. The modeling results of this study indicated that a substantial fraction of users will be exposed to pollutant concentrations that exceed health-based standards and guidelines when natural gas cooking burners are used without simultaneous kitchen exhaust ventilation. Modeling for Southern California suggests that each winter roughly 40–45 percent of the population living in households that have and use gas cooking burners will be exposed to concentrations that exceed the U.S. national ambient air quality one-hour standard for nitrogen dioxide, roughly 20–25 percent will be exposed to formaldehyde that exceeds federal guideline levels for acute exposure, and roughly 4–6 percent will be exposed to acute CO levels above established outdoor standards. The switch from conventional natural gas to liquefied natural gas is projected to increase the fraction of this subpopulation exposed at levels that exceeded the aforementioned standards by roughly 3.5 percent for NO₂ (one-hour standard), by about 2–2.5 percent for formaldehyde, and

by about one percent for CO (in absolute percentages). While these LNG-related increases are small relative to the fraction of this group (Californians that use gas cooking burners) that is already exposed to pollutant levels that exceed health-based standards and guidelines, the direction of the LNG effect is consistently negative at a population level.

The results of this study likely apply to the majority of homes with gas cooking burners throughout California since existing data suggests very low usage rates for kitchen exhaust ventilation during cooking and since the key physical parameters that affect concentrations were similar throughout the state.

The hazard posed by natural gas and exacerbated by LNG use in gas stoves can be mitigated through use of venting range hoods and other kitchen exhaust devices that can remove cooking burner combustion products (as well as cooking-related pollutants) before they mix throughout the home. Many installed range hoods may capture only a fraction of the emitted pollutants but the performance of most of these can be substantially improved by: (1) starting the fans at or before the start of cooking; (2) leaving the fan on for at least a few minutes after cooking; and (3) preferentially cooking on back burners to improve pollutant capture.

Subsequent to completion of this report, the researchers continued to develop the simulation model that is described in this report. Results obtained with a more advanced version of the model are reported in an article entitled "Pollutant exposures from unvented gas cooking burners: A simulation-based assessment for Southern California" that was published online November 5, 2013 by the journal *Environmental Health Perspectives* (EHP); the first author of that paper is J.M. Logue.

Project Benefits

This analysis provides quantitative estimates of residential pollutant exposures associated with use of conventional natural gas cooking burners and the impacts of switching to liquefied natural gas in Southern California. It also finds that the use of natural gas-powered cooking burners without a kitchen exhaust fan may commonly lead to indoor pollutant concentrations that exceeded health-based standards for outdoor air quality. The identification of this common hazard should help motivate action to reduce these potentially harmful exposures and thus improve the health of Californians.

CHAPTER 1: Introduction

1.1 Overview

Natural gas cooking burners—including cooktop, oven, and broiler burners—emit air pollutants that can affect residential indoor air quality, pollutant exposures, and related health risks. Emitted pollutants include carbon monoxide (CO), nitrogen dioxide (NO₂), formaldehyde (HCHO), and ultrafine particles (UFP). Though not toxic at typical environmental levels, nitric oxide (NO)—which is also emitted by gas burners—can react in the air or on surfaces to produce secondary air pollutants. Gas cooking burners (GCBs) are not typically the most important source of formaldehyde in indoor air—emissions from materials and consumer products typically dominate—yet emissions from gas appliances may add considerably to indoor exposures. Since HCHO is a carcinogen with no known threshold for activity, any increase in exposure adds to health risk.

The principal objective of this research is to quantitatively assess the impacts of liquefied natural gas (LNG) on residential pollutant concentrations and exposures associated with cooking burner use in California. Recent experiments conducted by Lawrence Berkeley National Laboratory (LBNL) found that, for some cooking burners, the use of LNG in place of conventional natural gas led to an increase in emissions of CO, NO₂, HCHO, and NO for many cooking appliance burners (Singer et al. 2009). Ultrafine particle concentrations—tracked by measurements of particle number concentrations (PN)—were influenced by operating conditions such as recent burner use and temperature setting for oven burners, but not discernibly by fuel properties. This research was conducted as part of a comprehensive evaluation of potential impacts of LNG use in California, California Energy Commission contract 500-05-026. Other research tasks conducted as part of this project are summarized in reports available from the Energy Commission and LBNL.

Since natural gas cooking appliances are prevalent in about half of the roughly twelve million housing units in California (U.S. BoC 2000 and EIA 2001), distribution of LNG in any part of the state has the potential to broadly impact indoor pollutant exposures and health risks. At the time of this report, LNG is being supplied to a large fraction of households in the San Diego area and to a fraction of residences in the South Coast Air Basin (predominantly in Riverside County).

In this analysis, the impact of LNG is assessed by first developing quantitative estimates of the distribution (across the population) of pollutant concentrations and exposures that result from use of conventional natural gas in cooking burners, then repeating the analysis for LNG use. Several different baseline distributions are calculated based on uncertainties in some key input parameters. For example, one distribution is calculated assuming only infiltration-based air exchange and another is developed using measured air exchange rates. For each baseline scenario, a companion LNG scenario uses all the same parameters except that the pollutant emission rates are those measured for LNG rather than for conventional NG.

The analysis is accomplished with a physics-based, data-supported simulation model designed to allow analysis at county, region, or statewide scales. The model builds sample cohorts of homes from a database that is representative of the population of California residences. Time-dependent pollutant concentrations within each home are calculated using a physically based mass balance model that accounts for emissions, dilution, deposition to surfaces, and removal by air exchange. Parameters that impact these processes – including building characteristics and household cooking activity patterns – are drawn from several sources, including the California Residential Appliance Saturation Survey (RASS) (CEC 2004).

The potential health impact of LNG is assessed through a set of quantitative exposure metrics. These include the distribution of peak and time-averaged concentrations in residences and among individual occupants of the study residences and the frequency at which health-protective exposure limits are exceeded.

Because there are no formal standards to assess indoor exposures, we rely on ambient air quality standards set by the U.S. Environmental Protection Agency (U.S. EPA) and California EPA, and on guidelines established by the Agency for Toxic Substances and Disease Registry (ATSDR) and California’s Office of Environmental Health Hazard Assessment (OEHHA). Table 1 summarizes the acute and chronic exposure standards and guidelines considered for this study. Acute exposure standards have averaging times of one hour for CO, NO₂, and HCHO, and eight hours for CO and HCHO. Chronic (annual) exposure limits are available for NO₂ and HCHO. When more than one benchmark concentration was available for a given averaging time, we chose the lower value. When the indoor concentration exceeds the level set as part of a relevant standard, we refer to this as an “exceedance.” We note, however, that standards can be strictly exceeded only within the domain to which they apply. Thus, an occurrence in which indoor CO is 9 parts per million (ppm) or higher over an eight-hour period does not constitute a formal exceedance of ambient air quality regulations, since the regulations apply only to outdoor air. Nevertheless, the level has been set to be protective of the general population. And any exposures to concentrations above that level deserve attention. Additionally, we consider the endpoint of increasing cancer risk using the U.S. EPA’s unit risk estimate (URE) for HCHO of 1.3×10^{-5} per micrograms per cubic meter ($\mu\text{g m}^{-3}$) (U.S. EPA 1991), as well as the updated, but preliminary (currently under external review), revised risk estimate of 1.1×10^{-4} per $\mu\text{g m}^{-3}$ (0.13 per part per million [ppm⁻¹]; U.S. EPA 2010c). We rely on the revised HCHO cancer risk estimate as an upper bound to assess cancer risk. Specifically, we consider the incremental cancer risk that results per year of exposure at the calculated chronic exposure concentration for each individual. This incremental risk is the lifetime URE, which assumes chronic exposure over a 70-year period, divided by 70.

Table 1: Relevant Pollutant Standard and Guideline Concentrations for Various Exposure Periods

Pollutant	1-hr	8-hr	Annual	Agency ^a
CO	20 ppm (23 mg/m ³)	9 ppm (10 mg/m ³)	n/a	CAAQS (CARB)
	35 ppm (40 mg/m ³)	9 ppm (10 mg/m ³)	n/a	NAAQS (EPA)
NO ₂	180 ppb (339 µg/m ³)	n/a	30 ppb (57 µg/m ³) ^b	CAAQS (CARB)
	100 ppb (188 µg/m ³) ^c	n/a	53 ppb (100 µg/m ³)	NAAQS (EPA)
HCHO	40 ppb (49 µg/m ³)	8 ppb (9.6 µg/m ³)	8 ppb (9.6 µg/m ³)	ATSDR (U.S. DHHS 2009)
	45 ppb (55 µg/m ³)	7.3 ppb (9 µg/m ³)	7.3 ppb (9 µg/m ³)	OEHHA non-cancer REL (CalEPA 2008)

^a ATSDR = Agency for Toxic Substance and Disease Registry; CAAQS = California Ambient Air Quality Standards set by the California Air Resources Board (CARB), listed in the Table of Standards in Section 70200 of Title 17 of the California Code of Regulations; NAAQS = National Ambient Air Quality Standards set by the U.S. EPA (U.S. EPA 1990); REL = Reference exposure level

^b California ambient air quality standard enacted March 20, 2008

^c U.S. EPA NO₂ 1-hr NAAQS enacted February 9, 2010, and effective as of April 12, 2010 (EPA 2010a)

Note: ppb = parts per billion

This exposure modeling and impact assessment was designed to support the analysis of incremental health risks of indoor pollutant exposures arising from use of LNG in cooking appliances. Health risks ensue from inhalation of pollutants emitted during burner use. Peak pollutant concentrations in air are determined by the mass emitted and by the well-mixed air volume of the residence. Pollutants are removed from the home by reaction, deposition to surfaces, or ventilation. The temporal profile and absolute values of pollutant concentrations resulting from natural gas burner use are functions of pollutant emission factors (mass of pollutant per amount of fuel used by cooking appliance), burner use (cooking) patterns and duration, residence volume, and air exchange (ventilation) rate. Overall concentrations will reflect emissions from natural gas burners and other sources. Most relevant to this study are situations in which emissions from gas burners substantially contribute to a health-based standard being exceeded. In this context, we include entry of CO, NO, and NO₂ into the home with outdoor ventilation air.

The model includes county-specific outdoor concentration profiles for winter and summer, derived from measurements recorded at ambient air quality monitoring stations throughout California. Though important overall to indoor air quality, this analysis did not include other indoor pollutant sources such as formaldehyde emissions from materials and consumer products. Relevant exposures occur when occupants are present during periods of elevated concentrations following burner use.

Key features of the exposure model developed and used for this analysis include the following:

- The model is physically based, with data-based input parameters to calculate temporally resolved pollutant concentrations in each home. Previous exposure modeling efforts

have used simplistic approaches assuming fixed concentrations that are unrelated to key physical parameters.

- Utilization of a representative database of household and home characteristics to allow population based assessment.
- Consideration of co-variances of key parameters such as home size, number of occupants, and cooking activity.
- Assessment of potential impacts for various spatial scales from county to statewide.
- Characterization of impact of indoor emission changes in context of time-varying concentrations of NO₂ and NO entering residences with outdoor air (using county-level outdoor profiles).
- Incorporation of near-source (proximity) exposure to cooker (adult ≥ 18 years old) and young child (0–5 years old).

By tracking estimated exposures for individuals within each household, the model allows assessment of impacts on sub-populations defined by building type, household, and demographic characteristics. This allows analysis for sensitive or potentially vulnerable sub-populations including children, the elderly, and renters.

1.2 Background

1.2.1 Pollutant Emissions and Health Effects Associated with Gas Cooking Appliances

Several peer-reviewed studies have investigated whether the presence or use of unvented gas appliances leads to pollutant levels that exceed health guidelines or associations with observed health-related endpoints. This short summary focuses on cooking appliances.

A number of studies have examined cooking and gas appliance-related exposures to NO₂ (Speizer et al. 1980; Dockery et al. 1981; Noy and Lebret 1986; Quakenboss et al. 1986; Spengler et al. 1994; Levy et al. 1998; Garcia Algar et al. 2004; Yang et al. 2004; Rotko et al. 2001) or CO (Fortmann et al. 2001; Raw et al. 2004; Henderson et al. 2006). Measured levels of CO arising from gas cooking events have generally not exceeded short-term guidelines (Henderson et al. 2006). However, Fortmann et al. (2001) reported that CO exceeded 8-hour average concentration guidelines (9 ppm) during a fish-broiling event. The same event resulted in indoor NO₂ levels that exceeded the newly adopted 1-hour NAAQS for NO₂. In the same study, an event of lasagna baking resulted in NO₂ concentrations that approached the 1-hour NAAQS. Other studies have found a statistical association between increased NO₂ exposure levels due to gas cooking and adverse health effects, such as respiratory symptoms, including wheezing and decreased respiratory function (Jarvis et al. 1996; Jarvis et al. 1998)

Adverse respiratory health effects are known to be associated with exposure to NO₂. At ambient concentrations NO₂ has been associated with exacerbation of asthma (Anderson et al. 1998; Hajat et al. 1999) and an increase in daily deaths (Touloumi et al. 1997). At high concentrations, NO₂ has been found to increase the sensitivity to allergens in asthmatic patients (Tunnicliffe et al. 1994). Recently, Morales et al. (2009) hypothesized that detoxification genes may modify the

neurologic effect of NO₂. They found an inverse association between cognitive scores in 0- to 4-year-olds and number of gas appliances in the home.

The hazards associated with unvented gas appliance use may not be limited to NO₂. Wong et al. (2004) found a significant dose-response relationship associated with household gas cooking and respiratory illness, using hierarchical regression models adjusted for socioeconomic, demographic, and indoor risk factors (including passive smoking). Seaton and Dennekamp (2003) have advanced the hypothesis that some adverse health effects attributed to NO₂ from gas appliances may instead be due to ultrafine particles. There is also research that suggests that some health effects attributed to NO₂ exposures may be attributable instead to NO. For example, Farrow et al. (1997) have hypothesized that although diarrhea in infants was significantly associated with NO₂ concentrations, it may instead have been related to exposures to high NO concentrations. Further, Dennekamp et al. (2001) have hypothesized that “prolonged exposure to NO, by influencing the natural production of NO by endothelial cells, could be responsible for some of the cardiac effects associated epidemiologically with NO₂.” The possibility that symptoms of NO₂ exposure may be due instead to NO is especially of concern, considering that NO can persist longer indoors when ozone is limited (NO removal from outdoor air is primarily by reaction with ozone). While there is currently no consensus NO exposure standard for the general population, the simulation model described in this report allows tracking of NO concentrations over various averaging times.

Relative to NO₂, NO, and CO, very few studies have focused on indoor HCHO levels due to cooking with gas appliances (Fortmann et al. 2001; Lovreglio et al. 2009 and supporting information therein which includes a summary of previously measured indoor HCHO concentrations). This is mostly because the primary source of indoor HCHO is emissions from materials and products. These include products that contain formaldehyde-bonded resin such as particleboard and plywood present in sub-floors, paneling, cabinetry and furniture, and latex paint (Zhang et al. 1994; Kelly et al. 1999; Salthammer et al. 2010 and references therein).

1.2.2 Impacts of LNG on Pollutant Emissions from Gas Cooking Burners

The objective of this research is to quantify the effect on residential HCHO, NO₂, NO, and CO indoor air exposures from cooktop and oven burner use resulting from a shift to LNG from conventional natural gas. To achieve these objectives, we rely heavily upon the experimental measurements conducted as an earlier task in this study and reported by (Singer et al. 2009). These experiments quantified the variation in pollutant emissions between LNG and typical California blends of conventional natural gas, as a function of Wobbe number (WN), a measure of energy delivery through a fixed orifice burner. Wobbe number is equal to the higher heating value divided by the square root of specific gravity, and in the United States has units of British thermal units per standard cubic foot (Btu/scf). Liquefied natural gas blends typically have WN values that are much higher than conventional natural gas supplied to California. A WN of about 1330–1340 is typical for the conventional natural gas supplied in much of the state of California. In the experiments reported by Singer et al. (2009) natural gas cooking burners were operated with conventional natural gas distributed in Northern California and with fuel blends having WN values around 1360, 1385–1390, and 1415–1420 Btu/scf.

Findings for the four indoor air pollutants of concern from the residential cooktop and oven burner experiments reported by Singer et al. (2009) include the following:

- Among cooking burners with substantial baseline CO emissions (≥ 100 nanograms per joule or ng J^{-1}), almost all had CO increase at rates of 5–40 percent per 50 WN fuel change.
- For cooking burners having substantial baseline NO_2 emissions ($\geq 5 \text{ ng J}^{-1}$), roughly half had NO_2 emissions increase; the increase was in most cases on the order of 20 percent or less for a 50 WN increase in fuel.
- Formaldehyde emissions were significantly elevated ($p > 0.05$) for a 50 WN increase in fuel for three of the cooktop burners and one of the oven burners.
- Nitric oxide (NO) emissions increased for nine of the thirteen cooktops, while only two of the thirteen oven burners had NO emissions increase at a statistically discernible level with a change in fuel of 50 WN.

1.2.3 Factors Affecting Indoor Levels of Pollutants Emitted from Gas Cooking Burners

Pollutants are emitted during gas cooking burner (GCB) use. Overall emissions are related to the pollutant specific emission factors (ng J^{-1}) and cooking activity. Cooking activity includes burner use frequency and number of burners used, as well as burner use duration. Cooking activity is related to household occupancy, including the household size and the age of the household members. As pollutants are emitted from cooking activities, they mix throughout the residence and are diluted. Pollutants are also removed from the residence by either mechanical or natural ventilation. Residential air exchange rates (AERs) are influenced by building characteristics such as size, type and age of the building, and by the strength of driving forces (indoor-outdoor temperature differences, wind), as influenced by location and climate. Figure 1 outlines the linkages between these household and building characteristics and emission factors that influence indoor pollutant concentrations arising from cooking with gas appliances.

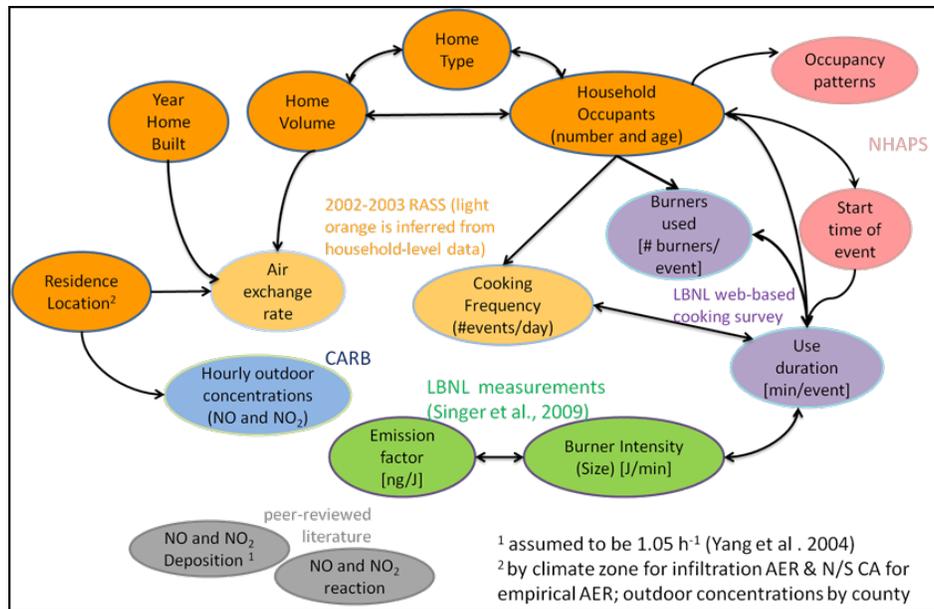


Figure 1: Exposure Model Inputs Influence Diagram

These inputs determine the indoor pollutant concentrations and exposures resulting from cooktop and oven burner use using conventional (Pacific Gas & Electric) natural gas and LNG fuel. The double arrows indicate a correlation between the inputs. Data references are provided next to the color-coded bubbles.

Note: NHAPS = National Human Activity Patterns Survey

CHAPTER 2: Methods

The following sections describe the modeling framework and data sources used to quantify indoor pollutant concentrations and exposure distributions related to conventional natural gas or LNG use in California. An emphasis is placed on understanding and characterizing the linkages between household activity patterns and building characteristics in order to quantify individual and household pollutant exposures from oven and cooktop use. Following a summary on model implementation, we provide detailed summaries of how each residence-level input was characterized. We conclude with a description of the metrics used to assess individual and household-level pollutant exposures to conventional natural gas and LNG.

2.1 Mass Balance Model of Pollutant Concentrations in Indoor Air

To characterize primary pollutant exposures to conventional NG and LNG for households and individual residents, we use a single-zone mass balance model to simulate the transport and fate of air pollutant emissions from cooking burner use in California homes. The indoor air model relies on the following governing mass balance equation:

$$V \frac{dC_i}{dt} = E_i - k_i V C_i - Q(C_i + p_i C_{i,out}) \quad (1)$$

In this equation, written for pollutant species i , V is volume of the residence (m^3), C_i is the indoor concentration ($\mu\text{g m}^{-3}$), E_i is the emission rate ($\mu\text{g h}^{-1}$), k_i is the indoor pollutant deposition rate (h^{-1}), Q is the air flow indoors and is equivalent to the flow outdoors ($\text{m}^3 \text{h}^{-1}$), p_i is penetration coefficient (h^{-1}) accounting for pollutants coming indoors from outdoors, and $C_{i,out}$ is the outdoor concentration ($\mu\text{g m}^{-3}$). E_i is estimated based on the emission factors (ng J^{-1}) measured experimentally in Task 9 and an average fuel use rate (7 kBtu/h, or $1.23 \times 10^5 \text{ J/min}$). As formulated for the analysis described in this report, the model does not include homogeneous or heterogeneous chemical reactions. The reaction of indoor-emitted NO with incoming ozone can appreciably affect NO₂ concentrations. However, since the modeling in this report is focused on wintertime conditions, this reaction was not deemed essential to the current analysis.

The equation above can be solved recursively for C_i , so that any of its parameters can be varied across time (i.e., they are constant within a given time step but can change from one time step to another). In addition, the equation can be used to separately track pollutant mass originating from indoor emissions and from outdoor sources, with total concentrations calculated as the sum of the contributions from the two sources. This superposition approach was used by Klepeis (1999) to combine discrete source emissions in a residence.

A recursive solution for the indoor concentration resulting from indoor (gas cooking appliance) emissions is presented in Equation 2a below, which is written for a time step of one hour (1 h).

$$C_{i,indoor-origin}(t) = \frac{E_i(t)\Delta t}{V(a+k_i)} \left(1 - \exp^{-(a+k_i)\Delta t}\right) + C_{i,indoor-origin}(t-1)\exp^{-(a+k_i)\Delta t} \quad (2a)$$

In this equation $C_{i,indoor-origin}$ are the indoor concentrations (of pollutant i generated from appliance use) at time t and at the previous time step ($t-1$), a is the air change rate (h^{-1}), Δt = time interval between concentrations, and E and V are as defined above.

The equation for the indoor concentration of pollutant i originating from outdoors is:

$$C_{i,outdoor-origin}(t) = \frac{Q_{in}C_{i,out}(t)\Delta t}{V} + C_{i,outdoor-origin}(t-1)\exp^{-(a+k_i)\Delta t} \quad (2b)$$

The total indoor concentration at time (t) is calculated as the sum of contributions from indoor and outdoor sources:

$$C_{i,total}(t) = C_{i,indoor-origin}(t) + C_{i,outdoor-origin}(t) \quad (2c)$$

The recursive model is implemented and solved in R-programming code. The output from the exposure model includes indoor concentrations of HCHO, NO, NO₂, and CO over a course of a week, at 1-minute scale resolution. For three outdoor air pollutants – NO, NO₂, and CO – we additionally consider indoor concentrations resulting from entry of the pollutants from outdoors. Development of county-level outdoor air concentration profiles is described further in the section titled *Pollutant Concentrations in Outdoor Air*.

The modeled residential exposure concentrations are linked with archetypal time-activity patterns of time spent indoors at a residence for each individual in a given household.

We also take into account near-source, or proximity, effects on the exposures to the household member that is doing the cooking (the “cook”), and to young children (aged 0–5 years) in the household who are at home and assumed to be near the cooking adult. The method used to characterize and implement this proximity effect are explained in more detail, along with a summary of relevant supporting research, in the section titled *Augmented Exposures for Occupants in Kitchen During Cooking Appliances*.

Additional technical documentation on the structure of the exposure model can be found in Appendix G.

2.2 Key Data Sources for Indoor Air Model

2.2.1 Residential Appliance Saturation Survey (RASS)

Our modeling framework was designed to study a set of California residences that include representative variations in the characteristics that impact pollutant emissions from cooking burners and associated occupant exposures. This is possible with publicly available data collected as part of the California Residential Appliance Saturation Survey (RASS). Since this model was developed prior to public release of the most recent (2009) RASS dataset, we used

RASS data collected in 2002–3 (CEC 2004). The 2002–3 RASS is a representative sample of the population served by the following four California utilities: Pacific Gas and Electric (PG&E), Southern California Edison (SCE), San Diego Gas and Electric (SDG&E), and Los Angeles Department of Water and Power (LADWP).

The RASS was conducted during 2002 and 2003, and contains anonymous data for almost 22,000 households. The RASS dataset serves as the key data source on residential building characteristics and cooking-related activity factors for the exposure modeling. Based on U.S. Census demographics, the RASS provides a cohort of residences that closely matched the population of California (CEC 2004). This cohort is used to assess the individual and household impact on the distribution of pollutant concentrations and exposures caused by the shift from traditional natural gas distribution to LNG across various spatial scales ranging from county level and scalable statewide.

The model builds a simulated study sample from any user-specific subset of the RASS database. Statewide, the database includes nearly 10,500 households that reported cooking with a natural gas cooktop or oven during the past week. Included in these households are roughly 30,000 individuals made up of roughly 4,200 seniors (65+ years old), roughly 8,500 children (0–18 years old), and over 17,600 adults (19–64 years old). The majority of RASS households with gas cooking appliance had at least one child (0–18 years of age) and roughly a quarter of all the households in this group had at least one senior member.

Figure 1 highlights (in orange) the key data available in the RASS dataset on household and building characteristics and household cooking activity. These linked building and household-level inputs include the following:

- Building type (single-family detached; single-family attached including townhome or duplex; 2–4 unit condo or apartment; and 5+ unit condo or apartment; mobile home).
- Building age (year home built).
- Volume (estimated from reported residential square footage, and assuming an eight-foot ceiling height).
- Location of residence (by ZIP code, and California Energy Commission forecast zone translated to climate zone).
- Presence of gas stove and/or oven in residence.
- Gas stove and/or oven cooking frequency over the course of a week.
- Household socio-demographic data (including ethnicity of head of household, number of residents, and age of household members).

Summary information about household and building characteristics of the RASS homes that used natural gas is included in Appendix A.

In addition to the residence-specific household and building characteristics data in RASS, other data sources (highlighted in Figure 1) were used to compile distributions for exposure model

inputs. These are introduced in the paragraphs that follow and described in detail in subsequent subsections.

As seen in Table 2, the distribution of building age in the 2002–3 RASS closely matched the age distribution of California homes in the year 2000 (U.S. Census 2000). At that time, the majority of households (68.4 percent) that reported using a gas cooking appliance were in homes built before 1979 (Table 2). Slightly less than 10 percent of households that reported using a gas cooking appliance lived in homes built after 1995. The remaining 22 percent of RASS 2002–3 households that used gas cooking appliances lived in homes built between 1980 and 1995.

Table 2: Statistics on Year of Construction for 2002–3 RASS Households That Reported Cooking and Presence of a Gas Cooking Appliance

Year built	RASS HHs reporting gas cooking	% of gas cooking RASS HHs (%)	CA housing Unit distribution based on Census 2000 (%)	CA housing unit distribution including new construction 2000–2008 ^a (%)
Pre-1950	2110	20.1	20	19
1951–1979	5074	48.3	50	47
1980–1995	2289	21.8	24	23
Post-1995	1026	9.8	6	11

^a based on Census 2000 estimate of housing units since 2000.

Relative to the 2002–3 RASS database, the current (2010) population of California homes includes many more buildings built since 1995. These newer buildings are generally more airtight, with lower rates of air infiltration and thus lower overall air exchange rates, as discussed in the upcoming subsection on air exchange rates. To allow analysis for a sample of homes reflecting the current age distribution, the model was designed to screen by year of construction. The post-1995 homes in RASS can be oversampled to produce an age (and infiltration AER) distribution that more closely reflects the current home age distribution.

2.2.2 Web-Based Cooking Survey

Detailed information about cooking activity patterns was collected through a web-based cooking survey developed and implemented by LBNL. The aim was to collect some detailed information that was not included in the RASS survey. Specific targets included frequency of oven and cooktop use (RASS only asked about using one or the other), the number of burners used when cooking occurred, and the meal-specific (breakfast, lunch, and dinner) number of burners and duration of use. The web-based cooking survey effort and analysis is described in the Cooktop and Oven Burner Use Patterns subsection of the Methods section.

2.2.3 National Human Activity Pattern Survey (NHAPS)

Additionally, this study used data from the National Human Activity Patterns Survey (NHAPS) (Klepeis et al. 2001) to establish meal times and time spent at home for each individual in each household. We defined archetypal activity patterns based on age and in some cases weekday vs. weekend day. These occupancy patterns were used to generate exposure estimates from the

calculated household concentration profiles. The occupancy and meal preparation algorithms are described in the upcoming Household Occupancy Patterns section.

2.2.4 Measured Emission Factors

This study also relied on measured emission factors of NO, NO₂, CO, and HCHO from Task 9 of this project (Singer et al. 2009). These laboratory measurements were conducted at LBNL for twelve cooktop-oven units. The assignment and use of these cooktop and oven emission factors to each gas appliance-cooking RASS household is described later, in the Pollutant Emission Factors section.

2.3 Exposure Model Implementation - Overview

For each residence in our sample, basic household and residential building characteristics (shaded orange in Figure 1) are defined directly from the publicly available RASS database. The study sample only includes residences that reported using either their gas cooktop or oven at least once during the course of a typical week to cook a given meal (breakfast, lunch, or dinner). Supplemental data on household cooking activity patterns and individual time-activity patterns (purple- and pink-shaded in Figure 1, respectively) are assigned to each residence from publicly available databases and/or cooking survey conducted by LBNL. These supplemental data are assumed to remain constant across season and are not influenced by fuel type.

We simulate two weeks of activity – one in summer and one in winter – for each residence in our sample. Each week is simulated for homes using either conventional natural gas or LNG. Each household has a specified schedule of gas cooking burner (GCB) use that is assumed to be the same in winter and summer. (Despite anecdotal evidence that this assumption may not hold, we did not have a data basis for setting different schedules.) However, seasonal differences in outdoor pollutant patterns and air exchange rate are accounted for. The results from the separate summer and winter simulations include minute-by-minute indoor concentrations profiles for NO₂, CO, and HCHO for each home. These profiles are aligned with archetypal occupancy patterns to calculate exposure concentrations for individuals.

The exposure model can be run for a representative set of households at various spatial scales across California – from individual county level to the entire state – to characterize the change in pollutant exposures arising from a given shift from conventional natural gas to LNG across households and individual residents.

As reference for this analysis, we considered a projected maximum near-term LNG distribution scenario that was developed and used for outdoor air quality modeling as part of another task of this multiyear project. This scenario – Scenario 7 from Sospedra et al. (2011) – considers the existing capacity of the LNG receiving plant in Baja California, the existing gas distribution infrastructure, and spatially resolved demand in Southern California. This LNG distribution scenario translates to 100 percent LNG penetration – i.e., LNG going to all residences that use natural gas in San Diego County, and to 35 percent of gas-fueled residences in Riverside County. Liquefied natural gas currently reaches a very small fraction of residences in other Southern California counties. This study therefore focuses on reporting model simulation results pertaining to the Southern California (SoCal) region, with a particular emphasis on San

Diego and Riverside county households. The following six counties are included in the SoCal Region: Los Angeles, San Bernardino, Riverside, San Diego, Orange, and Ventura County.

Using all RASS households within the SoCal region as the simulation sample allows us to explicitly capture key co-variances among factors that impact exposure to pollutants emitted from gas cooking burners. For each residence, we do the following:

- Account for linkages between household demographics—specifically the number of household members in each age group—and cooking activity patterns.
- Sample a value from a (lognormal) distribution of cooking duration, as a function of household size and age distribution, to assign the cooktop and oven burner use duration for each meal.
- Randomly assign sets of emission factors for one cooktop and one oven, based on measurements of Singer et al. (2009). A home may receive emission factors from an oven and a cooktop that are not from the same cooking range (appliance that contains both an oven and a cooktop). But the assignment of a burner from the results of Singer et al. carries with it the emission rates of all of the pollutants measured from that burner. Each burner will thus have associated baseline emission rates of CO, NO₂, NO, and HCHO, along with the change in emissions with WN for each.
- Assign an annual average AER that captures the variation between homes based on air leakage and climate, but excluding natural (open windows) and mechanical ventilation (e.g., kitchen vents or any other system that mechanically draws in outdoor air).
- Incorporate typical county-level outdoor air concentrations of NO₂, NO, and CO to estimate the impact of natural gas to overall exposures and potential exceedances of standards for these pollutants. We do not incorporate ambient HCHO data because (a) outdoor levels are typically an order of magnitude lower than indoors, (b) the effect of LNG on HCHO-related cancer risk can be assessed based on incremental exposure and is not a threshold-based concern. For reference, we note that average outdoor air levels of HCHO are roughly 3 ppb (CARB 2004).

The following subsections describe in detail the LNG exposure modeling inputs and model implementation, including the following:

- Air Exchange Rates (AER)
- Cooktop and Oven Burner Use Patterns
- Baseline Natural Gas and LNG Cooktop and Oven Burner Emission Factors
- Household Occupancy Patterns (time spent indoors at a residence)
- Outdoor Air Pollutant Concentrations (CO, NO, and NO₂)
- Output Metrics

2.4 Air Exchange Rate (AER)

Outdoor air exchange is a combination of air leakage through cracks and gaps in the building envelope, airflow through open windows and doors, and mechanical ventilation. Leakage airflow is driven by temperature and pressure gradients across the building shell. Driving forces are related to outdoor conditions, indoor temperatures and indoor-outdoor temperature differences, home height, shielding from wind and sun, home construction, and other factors. Operation of vented combustion devices that draw combustion air from the conditioned air in the home also increases driving forces. Mechanical ventilation is supplied by vented bath and kitchen fans, and in an increasing number of homes, a whole-house fan.

Air exchange rates vary between homes and over several time scales (seasonal, diurnal, day of week) within each home. The variation within a home can be separated into that which is due primarily to ventilation (natural and/or mechanical ventilation) and the contribution from infiltration (home leakiness). Owing to variations in outdoor conditions, the same home will experience varying driving forces for air leakage depending on the climate at its location. Variations in home operation including thermostat settings, window and door opening, and vented appliance operation can dramatically affect air exchange rates.

Taking these factors into consideration, we have structured the indoor exposure model such that air exchange can either be modeled assuming infiltration only or sampled from a lognormal distribution of empirical (measured) AERs. The following two sections provide details on these two approaches, respectively, that are used to assign an AER to each RASS household.

2.4.1 Infiltration-Only AER

To explore the impact of fuel changes on emissions and exposures in the most affected homes – namely, those that keep windows closed routinely through the winter – the model allows for air exchange rates to be set based solely on infiltration (the unintentional entry of air into the well-mixed volume). For this implementation, windows are assumed to be closed at all times.

To assess the annual-average AER from infiltration, we apply ASHRAE Standard 136-1993 (ASHRAE 2001). Using this method, AER is characterized as:

$$\text{AER} = \text{NL} \times W \quad (3)$$

In this equation NL is normalized leakage [unitless] and W is a factor that takes into account local weather effects. As seen in Table 3, the W factor ranges between 0.57 and 0.92 throughout California based on a typical meteorological year.

Table 3: Values for W [ACH] in California Cities in a Typical Meteorological Year (ASHRAE 2001) and California Energy Commission Title 24 Climate Zone for the City

City	W [ACH]	CEC Title 24 Climate Zone
Arcata	0.74	1
Bakersfield	0.68	13
China Lake	0.67	14
Dagget	0.90	14
El Toro	0.57	8
Fresno	0.69	13
Long Beach	0.64	6/8
Los Angeles	0.66	8/9
Mount Shasta	0.78	16
Point Mugu	0.63	6
Red Bluff	0.81	11
Sacramento	0.75	12
San Diego	0.67	7/10
San Francisco	0.92	3
Santa Maria	0.70	5
Sunnyvale	0.63	4

Note: ACH = air changes per hour

For single-family detached homes (SFDH) that are not low-income and not part of an energy efficiency program, the multivariate linear regression analysis of Chan et al. indicates that the year the home was built and the floor area explain about 41 percent of the variation in the NL of conventional SFDHs in the United States (the R^2 is 0.41) (Chan et al. 2003 and 2005). Therefore, NL was set as a function of year the home was built (YearBuilt) and residence floor area (Area [m²]) using the following equation from Chan et al. (2003):

$$NL = \exp[20.7 + -0.011 \text{ YearBuilt} + (-0.0022 \cdot \text{Area})] \quad (4)$$

Appendix B includes a table summarizing the expected geometric mean (GM) and geometric standard deviation (GSD) of normalized leakage for all SFDHs contained in the Chan et al. (2003) database, by floor area and year built.

To characterize annual-average AER from infiltration in multi-family apartments (5+ unit apartments and condos), the study assumed that multi-family RASS residences are assigned an NL that is 1.5 times the value derived from the Chan et al. (2003) analysis (Eqn. 4). This increased leakage is based on the conclusions of Price et al. (2006) that “the observed apartment leakiness values in the range of 3 to 8 liters per second per square meter ($Ls^{-1} m^{-2}$) are approximately 1.5 to 2 times the values observed in single-family houses.”

2.4.2 Empirical AER Distributions

We located previous studies reporting AER in winter and non-winter (i.e., summer, spring and fall) throughout California. Appendix B provides summary statistics and additional information, including home age, location (i.e., Northern or southern California), and AER measurement method of the full suite of these studies. We also obtained raw data on measured AER throughout California from several sources. The AER based on these empirical AER measurements is log-normally distributed and varies by winter and non-winter seasons, and by location. Figure 2 and Figure 3, display winter and non-winter AERs, respectively, across California homes. As these figures show, winter AERs in Northern California homes diverge from those measured in Southern California at the seventy-fifth percentile (Figure 2). Additionally, non-winter AER tends to be lower in the north than in Southern California homes (Figure 3). Because the research team was not able to locate a sufficient sample of AERs measured in Central Valley homes, it was assumed that the distribution of AERs in the Central Valley is roughly that of Northern California in the winter, and similar to Southern California in non-winter seasons.

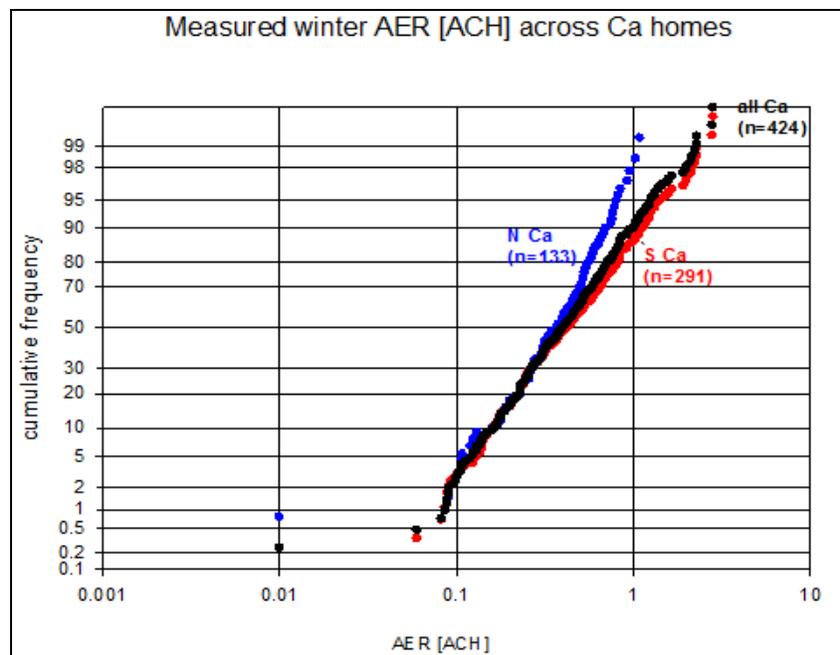


Figure 2: Distribution of Measured Winter AERs in California

Source Data: Wilson et al. (1993, 2003); Offermann (2009); and RIOPA Los Angeles (AER 2010)

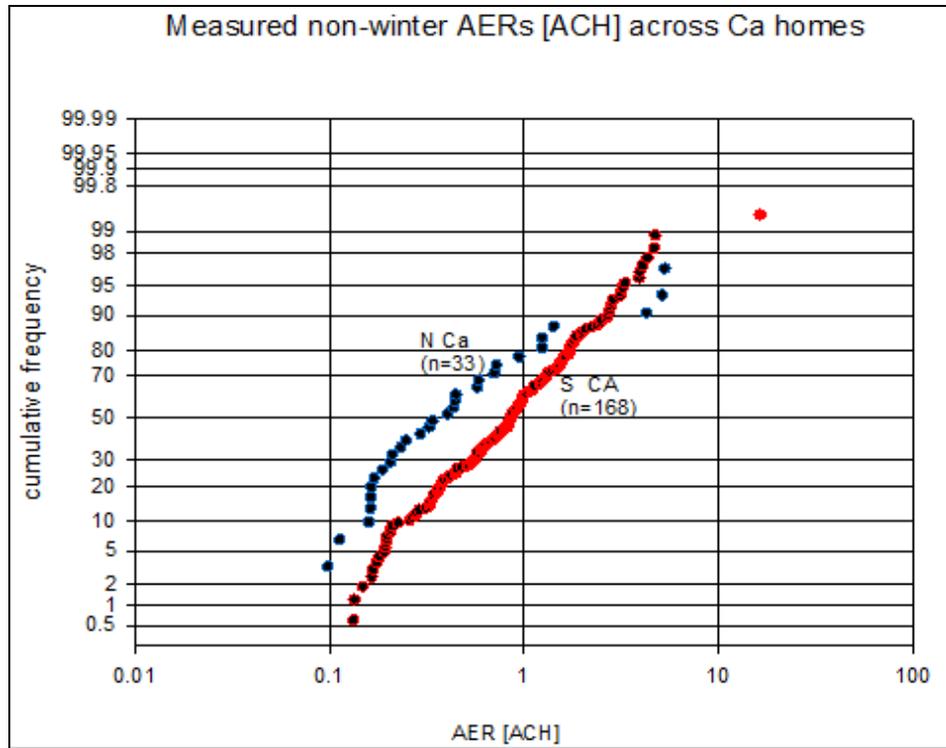


Figure 3: Distribution of Measured Non-winter AERs in California

Source Data: Offermann (2009) and RIOPA Los Angeles (AER 2010)

Other factors besides season and region can also significantly influence AER. These factors include building age and size (volume or floor area) of home. While we were not able to identify a sufficient sample of homes that reported measured AER and size of home, we were able to review and analyze measured AER data by age of home, season (winter and non-winter), and building age, from the following five studies:

- 13 existing Southern California homes built between 1966 and 1987 (Wilson et al. 2003)
- 37 newly constructed homes built in 2002 in Southern California (Wilson et al. 2003)
- 171 Northern and 112 Southern California homes built before 1990 (Wilson et al. 1993)
- 52 Northern and 54 Southern California homes built after 1995 (Offermann 2009)
- The Los Angeles Relationship of Indoor, Outdoor and Personal Air (RIOPA) home cohort including 45 winter measurements and 129 non-winter measurements (AER 2010).

Table 4 provides summary statistics of AER based on region, season (winter and non-winter), and age of home (year built) from these five studies for Northern California and Southern California. The GM (GSD) defines the lognormal distribution calculated for each combination of location and season with data that are sufficient to define such distributions.

Table 4: Distributional Parameters for Winter and Non-Winter Empirical Air Exchange Rates in Northern and Southern California, by Year of Construction. ^a

Season and Location	Pre-1980				1981–1995				Post-1995			
	Mean (SD)	GM (GSD)	Min–max	N	Mean (SD)	GM (GSD)	Min–max	N	Mean (SD)	GM (GSD)	Min–max	N
Winter												
Southern Cal	0.72 (0.54)	0.63 (1.89)	0.06–2.91	151	0.51 (0.33)	0.42 (1.81)	0.13–1.58	54	0.23 (0.17)	0.20 (1.93)	0.08–1.32	69
Northern Cal ^b	0.46 (0.21)	0.40 (1.56)	0.01–1.09	79	0.38 (0.25)	0.32 (1.81)	0.1–1.4	30	0.24 (0.15)	0.20 (1.8)	0.09–0.66	21
Non-winter												
Southern Cal ^c	1.51 (1.03)	1.22 (1.85)	0.20–4.75	67	0.97 (0.50)	0.85 (1.62)	0.26–2.49	23	0.77 (0.81)	0.53 (2.36)	0.13–3.95	70
Northern Cal ^d	n/a				n/a				1.08 (1.72)	0.49 (3.07)	0.10–6.47	31

^a Appendix B provides information about each study referenced below. N = number of homes.

^b Includes only Wilson et al. (1993) Indoor Air Quality Study for homes built before 1995

^c Includes only AERs measured in RIOPA (Los Angeles) for homes built before 1995.

^d Includes only Offermann (2009) measured AERs for homes built after 1995.

2.5 Cooktop and Oven Burner Use Patterns

Gas cooking burner use activity patterns were developed from available and newly acquired information and used in the calculation of time-resolved indoor pollutant concentrations. The GCB use schedule for each residence started with a RASS question about weekly frequency of cooking breakfast, lunch, or dinner using a gas cooktop or oven. Then, for each cooking event, it was necessary to specify all of the following information:

- Use of cooktop, oven, or both for a given meal
- If cooktop used, number of burners (# burners/meal)
- Fuel use rate or firing rate (Btu/h or J/minute)
- Duration of each burner use (minutes/meal)
- Start time of cooktop and/or oven burner use

2.5.1 Schedule and Frequency of Gas Cooking Appliance Use

Each household in the RASS was asked about the frequency of cooking breakfast, lunch, and dinner with a stove and/or oven. Only those households that reported using a natural gas stove and/or oven are included in our indoor model simulation cohort of SoCal households (n = 6,634 households). The RASS survey included the following question posed to each respondent:

“During a typical week, how often do you use your range or oven?” to cook a given meal.

The categorical responses include:

- Never
- Rarely (less than once per week)
- Occasionally (1–2 times per week)
- Sometimes (3–4 times per week)
- Often (5–7 times per week)

Responses are provided separately for breakfast, lunch, and dinner. The reported categorical variable that described the frequency of gas stove and/or oven use during a typical week was randomly translated to a corresponding cooking frequency. We assumed that no specific meal cooking activity occurs for the “never,” “rarely,” and “no response” categorical variables responses.

The next activity assignment was to develop a specific meal pattern (over course of week, which meals included cooking) based on the number of times cooking was reported for each meal.

If the meal-specific, self-reported frequency of range or oven use was “occasionally” (1–2 times per week), we assigned a random probability for 1 day or 2 days and selected the frequency with higher probability value. Occasional cooking for breakfast or lunch was assumed to occur on weekends, i.e., Saturday or Sunday. Occasional cooking for dinner could occur on any given day of the week. If the meal-specific, self-reported frequency of range or oven use was “sometimes” (3–4 times per week), we assigned a random probability for either 3 or 4 days and selected the frequency with higher probability value. The specified number of meals was then randomly assigned throughout the week.

The same method was applied to characterize meal patterns for self-reported range or oven use of “frequently” (5–7 days), i.e., a random probability for 5, 6, or 7 days and then randomly generate a meal pattern for that household that corresponds with the selected discrete cooking frequency.

2.5.2 Web-Based Cooking Survey to Supplement RASS Cooking Activity Data

RASS provided some but not all of the specifications required for GCB activity. The RASS activity question and stored data do not differentiate between oven and cooktop use, specify number of burners used or the amount of time the GCB was on. We could find no other public information about these parameters.

The use duration will have a first-order effect on modeling results (pollutant concentrations) since emissions are related to the amount of activity (in this case, burner use). Reason suggests that the amount of burner use per cooked meal should be related to the number of household residents, type of food cooked, and potentially to the frequency of cooking (cooked meals may be more elaborate and involve more burners in households that cook regularly). Indeed, the RASS dataset indicates that the number and age of household members appears to influence cooking activity (i.e., frequency of cooking a given meal using a gas stove and/or oven) to a

larger extent than total number of household occupants, ethnicity, and home building type (analysis and findings are included in Appendix C). In summary, we found the following:

- The distribution of cooktop and/or oven use for a given meal is fairly consistent across building types, with the exception of cooking dinner among the “often” category (5–7 times per week). Over 47 percent of single-family detached home households fell into this category, but only 37 percent of all households living in mobile homes did.
- The distribution in cooking frequency by household occupancy (number of residents) varies more than by building type, especially with respect to the frequency of range or oven use to cook dinner. As household occupancy increases, there is a general trend of increased frequency of oven or range use to prepare breakfast, lunch, and dinner. This is particularly evident in the “often” (5–7 times per week) oven or range use category. Nearly 57 percent of all five-or-more-person households report using their range and/or oven frequently (5–7 times per week) to cook dinner, while only 24 percent of one-person households report doing so.
- White/Caucasian households tend more to “never” cook breakfast or lunch using their range and/or oven, relative to other ethnicities. Hispanic/Latin households tend to cook breakfast and lunch more frequently than other ethnicities. Asian/Pacific Islanders tend to cook dinner most frequently (5–7 times per week), relative to other ethnic groups.

To obtain supplemental household cooking activity information to the RASS, we created and deployed a web-based cooking activity survey. This survey provides additional supplemental meal-specific (breakfast, lunch and dinner) information on the following cooking activity factors:

- Use of oven and oven cook-time for meal preparation (breakfast, lunch and dinner)
- Use of cooktop and cooktop cook-time for meal preparation (breakfast, lunch and dinner)
- Weekend vs. weekday cooking activity
- Total household occupancy, and age distribution (0–17 years old, 18–65 years old, and over 65 years old) of household occupants during cooking event
- Number of cooktop burners used during a given cooking event

The web-based cooking survey also asked about household characteristics, including:

- Ethnic representation in household (American Indian/Alaska Native, Asian or Pacific Islander, Black/African American, Hispanic/Latino, White/Caucasian, or Other)
- The building type of the residence (single-family detached, townhome/duplex, 2–4 unit condo or apartment, or mobile home)
- Additional characteristics, such as location of residence (in or outside of California)

The Human Subjects exempted web-based cooking survey is provided in Appendix D.

Over a period of roughly one month during spring 2010, we received 370 responses to the web-based cooking survey. Obtaining information from even a small, non-random sample of actual households provides estimates of the key parameters that will be much better than values we would otherwise assume. Although the web-based survey design is not population-representative, we collected data from a sample that includes enough variability in the key independent variables to provide at least first-order estimates of how the dependent variables of interest (cooking time per meal, oven versus cooktop use) relate to these independent variables.

Based on the responses to the web-based survey, we defined distributions of cooking duration for each meal (breakfast, lunch, dinner, and “other”) and cooktop burner use as a function of household occupancy and age of household numbers, based on four household occupancy categories outlined in Table 5.

Table 5: Household Occupancy Categories and Counts (N) from RASS and the Web-Based Cooking Survey

Household Members	Additional Household Specifications on Members	N (RASS Households) ¹	N (Web-based Cooking Survey Households)
Kids(s) + Adult(s)/Senior(s):	Households with at least 1 child (0-18 yrs) and 1 adult or senior (18-99 yrs)	7,268 (34.2%)	112 (33.3%)
2+ Adult(s) and/or Senior(s)	Households with 2 or more adults and/or seniors (18-99 yrs) and no kids	9,336 (43.9%)	159 (47.3%)
1 adult	Households with only 1 adult (18-65 yrs), no kids, no seniors	2,498 (11.8%)	53 (15.8%)
1 senior	Households with only 1 senior (65-99 yrs), no kids, no adults	2,141 (10.0%)	12 (3.6%)

¹ Among all RASS households

Table 8 provides information on the proportion of RASS households that reported their frequency of cooking with a gas stove and/or oven during a typical week. Table 8 also compares the proportion of RASS and web-based survey households that reported “never” using their cooktop and/or oven and those that reported using it 1–2 times per week, 3–4 times per week, and more frequent use (5–7 time per week). Because the bulk of the households in the web-based cooking survey fall into either the “never” or “frequent” category, Table 8 provides the proportions of cooking frequencies derived from the web-based cooking survey from these two categories.

Likely because the web-based survey respondents have higher socioeconomic status (SES), and the adult and senior members of the respondent households are employed outside the home during the day, the proportion of respondents in each household member profile that reported “never” using the cooktop and/or oven to cook breakfast and lunch is generally much higher among survey respondents than among RASS respondents. Further, the proportion of households who use the cooktop and/or oven to prepare a meal frequently is much lower for breakfast and lunch among the web-based survey respondents. However, the proportion of respondents in the “never” and frequent (5–7 times) use categories for dinner agrees fairly well between the two studies (Table 8), with the exception of one-person senior households; the proportion of these households that reported cooking frequently with a cooktop and/or oven

during the week was higher in the web-based cooking survey than in the RASS (50.0 percent versus 30.8 percent).

Table 6: Cooking Frequency by Meal and Household Composition Based on RASS 2003 Data.^a

Household Composition	<Once per week ^b	1–2 times per week	3–4 times per week	5–7 times per week
Breakfast				
Kid(s) + Adult(s)/Senior(s)	37.4 (71)%	23.8%	13.1%	16.7 (5.4)%
2+ adults and/or seniors	41.8 (77.4)%	21.1%	10.8%	17.1 (12.6)%
1 adult	56.4 (84.9)%	16.9%	6.8%	11.4 (7.5)%
1 senior	37.7 (91.7)%	15.1%	10.1%	21.9 (8.3)%
Lunch				
Kid(s) + adult(s)/senior(s)	45.7 (63.0)%	21.2%	10.8%	9.9 (0.9)%
2+ adults and/or seniors	50.6 (72.3)%	19.0%	9.5%	8.1 (4.4)%
1 adult	64.7 (73.4)%	15.3%	4.9%	2.9 (1.9)%
1 senior	43.0 (83.3)%	15.2%	8.6%	9.4 (0%) ¹
Dinner				
Kid(s) + adult(s)/senior(s)	8.4 (6.3)%	11.5%	27.0%	48.6 (52)%
2+ adults and/or seniors	8.0 (8.8)%	14.0%	29.7%	45.2 (45.9)%
1 adult	20.2 (11.3)%	24.7%	30.6%	21.9 (28.3)%
1 senior	17.5 (16.7)%	20.0%	23.4%	30.8 (50.0)%

^a The proportion of RASS households who reported using a range or oven to cook breakfast, lunch, or dinner “never,” “1–2,” “3–4,” or “frequently” (5–7 times per week) in a typical week. Proportion of households from the web-based cooking survey are also provided (in parentheses) for the “never” and “frequent” oven and/or cooktop using households.

^b Includes “never” and “rarely” (<1/week) responses; no cooking events are assigned to this group.

2.5.3 Burner Use Frequency and Burner Intensity

Based on the web-based cooking survey results in Table 9, we randomly assign the use of one or two cooktop burner(s) to 70 percent and 30 percent, respectively of all RASS households that cooked breakfast. If lunch was cooked in a household, we randomly assign one cooktop burner to 70 percent of these households, and two cooktop burners to 30 percent of all the households that cooked lunch. If dinner was cooked in any households, we assume that two cooktop burners were used. A fuel use rate corresponding to 7,000 Btu/hr is assumed for each cooktop burner.

Table 7: Number of Burners Used to Cook “Breakfast,” “Lunch,” and “Dinner” (Yesterday). Responses Obtained from the Web-based Cooking Survey.

Household Composition	Median	Mean	Std Dev	N ^a	% of Responses Indicating # of CT Burners Used
Breakfast					
Kid(s) + Adult(s)/Senior(s)	1	1.4	0.6	54	48%
2+ Adults and/or seniors	1	1.2	0.5	77	48%
1 adult	1	1.4	0.5	20	38%
1 senior	1	1.3	0.5	7	58%
Lunch					
Kid(s) + Adult(s)/Senior(s)	1	1.4	0.8	27	24%
2+ Adults and/or seniors	1	1.3	0.5	34	21%
1 adult	1	1.3	0.5	11	21%
1 senior	1	1.3	0.6	3	25%
Dinner					
Kid(s) + Adult(s)/Senior(s)	2	1.8	0.8	90	80%
2+ Adults and/or seniors	2	1.9	0.8	118	74%
1 adult	2	1.8	0.7	32	60%
1 senior	2	2.1	0.6	9	75%

^a Number of responses to the question “how many cooktop burners were used” for a specified meal

2.5.4 Duration of Cooktop and Oven Burner Use

The following Tables 10 and 11 summarize web-based cooking survey responses on the household meal-specific cooktop burner use duration, and oven duration, respectively. The summary statistics provide in Tables 10 and 11 apply to household that provided a response as to whether or not the cooktop or oven was used yesterday.

Because less than 10 percent of all respondents, and less than 30 percent of all households that used their cooktop, in the web-based cooking survey households indicated using the oven to prepare Breakfast or Lunch (based on frequencies in the last column of Table 11), with the exception of one-senior households for breakfast, we assume that the oven is used solely for dinner.

If a RASS household cooked breakfast or lunch on a given day, then we sample from a lognormal distribution of cooktop-use duration (based on the GM and GSD reported in Table 10) specific to one of the four household occupancy category (defined in Table 7).

Considering as a basis the households that reported using the cooktop or oven to do any cooking during a particular meal, Table 9 shows the percentage that reported the amount of time they used their oven in the specified meal.

In some household composition types, the proportion of oven-users among cookers was close to 10 percent. However, on the order of half the households in each category reported using the oven to prepare dinner. For simplicity, the exposure model assumes that oven use is associated solely with dinner cooking. Among the RASS gas cooking appliance households, we therefore assume that oven-use is in addition to cooktop use, and randomly assign oven use to 50 percent of these household-occupancy types.

Table 8: Summary Statistics on Duration of Cooktop Use [in Minutes] for a Given Meal Based on Household Responses from the LBNL Web-based Cooking Survey.^a

Household Composition	Median	Mean	Std Dev	GM	GSD	Count ^b	% of Each HH Type Reporting the Duration of CT Use to Cook a Given Meal
Breakfast							
Kid(s) + Adult(s)/Senior(s)	10	16.1	16.9	12.0	2.4	58	52%
2+ Adults and/or seniors	10	12.0	7.6	10.3	1.8	82	52%
1 adult	10	14.5	13.0	11.1	2.2	22	42%
1 senior	10	12.9	8.1	11.2	1.8	7	58%
Lunch							
Kid(s) + Adult(s)/Senior(s)	10	24.3	34.7	13.8	2.9	28	25%
2+ Adults and/or seniors	15	20.0	15.5	15.4	2.0	38	24%
1 adult	10	16.8	12.7	13.3	2.0	11	21%
1 senior	5	13.3	14.4	9.1	2.4	3	25%
Dinner							
Kid(s) + Adult(s)/Senior(s)	30	34.9	22.3	28.7	1.8	94	84%
2+ Adults and/or seniors	30	32.7	20.9	26.6	1.8	126	79%
1 adult	30	35.2	24.2	26.7	1.9	33	62%
1 senior	30	32.3	15.4	28.5	1.6	11	92%

^a Respondents selected from following options: 0, 1–5 min, 6–10 min, 11–15 min, 16–30 min, 31–45 min, 46–60 min, 61–90 min, 91–120 min, and more than 120 minutes, “don’t know” and “decline to state.” We rounded all responses to the highest value in a given range, but “more than 120 minutes” was assumed to be 120 minutes.

^b Number of households of a given composition that reported using their cooktop for a given meal

Table 9: Summary Statistics on Duration of Oven Use [in Minutes] for a Given Meal Based on Household Responses from the LBNL Web-based Cooking Survey.^a

Household Composition	Median	Mean	Std Dev	GM	GSD	Count ^b	% of Households that Report Using Cooktop that Also Report Using Oven for the Specified Meal. ^c
Breakfast							
Kid(s) + Adult(s)/Senior(s)	15	23.2	15.0	19.6	1.8	11	18%
2+ Adults and/or seniors	10	12.3	9.6	9.6	2.0	11	13%
1 adult	10	23.0	22.8	15.5	2.3	5	23%
1 senior	7.5	7.5	3.5	7.1	1.6	2	29%
Lunch							
Kid(s) + Adult(s)/Senior(s)	15	12.5	5	11.4	1.5	4	13%
2+ Adults and/or seniors	15	16.0	10.5	12.8	1.8	10	25%
1 adult	30	35.0	22.9	30.0	1.8	3	25%
1 senior	5	5.0	n/a	5.0	n/a	1	33%
Dinner							
Kid(s) + Adult(s)/Senior(s)	45	49.5	27.5	40.6	1.7	57	55%
2+ Adults and/or seniors	30	44.4	26.7	36.3	1.7	62	47%
1 adult	30	28.9	17.5	23.4	1.8	18	50%
1 senior	30	31.7	12.9	28.6	1.5	6	55%

^a Respondents selected from following options: 0, 1–5 min, 6–10 min, 11–15 min, 16–30 min, 31–45 min, 46–60 min, 61–90 min, 91–120 min, and more than 120 minutes, “don’t know” and “decline to state.” We rounded all responses to the highest value in a given range, but “more than 120 minutes” was assumed to be 120 minutes.

^b Number of households in a given HH category that reported using their oven to prepare for a given meal

^c Proportion based on all households that reported cooktop and/or oven use.

Interestingly, the median dinner cooktop and oven cooking durations across all household occupancy categories (Tables 10 and 11) are similar to those reported by occupants of 3- to 5-year-old homes in California in 2007-8 (Offermann 2009). That study found a median total cooking activity time of 35 minutes (range from 0.3 minutes to 295 minutes) based on occupant-reported cooking activity over a 24-hour period. Our model assigns a median dinner cooktop burner use duration of 30 minutes, across all households (Table 10). For oven use during dinner, the median web-based cooking survey responses are 30 minutes for all households, with the exception of 45 minutes for households with kids (0-18 years old); this value is similar to the median oven baking time of 45 minutes reported by Offermann (2009).

2.5.5 Oven Burner Use Algorithm

The reported overall oven use durations must be translated to burner operation times to account for on/off cycling of oven burners. When an oven is started, the burner ignites and remains on until the thermostat reaches (or with modern controls, approaches) the desired temperature. The burner is then stopped and the temperature of the oven will slowly drift downward as heat is lost to surroundings and any food that is being cooked. The burner is restarted when some lower temperature is reached. The oven burner will then continue to cycle to maintain the temperature within some bound of the set point. While a small percentage of ovens have modulating burners, most cycle on and off, operating at a single firing (fuel input) rate. The cycling schedule varies by oven and is in large part a function of oven construction (e.g., insulation) and burner firing rate.

To capture the total oven burner “on” time, we extracted on/off cycling patterns from the 10-second resolved experimental data from Singer et al. (2009) to determine a burner firing algorithm for each oven used in our simulation. These oven-specific algorithms were used to translate the reported oven use durations (from web-based survey) to burner operation times. The oven burner algorithms are specified using the following parameters:

- Oven ramp time (initial burner “on time”).
- Fraction of time burner is operating after initial firing to first reach temperature set point.
- Total oven use duration; this is provided by the oven cooking duration reported by the web-based cooking survey respondents.

The oven burner time algorithm, and firing rate [kBtu/h] for each of the twelve ovens is summarized in Table 13.

Table 10: Equations Used to Translate Reported Oven Use Times to Oven Burner Operation Times.^a

Oven ID	Measured Firing Rate [kBtu/hr]	Nominal Firing Rate [kBtu/hr]	Oven Burner Operation Time
OV01	15.7	15.5	$5.8 + 0.33 * (\text{Oven use} - 5.8)$
OV02	16	18	$6.0 + 0.25 * (\text{Oven use} - 6.0)$
OV03	18.5	18	$7.2 + 0.17 * (\text{Oven use} - 7.2)$
OV05	18	18	$7.8 + 0.43 * (\text{Oven use} - 7.8)$
OV06	16	16	$7.5 + 0.20 * (\text{Oven use} - 7.5)$
OV07	18	18	$10.3 + 0.39 * (\text{Oven use} - 10.3)$
OV08	18	18	$5. + 0.18 * (\text{Oven use} - 5.2)$
OV09	18	18 ^b	$7.0 + 0.23 * (\text{Oven use} - 7.0)$
OV10	15	18	$11.0 + 0.5 * (\text{Oven use} - 11.0)$
OV11	8.6 ^c	16	Same as oven use. ^c
OV12	16	16	$7.9 + 0.13 * (\text{Oven use} - 7.9)$
OV13	17	18	$7.3 + 0.17 * (\text{Oven use} - 7.3)$

^a "Oven use" is the total duration of use (in minutes), assigned in simulations from a lognormal distribution based on web-based cooking survey responses (Table 11). Burner operation time depends on firing rate, insulation, and other device-specific parameters. These equations are based on oven experiments reported in Singer et al. (2009).

^b The nominal firing rate of OV09 was not legible on the appliance label. The value was determined from product information.

^c The OV11 burner operated at a lower firing rate and did not regularly cycle. This improperly functioning burner was retained in the data set to represent marginal appliances that are known to exist in the population. This report's results were produced with the measured firing rates shown in Table 10. Nominal firing rates were inadvertently used in the quality assurance run.

2.5.6 Cooking Start Time for Breakfast, Lunch, and Dinner

Each meal cooked in a RASS residence is assigned a start time. The start time can be any one of six meal start times, as a function of weekend/weekday and the age and number of household occupants. Single-person (adult and/or senior only) households tend to have different meal start times than households with children.

The median start time reported in the NHAPS diaries for "preparing a meal" is taken as a reasonable estimate for the cooking start times. These cooking event start times are summarized in Table 11. The start times listed are visually assessed by the NHAPS food-preparation plots provided in Appendix C, and tend to be consistent for 18- to 64-year-olds and 65+-year-olds.

Table 11: Meal Preparation (Cooking) Start Times Included in the Exposure Model Simulation

Household Composition	Breakfast		Lunch		Dinner	
	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend

Adult(s) and/or Senior(s) plus kid(s) (0-18 yrs)	7:00 am	8:00 am	noon	noon	5:30 pm	6:00 pm
Senior(s) only (>65 yrs)	7:00 am	7:00 am	11:30 am	11:30 am	5:00 pm	5:00 pm
Adult(s) only (19-64 yrs), no kids	7:00 am	9:00 am	noon	noon	5:30 pm	6:00 pm

2.6 Pollutant Emission Factors

The data source for measured CO, HCHO, NO, and NO₂ baseline natural gas and LNG emission factors is Singer et al. (2009). The report presents pollutant emission factors measured from 13 gas ranges, specifically examining 13 sets of cooktop burners, 12 ovens, and 5 broiler burners (distinct from oven burners that can be used in broil mode) operated with PG&E line gas (representing California baseline) and several mixtures intended to simulate liquefied natural gas. The fuels varied in composition and in Wobbe number (WN), a measure of energy delivery rate for fixed orifice burners. For this reason, WN is used by the gas industry to characterize fuel variability. The baseline fuels in most cases had Wobbe numbers in the range of 1,330–1,340 Btu/scf. Although PG&E gas is not distributed throughout California, its properties (WN and composition) can be considered representative of the conventional fuel used by much of the state’s population. Simulated LNG mixtures had Wobbe numbers around 1,415–1,425, 1,380–1,390, and 1360 Btu/scf.

Emission factors were fit to linear bivariate or multivariate regressions with fuel Wobbe number as an independent variable. Cooktops were operated with all burners at maximum firing rate; ovens were operated at temperature settings of 350°F, 425°F, and 500°F. Multivariate regression was used to analyze oven results because temperature setting was found to have an independent impact on emissions. The result of the regression analysis was a calculated change in the emission factor per increase in fuel Wobbe number of 25 Btu/scf. This slope can be scaled to estimate the emissions change for any Wobbe number increase. This analysis examined the effect of a 50 WN increase from conventional (PG&E) gas. The LNG emission factor associated with an increase in WN to 1385 is characterized by doubling the 25 Btu/scf WN change in emissions.

Table 12 and Table 13 present the individual burner emission factors used in this analysis. For each burner we present the baseline emission factors (EF_{base}) and the estimated change in emission factors for a 50 Btu/scf increase in fuel WN. These tables have been developed from the primary results of Singer et al. (2009), who reported results based on a WN increase of 25 Btu/scf. The change with higher WN is expressed as a mean estimate and a 95 percent confidence interval. Mean estimates are sometimes negative, indicating an estimated reduction in emissions with increase in WN. In many cases the confidence interval extends beyond zero, indicating that the estimated impact is not statistically discernible from no impact at the 95 percent confidence interval. We incorporate the confidence interval by sampling from the implied distribution for each simulated case, as described below.

The emission factors and WN effects shown in the tables below are based on emissions occurring over complete burns, including transient effects, and not solely on stabilized (fully

warmed) burner operation. Results for cooktops were obtained during experiments in which the four corner burners were operated on the highest firing rate for 15 minutes while a 5-liter (L) pot containing 4 L of water was on each burner. Oven emission factors were measured during ramp-up burns, as the oven was set first to 350°F, then 425°F, then 500°F. Since oven emission factors varied with the temperature setting and there were few replicates at each setting, we used the multivariate analysis results for effect of fuel WN on oven emissions of CO, NO₂, and NO, as presented by Singer et al. (2009). Formaldehyde was quantified from integrated samples collected during full cycles of operation, including all three of the temperature settings; therefore, the effect of WN on HCHO emission factors is based on bivariate regression (ibid).

Among the appliances tested by Singer et al. (2009), there was no clear trend with age for either cooktop or oven baseline emission factors and the emission factors for cooktops and ovens from the same ranges were not strongly correlated.

Each household was randomly assigned emission characteristics (a set of baseline emission factors and changes with higher WN) from one of the 12 cooktops and one of the 12 ovens. These were selected independently, meaning that a given household was likely to have emission characteristics from a cooktop and an oven from different ranges tested by Singer et al. (2009) This separation is warranted because the oven and cooktop emission factors were not correlated with each other or with age. By not matching the measured oven and cooktop emission factors, we increased variability in a key input factor, with a first-order effect on indoor concentrations.

For each household simulation, we calculated an LNG emission factor based on the assigned baseline emission factors and the associated estimates of changes in emission factors for a change of 50 Btu/scf of fuel WN. This is summarized in the equation below:

$$EF_{LNG} = EF_{base} + \Delta EF / \Delta 50WN \quad (5)$$

For each pollutant, we select a value for $\Delta EF / \Delta 50WN$ based on the estimated distribution of values summarized in Table 12 and Table 13. The distributions are assumed to be normal, described by the mean and 95 percent confidence interval values. Thus, for all homes that are assigned the same baseline emission factor for cooktop CO emissions, the emission factors for LNG use in those same homes are a distribution of values whose mean is equal to the baseline plus or minus the mean estimated change in emission factor with a 50 Btu/scf WN increase.

The assignment of baseline and LNG emission factors is by household. Once assigned, these emission factors will be used for all cooking activity in that household.

For reference, the mean $EF_{PG\&E}$ and the $\Delta pollutant / \Delta 25WN$ (with 95 percent CI) reported in Singer et al. (2009) are provided in Appendix E. The cooktops and ovens that had estimated mean changes with LNG that were statistically discernible at 95 percent confidence interval (or $p < 0.05$) are also highlighted in the Appendix E tables.

Table 12: Emission Factors [ng of Pollutant per J of Fuel Use] for Cooktop Burners^a

ID	Age (yrs)	CO		NO ₂		HCHO		NO	
		EF _{base} [ng J ⁻¹]	ΔCO/Δ50WN mean (95% CI)	EF _{base} [ng J ⁻¹]	ΔNO ₂ /Δ50WN mean (95% CI)	EF _{base} [ng J ⁻¹]	ΔHCHO/Δ50WN mean (95% CI)	EF _{base} [ng J ⁻¹]	ΔNO/Δ50WN mean (95% CI)
CT01	12	11	2 (0,6)	6.7	1 (0.4, 1.6)	0.31	0.10 (0.06, 0.16)	24.8	0.06 (-0.92, 1.06)
CT02	9	29	4(0,6)	8.5	0.48 (0.03, 0.94) ^b	0.55	0.08 (-0.58, 0.76)	28.7	0.4 (-1.64, 2.42)
CT03	6	231	68 (42,96)	12.1	2.4 (1.4, 3.4)	1.00	0.62 (0.44, 0.80)	22.8	-0.88 (-2.42, 0.66)
CT04	2	42	4 (-30,38)	10.0	0.2 (-1.0,1.6)	-	-	37.3	0.20 (-2.36, 2.78)
CT05	5	87	-2 (-4,2)	11.2	0.4 (-0.6,1.2)	0.67	0.02 (-0.26, 0.30)	30.8	1.56 (1.30, 1.84)
CT06	11	13	12 (6, 16)	5.0	0.0 (-0.4,0.4)	0.12	0.00 (-0.12,0.12)	33.5	0.68 (-0.36, 1.72)
CT07	13	59	10 (4, 14)	7.3	0.8 (0.4, 1.4)	0.44	0.16 (0.06,0.26)	27.0	-0.52 (-0.88, -0.18)
CT08	16	7	2 (0,4)	6.7	0.2 (-0.2, 0.6)	0.09	0.00 (-0.04,0.04)	26.8	0.26 (-0.76,1.28)
CT09	2	823	48 (22,74)	17.7	0.2 (-0.2, 0.8)	4.67	0.00 (-0.56,0.54)	7.25	-0.84 (-1.52, -0.16)
CT10	12	57	16 (12,18)	9.6	-0.2 (-1.8,1.6)	1.15	-0.32 (-0.90,0.26)	26.6	0.48 (-1.54, 2.52)
CT11	8	107	24 (12,38)	7.6	0.4 (-0.2, 0.8)	0.31	-0.04 (-0.18,0.10)	22.1	0.34 (-0.34, 1.02)
CT12	17	123	50(32,66)	10.2	1.2 (0.2, 2.0)	0.81	0.08 (-0.12,0.26)	24.3	-1.78 (-2.16, -1.40)
CT13	6	48	26 (20,32)	7.1	0.8 (0.0,1.6)	0.10	0.02 (-0.14,0.20)	27.8	-0.28 (-1.10, 0.56)

^a Each row represents one set of cooktop burners, corresponding to Table 34 (CO), Table 38 (NO₂), Table 42 (HCHO), and Table 45 (NO_x) of Singer et al. (2009). Baseline emission factors (EF_{base}) were measured with PG&E line gas. Change in emission factors with LNG calculated from results of experiments with simulated LNG blends having higher Wobbe numbers (WN). Change is expressed as mean (lower and upper bounds of 95 percent confidence interval) per increase in fuel WN of 50 Btu/scf. Details are provided in Singer et al. (2009).

^b The additional digit was included to avoid apparent asymmetry that would appear from rounding to two significant figures.

Table 13: Emission Factors for Oven Burners^a

ID	Age (yrs)	CO		NO ₂		HCHO		NO	
		EF _{base} [ng J ⁻¹]	ΔCO/Δ50WN mean (95% CI)	EF _{base} [ng J ⁻¹]	ΔNO ₂ /50WN mean (95% CI)	EF _{base} [ng J ⁻¹]	ΔHCHO/Δ50WN mean (95% CI)	EF _{base} [ng J ⁻¹]	ΔNO/Δ50WN mean (95% CI)
OV01	12	16	6 (4,8)	3.8	0.2 (-0.4, 1.0)	0.49	-0.02 (-, -)	32.1	0.4 (-0.4, 1.2)
OV02	9	99	34 (-6,74)	7.5	1.4 (0.6, 2.2)	0.38	0.04 (-0.04,0.14)	26.8	-1.4 (-3.7, 0.9)
OV03	6	61	56 (46, 66)	5.1	0.8 (0.4, 1.2)	0.46	-0.02(-0.38,0.32)	32.1	-1.6 (-3.8, 0.5)
OV04	Not evaluated.								
OV05	5	163	40 (34, 44)	13.9	0.2 (-0.2, 0.6)	0.43	0.10 (0.04,0.24)	17.5	-1.1 (-1.6, -0.6)
OV06	11	124	12 (6, 18)	8.1	0 (-0.2,0.2)	1.01	-0.02(-0.26,0.24)	24.9	0.4 (-0.8, 1.7)
OV07	13	156	10 (4, 14)	6.1	0.6 (0.2, 0.8)	0.57	0.04(-0.20,0.28)	25.6	-1.3 (-1.7, -0.9)
OV08	16	108	32 (18, 48)	5.5	0.6 (0.2, 1.0)	2.98	-0.62(-1.88,0.64)	27.8	-1.9 (-2.8, -1.0)
OV09	2	174	34 (6, 62)	11.3	0 (-0.2,0.2)	0.60	-0.06(-0.96,0.86)	16.1	-2.0 (-3.1, -0.9)
OV10	12	58	14 (12, 18)	4.4	1.0 (0.8, 1.2)	0.32	0 (-0.06,0.04)	28.5	-1.0 (-1.4, -0.6)
OV11	8	528	-74 (-124,-24)	13.2	0.4 (-0.4,1.0)	5.51	-0.2(-1.38,0.96)	27.3	0.6 (-0.5, 1.8)
OV12	17	36	6 (4, 8)	5.6	0.6 (0.2, 0.8)	0.25	0 (-0.04,0.02)	28.9	-1.3(-1.9, -0.7)
OV13	6	70	32 (26, 40)	6.3	2.4 (1.6, 3.2)	0.33	0.06(0.06,0.08)	33.4	-3.0 (-3.7, -2.3)

^a Each row represents one set of cooktop burners, based on Table 34 (CO), Table 38 (NO₂), Table 42 (HCHO), and Table 45 (NO_x) of Singer et al. (2009). Baseline emission factors were measured with PG&E line gas. Change in emission factors with LNG were calculated from the results of experiments with simulated LNG blends having higher Wobbe numbers (WN). The change is expressed as mean (lower and upper bounds of 95 percent confidence interval) per increase in fuel WN of 50 Btu/scf. Details are provided in Singer et al. (2009).

2.7 Pollutant Concentrations in Outdoor Air

Outdoor concentrations of NO, NO₂, and CO vary both temporally and spatially. Temporal variability occurs on diurnal, weekly, and seasonal time scales. Diurnally variability results from time-variations in emissions (e.g., with variations in light-duty and heavy-duty vehicle traffic), atmospheric mixing and transport, and chemistry. Day-of-week variability results from variations in emissions related to traffic and power generation. Seasonal variability results from variations in atmospheric conditions that affect mixing, transport, and chemistry. Spatial variations apply to both time-averaged (e.g., annual mean) concentrations and the temporal patterns. Spatial variations exist both between and within regions/air basins, down to the scale of near roadway effects. Extensive modeling and measurement-based research has been conducted to characterize and understand the temporal and spatial variations in ambient air pollutant concentrations.

Our objective in incorporating outdoor pollutant concentration profiles was to assess the impact of indoor emissions adding to (unavoidable) entry of outdoor pollutants to yield overall concentrations above health-based standards. To accomplish this objective, we utilized records of measured outdoor concentrations to develop profiles that capture major temporal and spatial variations and reflect typical outdoor pollutant levels around the state. As a data source, we used hourly data collected in 2008 by state and local air pollution agencies through a network of spatially distributed air pollutant monitoring stations. Summary data for each monitor is available from the U.S. EPA's AIRData website (U.S. EPA 2010b).

Outdoor concentration profiles used in our simulations were resolved as follows. Temporal variability was captured by specifying one-week outdoor profiles for summer and winter conditions. Separate weekday and weekend profiles are available for both seasons. Summer conditions include higher mixing depths, longer days with more photochemistry, and distinct emission profiles. Winter conditions include nighttime inversions that can lead to concentration and retention of evening rush hour emissions among other distinct characteristics. Summer was represented by ambient concentrations measured in the month of June. A profile was developed for each day of the week by calculating the average concentration during each hour of the day from all available days. This approach retains the distinct patterns that can persist, e.g., for weekdays versus weekends. A winter profile was developed using the same approach with concentrations measured during the first three weeks of December; the final week of December is atypical because of holiday-related activities and schedules.

Broad spatial resolution was captured by selecting data from a representative air monitoring site for each county. In 2008 and 2009, there were 102 NO₂ and NO monitoring sites, and 74 CO monitoring sites, across California, according to the AIRData website. From these sites, we selected a typical NO₂ and NO monitor to represent a given county. For counties with more than one site measuring NO₂ and NO concentrations, we selected the site with an "arithmetic mean annual concentration" at the median of all sites within the county. Preference was given to monitors that belong to the SLAMS (State and Local Air Monitoring Site) network, but if a SLAMS monitor was not available in a given county, then another monitor with available hourly concentrations in the month of June and December was used. If two NO₂ monitors had

the same median arithmetic mean annual concentration, then the one with the lowest “maximum 1-hour NO₂” was chosen.

Once the NO₂ monitor was selected, hourly averaged CO- and NO-monitored concentrations were also requested at the site. However, in cases where the CO was not monitored at the selected NO₂ site, another CO monitoring site within the county was selected. If there were more than two CO monitoring sites in a given county, the CO site with the median maximum 1-hour CO concentration was selected. In some counties however, there are no CO monitors, and surrogate hourly average CO concentrations from a neighboring county were used.

Outdoor profiles were assigned to residences in our cohort based on the ZIP code provided in the RASS dataset. All homes in a given county had the same outdoor pollutant profiles.

Figure 4 displays the location of the selected NO₂ (and NO) and most of the CO monitors throughout California. Appendix F provides detailed information on the selected monitoring site, including the AIRData monitor site ID, location (latitude/longitude), and the counties to which the ambient monitoring data are assumed to apply.



Figure 4: Location of NO₂, NO, and CO Air Monitoring Stations Reporting Hourly Average Concentrations

2.8 Household Occupancy Patterns

The RASS dataset includes the age of each household member, allowing age-appropriate consideration of occupancy patterns. Using the National Human Activity Pattern Study’s (NHAPS) database (Klepeis et al. 2001), we defined age-specific time-location profiles and assigned the appropriate profile to each resident in each household. The NHAPS dataset contains 9,386 time-location diaries from which we identified typical time-location profiles for the following four age-defined groups: 0- to 5-year-olds; 6- to 18-year-olds; 18- to 64-year-olds; and 64+-year-olds. The major difference among the archetypal weekday activity patterns for these age groups is dependent on whether or not the individuals stayed at home, or were away from the residence the majority of the time. We applied a stay-at-home pattern for all 0- to 5-year-olds, and to one household member (19+-years-old) if lunch was reportedly cooked in the RASS household on any weekday; i.e., the specific household data contained in RASS indicates that the range or oven was used occasionally (1–2 times), sometimes (3–4 times) or often (5–7 times) during the week. All other household members are assumed to follow the archetypal “away from home” pattern during the weekdays. For the weekend, we assume an archetypal time-location pattern for each of the four age groups. The weekday and weekend profiles for each group are presented in Table 14.

Table 14: Archetypal/Simplified Time-Location Patterns Based on NHAPS Data

	Weekday Stay-at-Home Pattern^a	Weekday Away-from-Home Pattern^c	Weekend Pattern
0–5 years	If senior(s) is present in household, same pattern as 65+-year-olds. If no senior(s), same pattern as stay-at-home 19- to 64-year-olds	Not at home b/w 8:30 am to 5:30 pm. Home at all other times.	At home, except 2 pm–4 pm.
6–18 years	n/a	Not at home b/w 8:30 am to 3:00 pm. Home at all other times.	Same as 0–5 year weekend pattern
19–64 years	Home all the time ^b	Leave at 8:30 am, return at 5:30 pm and stay home until following morning.	Same as 0–5 year weekend pattern
65+ years	Always at home, except b/w 10–11 am (dark grey/black and white bars in the NHAPS plots seem to suggest this as reasonable)	n/a	Same as senior weekday stay-at-home pattern

^a Except for seniors, this archetypal pattern only applies if any lunch cooking occurred in a RASS household on any given weekday.

^b Only applies to one 19- to 64-year-old living in the household, if no senior(s) are residents.

^c Applies if cooking lunch with a gas stove and/or oven never occurred during weekday in a RASS household.

2.9 Exposures for Occupants Near to Source during Cooking

2.9.1 Background on Proximity Effect

Close proximity to a point source of indoor air pollutant emissions results in higher exposure concentrations than are predicted by assuming instantaneously perfect mixing throughout the residence or even the room in which the source and exposed person are located. Similarly,

concentrations generally are higher for those present in the same room or zone as the source, relative to other areas of the home. Concentrations predicted with a single-zone mass balance model will therefore under-predict exposures to cooking-related pollutants for those present in the kitchen during and shortly after cooking.

The “proximity effect” as described by McBride et al. (1999) has been studied experimentally and through simulation, examining both the effect of physical proximity within a room and variations in time-concentration profiles between zones or rooms. In experiments conducted in a large common room of a single-family house with open floor plan, McBride and co-workers found that measured near-source concentrations varied considerably while a CO source was on, and generally were higher than those predicted by a mass balance model assuming instantaneous mixing. Variations in near-source concentrations were attributed to micro-plumes that appeared as short-duration concentration peaks. After the CO source was turned off, the proximity effect attenuated rapidly and measured CO concentrations near the source approached the mass balance model predictions (McBride et al. 1999). Averaged over the entire six-hour experimental period, CO concentrations measured 0.5, 1.0, and 2.0 m from the source were, respectively, 4.1, 2.4, and 2.1 times the average of the CO concentration in the room (McBride et al. 1999).

Focusing on CO and secondhand smoke, Klepeis (1999) developed and demonstrated a simulation approach to track time concentration profiles in various rooms resulting from continuous smoking in one room. The approach uses superposition, whereby the source is divided into a series of “sub-sources” that are treated as separate emission events in various rooms at staggered start times. The concentration time series for each sub-source is then superimposed to get a concentration profile for each room in the residence. Other analytical methods to capture near-source exposures have also been reported by Miller et al. (1997), McBride et al. (1999), and Ott et al. (2003). For example, Ott et al. (2003) presented a Laplace transform approach to solve a two-compartment dynamic mass balance model. They used this approach to verify the well-mixed assumption for CO emitted to a room and also to predict concentrations of CO in multiple rooms of a home (ibid).

Ott et al. (ibid) also presented experimental results for concentration time series following smoking of a single cigarette. Concentrations were measured at multiple locations in the same room and in adjacent rooms. Concentrations at various points in the source room did not differ by more than 19–33 percent of the mean CO in the room. With doors open, concentrations of respirable suspended particles (RSP) from cigarettes smoked in adjacent rooms converge 45 minutes after smoking commenced (ibid).

2.9.2 Background on Proximity Effect as it Relates to Cooking Exposures

Previous studies characterizing CO and NO₂ exposures arising from gas cooking appliances provide relevant data on the “proximity effect” specific to this source. Sterling and Sterling (1979) found that in a study of nine different homes using gas stoves, CO diffuses rapidly through all rooms. However, 90 minutes after the stove was turned off, kitchen levels of CO were still slightly elevated relative to the living room and dining rooms of the home. As part of an extensive probability-based study to characterize residential CO and NO₂ exposures,

Sheldon et al. (1989) found that the seven-day average NO₂ concentration arising from gas-stove use indoors resulted in concentrations that were generally between 20–30 percent greater in the kitchen than in other rooms. Table 18 summarizes several additional studies that have reported average NO₂ concentrations in the kitchen that are generally between 20–40 percent greater than in other living areas of the house (Berwick et al. 1989; Garrett et al. 1999; Zota et al. 2005).

However, there can be a large degree of variation between concentration levels in the kitchen compared with other living areas of a home. Sheldon et al. (1989) found that the daily average NO₂ concentrations measured in the kitchen ranged from nearly equivalent to those measured in the living room, to a factor of two greater. Closer examination by Klepeis (2004) of individual homes in the Sheldon et al. (1989) study reveals that in one home “kitchen levels were consistently two to three times higher than those in the living room.” Likewise, Palmes et al. (1977, 1979) reported that NO₂ levels in homes with gas stoves can have kitchen levels between two to three times higher than “sourceless” or non-kitchen rooms. Wade and co-workers found that kitchen levels of NO₂ were consistently at least double those measured in other indoor living spaces (i.e., living room and bedroom). Hoek et al. (1984) reported that the ratio of the arithmetic mean of the average weekly NO₂ concentrations was roughly a factor of 2 and 3 higher in the kitchen, than in the living room and bedroom, respectively (Table 15). However, in a small study (n = 2 homes) by Melia et al. (1978), the hourly average NO₂ concentrations in gas-stove homes at 2 feet and 7.5 feet from the cooker were nearly equivalent (67.6 ppb and 72.0 ppb, respectively). Their findings, however, suggest that the similar concentrations may be the result of plume dynamics, such as the occurrence of micro-plumes reported by McBride et al. (1999).

Table 15: Mean NO₂ Concentrations Measured in Homes that Used a Gas Stove Located in the Kitchen

Study Reference	Kitchen	Living Area(s)	N (homes)
Hoek et al. (1984) ^a	144.0 µg/m ³	80.0 µg/m ³ (living room) 50.9 µg/m ³ (bedroom)	226
Berwick et al. (1989)	40.9 µg/m ³	24.9 µg/m ³ (living room) 28.5 µg/m ³ (bedroom)	13
Garrett et al. (1999)	15.3 µg/m ³	12.8 µg/m ³ (living room) 12.1 µg/m ³ (bedroom)	15
Zota et al. (2005)	50 ppb (heating season) 33 ppb (non heating season)	43 ppb 26 ppb	57 43

^a Homes with gas and electric appliances are included in this sample and weekly average concentrations reported.

A coherent understanding of the results described above requires consideration of the physical processes related to emissions and mixing of pollutants generated by gas cooking burners. During cooking (active burner use), pollutant concentrations should be much higher in the near vicinity – especially just above – the burners, and overall concentrations in the kitchen should be higher than in the rest of home. As air from the room or zone containing the kitchen mixes through the home, pollutant concentrations around the home will become more uniform. This

homogenization will necessarily be incomplete until sometime after emissions cease. Thus, during and after cooking, there will not be a uniform spatial distribution of mass emitted in one part of the home, e.g., from cooking appliance use. In contrast, if pollutant mass entering with outdoor air enters from multiple locations throughout the home, the indoor distribution of the mass from outdoors should be relatively uniform. (This is not the case if outdoor airflow entry and exhaust is predominantly directional and the pollutant deposits as the air moves through the home; this analysis ignores these effects). The overall distribution of concentrations of a pollutant with both the single location indoor source and coming in from outdoors will reflect the sum of these two processes.

Consistent with these processes, pollutant levels measured during and shortly after cooking have shown higher concentrations in the kitchen compared to other rooms in the residence (as described above). The difference reflects not only the proximity effect but also the relative magnitudes of the indoor and outdoor pollutant sources. Time-integrated measurements over longer periods reflect a combination of the relatively large differences between kitchens and other areas that occur during cooking and the smaller or non-existing differences that exist during periods not affected by cooking. In consideration of the literature described above, note that for both NO_x and NO₂, the ratio of kitchen to other room concentrations will be higher over time in homes containing cooking appliances with pilot lights. Pilot lights are uncommon today but were very common in the 1970s through 1990s, when many of the existing data were collected. Thus, the results from time-integrated sampling likely include the pilot burner effect.

The time-evolution of the ratio of exposure concentrations for someone nearby to the cooking appliance compared with those in other parts of the home depends on a suite of physical factors. Based on the literature summarized above, these factors include the following:

- Door positioning (closed or open doors between zones)
- Windows open or closed
- Temperature profile in room(s)
- Presence or use of mechanical ventilation units (i.e., range hoods)
- Presence of ceiling fans or other air circulation units
- Use of heating and cooling units
- Number of stories in the home
- Open or compartmentalized kitchen (related to age of home)
- Higher/lower ceilings

Apart from the use of heating and cooling units and the number of stories in the home, we do not have data on these household and building factors for each RASS gas appliance household. We rely instead on an ad-hoc approach that employs an exposure augmentation factor to estimate the proximity effect. Our approach is designed to estimate the increased exposure concentrations for the cooker and those in the kitchen during a cooking event with a gas appliance, relative to the exposure concentrations in the rest of the house (i.e., all living areas outside of the kitchen).

2.9.3 Estimation of Proximity Effect in Simulation for LNG Impacts

Based on the literature and physical considerations described above we use a statistical approach to estimate the higher exposure concentrations experienced by cooks and others who are likely to be close to the gas appliance during cooking. To calculate exposure concentrations for these individuals, a source-proximity factor (F_{prox}) is applied to the time-dependent concentration of indoor-origin pollutants, as presented below in Equation 6. This factor is applied only during the duration of cooking and only for the purpose of calculating exposure concentrations for the occupant(s) nearby to the source.

$$C_{i.exp}(t) = F_{prox} C_{i.indoor-origin}(t) + C_{i.outdoor-origin}(t) \quad (6)$$

A distinct F_{prox} is applied to the cooker, and to any young child(ren) between the ages of 0 and 5. For each cooking event, a single adult (18–64 years old) or senior (65+ years old) in the home is assumed to be the person cooking, and thus closest to the source. We assume that the cook experiences exposure concentrations that are 2.0 times the residence average value calculated assuming perfect mixing, therefore $F = 2.0$ for the adult cooker. This value incorporates both the near-source and room-level increments. If the household includes one or more adults aged 18–64, one (and only one) of these is assumed to be the cook. If all adults are seniors, then one (and only one) of the seniors is assumed to have this incremental exposure concentration. If the household includes both senior and non-senior adult occupant(s), we assume that the meal is cooked by a senior. Young children (age 0–5) are assumed to be nearby – in the kitchen or connected open room – and thus to experience exposure concentrations that are 1.5 times the calculated well-mixed residence value for indoor generated pollutants. Thus, $F_{prox} = 1.5$ for children 0–5 years of age. Table 16 summarizes the F_{prox} values for all members of the household.

It is assumed that the cook and young children leave the kitchen when cooking has finished and that mixing throughout the home happens quickly after emissions cease. All other household occupants are assumed to experience exposure concentrations at the calculated well-mixed level throughout the cooking event. Per the occupancy patterns outlined in Table 12, all other residents are either at home in a living area outside of the kitchen, or away from home when cooking with a gas appliance occurs.

Table 16: Assumed F_{prox} Value to Characterize Proximity Effects of Indoor Exposure Concentrations for Individual Household Occupants^a

Household Occupant	F_{prox}
Cook (senior or adult) ^b	2.0
Young child (0–5 years old)	1.5
Child (6–18 years old)	1
Non-cooking senior or adult	1

^a The predicted C_{inj} (Eqn. 2) are multiplied by F_{prox} during the use of gas cooking appliances to characterize individual exposures.

^b The cook is assumed to be a non-senior adult if present, or a senior adult if only seniors are present.

As part of the LNG impact assessment, we evaluate the sensitivity of the occupant (resident) output metrics based on varying the F_{prox} assumption from unity, i.e., no consideration of the proximity effect, to a doubling of the F_{prox} baseline assumption (Table 16). The specific F_{prox} sensitivity analyses are described further in the Modeling Scenarios section, below.

2.10 Outcome Metrics and Impact Assessment

The one-week, minute-by-minute indoor pollutant concentrations calculated for each residence and the associated exposure concentration profiles for each individual in our sample are used to assess both baseline and LNG-related public health impacts of pollutant emissions from natural gas cooking burners in the six-county SoCal region. Impacts are assessed through quantitative metrics for residences, and separately for individuals. Impacts are translated to the population by scaling from the number of homes and individuals in our simulation cohort to the number of homes and people receiving LNG. Impacts of LNG are assessed by comparing the outcomes associated with baseline fuel to the outcomes calculated for simulations in which LNG was used.

Impacts include both carcinogenic and non-cancer adverse health effects. Non-cancer adverse health outcomes are related to acute and chronic individual exposure and residential pollutant concentrations, and the frequency of exceedance events during which exposure limits are exceeded. Chronic exposures to HCHO affect individual and cumulative population cancer risk.

Table 17 summarizes relevant acute and chronic non-cancer health-based metrics. Exceedances of exposure limits or guidelines are considered in relation to the values presented in Table 1. Exceedances of acute standards are tracked at the level of individual meals for 1-hr averaging times and at the level of the day for 8-hr averaging times. Exceedance-based output metrics are tracked by calculating all occurrences of an acute standard for households, and separately for individuals. We then present results in terms of the fraction of households (HHs) (or individuals) that have at least one occurrence of a time-averaged concentration that exceeds a given standard.

Concentration-based metrics are considered as distributions across the population of residences and individuals. This allows consideration not just of mean or median values, but also of the percent exceeding some specific level of interest. Concentration metrics are calculated for acute and chronic (one-week) periods.

Whereas the assessment of chronic exposures would ideally consider longer averaging times, we consider these standards and calculate concentration on the basis of one-week averages.

The outcomes listed in Table 17 are characterized for conventional (baseline) NG and compared with the corresponding exposure metrics using LNG. Each outcome is reported across all six-county SoCal HHs ($n = 6,634$), as well as across all individuals living in these HHs ($n = 19,323$).

Table 17: Summary of Outcome Metrics for Characterizing Non-Carcinogenic Adverse Health Effects.

Outcome metrics are provided separately for concentrations resulting only from emissions of gas cooking burners (GCB) and considering both GCB emissions and outdoor sources.

Outcome	Pollutants	GCB only	GCB + outdoor sources
Maximum 1-hr concentration	CO	X	X
	NO ₂	X	X
	HCHO	X	
Maximum 8-hr concentrations	CO		X
	NO ₂		X
	HCHO	X	
Average 1-week concentration	CO	X	X
	NO ₂	X	X
	HCHO	X	
Exceeds 1-hr standard/guideline	CO	X	X
	NO ₂	X	X
	HCHO	X	
Exceeds 8-hr standard/guideline	CO		X
	HCHO	X	

Results for concentration-based output metrics are displayed using box plots.

Figure 5 displays the summary statistics that are included in each box plot. Because we are interested in presenting impacts associated with typical exposure concentrations, we present the 5th to 95th percentile range in output concentrations across households and separately for individual residents. The box plots of the time-averaged concentrations are followed by tables which include summary statistics (mean, standard deviation, median, and 25th and 75th percentile) of the distribution, and the proportion of HHs (or individuals) that have at least one exceedance of an applicable standard during a typical week (in summer and winter).

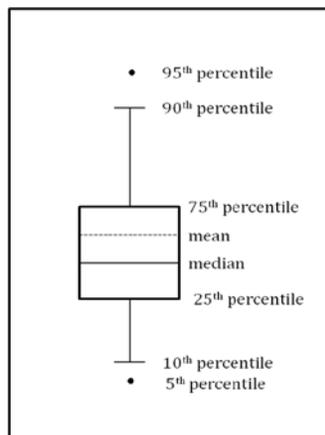


Figure 5: Definitions of Markers on Box Plots Used throughout This Report

2.11 HCHO Cancer Risk Assessment

For HCHO, we also considered the potential incremental cancer risk from cooking with gas appliances attributable to a shift from conventional natural gas to LNG. Incremental cancer risk is associated with an increase in chronic exposure concentrations.

2.12 Modeling Scenarios

We ran simulations that capture key variations in parameters to assess the impacts of GCB use associated with LNG relative to baseline natural gas, on exposures to CO, NO₂, and HCHO, and cancer risk due to HCHO in Southern California. We did this by applying the exposure model to a representative cohort of HHs located in six Southern California (SoCal) counties, including Los Angeles, San Bernardino, Riverside, San Diego, Orange, and Ventura counties. The model scenarios vary based on season (winter and summer) and associated assumptions of AER, value of F_{prox} , and baseline or LNG emission factors.

First, we compared output metrics for baseline NG and LNG based on varying season and AER assumptions. We ran simulations with baseline NG and LNG emission factors, using baseline F_{prox} (Table 16) and the following season and AER assignments:

- Winter, AER based on infiltration only
- Winter, AER from empirical distribution
- Summer, AER from empirical distribution

We also conducted sensitivity analyses on the modeled output metrics associated with varying the value of F_{prox} , using winter empirical AER. We select winter empirical AER scenario for these F_{prox} sensitivity runs because winter is the most sensitive time for exposure, as there is less window use/natural ventilation, and both the quantity and quality of winter AER data were slightly more favorable over the summer empirical AER data. In addition to the model runs with baseline F_{prox} (Table 16), we ran the exposure model with baseline NG then LNG emission factors and winter empirical AER with the following F_{prox} assumptions:

- F_{prox} of 1 for all young children and cooks. This can be considered as a bounding analyses to characterize the effect on output metrics if F_{prox} is not considered.
- F_{prox} that is double the baseline value (“2 x baseline”) or 3.0 for young children (0–5 years old) and 4.0 for adult cooks.

The $F_{\text{prox}} = 1$ scenario was run only for baseline NG, to assess the impact of F_{prox} on baseline results. We run the $F_{\text{prox}} = 2 \times$ baseline scenario twice—once with baseline NG, then for LNG emission factors—to assess the potential effect of LNG if F_{prox} is larger on average than estimated for our primary set of modeling scenarios.

The complete set of modeling simulations is summarized in Table 18. For each of these scenarios, we present box plots and/or summary statistics in tables for each of the output metrics shown in Table 17. The output metrics are characterized for baseline NG and compared with the exposure metrics assuming LNG emission factors. We estimate impacts in terms of the difference between the LNG and baseline scenarios. Exceedances of a given pollutant standard

(Table 1) associated with a given scenario are provided in terms of exceedances per 1,000 HHs and exceedances per 10,000 individuals.

Table 18: Modeling Scenarios Applied to the Full Six-County SoCal Cohort

	Winter		Summer
	Empirical AER	Infiltration Only	Empirical AER
Baseline NG emission factors			
$F_{prox} = \text{baseline}^a$	X	X	X
$F_{prox} = 1$	X		
$F_{prox} = 2 \times \text{baseline}^a$	X		
LNG emission factors			
$F_{prox} = \text{baseline}^a$	X	X	X
$F_{prox} = 2 \times \text{baseline}^a$	X		

^a Values of $F_{prox} = \text{baseline}$ provided in Table 16

2.13 Scaling Model Results to Scope of LNG Use

The overall impact of LNG depends, of course, on the scope of its use. Several key output metrics of the exposure model are formulated as the number of meals or number of homes in which an air quality standard is exceeded per 1,000 homes that receive LNG and use their gas cooking burners. We also present results for the number of exceedances of various exposure standards per 10,000 individuals living in homes that use GCBs. To understand the cumulative impacts, it is therefore necessary to have an estimate for the number of homes that use GCBs and receive LNG, and the number of people living in those homes. This section describes how we estimated the current and near-term expected scope of LNG distribution and the theoretical potential region wide scale of impacts, based on the total number of homes that use GCBs.

To assess the potential scale of these impacts, we first quantify the total number of HHs with gas appliances in the six-county SoCal region, and then estimate the number of these HHs that are likely to receive LNG.

The number of HHs in each county within the six-county SoCal region that use GCBs ($N_{GCB\ HHs}$) is estimated from U.S. Census counts of the county-level HHs, and from information on the prevalence and use of natural gas cooking appliances. Specifically, $N_{GCB\ HHs}$ is estimated as:

$$N_{GCB\ HHs} = N_{county\ HHs} \times \%_{NG\ HHs} \times \%_{GCB\ use\ HHs} \quad (7)$$

where,

$N_{county\ HHs}$ is the total number of HHs in a SoCal county reported by the 2000 Census.

$\%_{NG\ HHs}$ is the percent of all HHs that have natural gas cooking appliances. Based on the entire RASS cohort, 57.5 percent of households have a gas cookstove and/or oven, and we assume that this proportion applies to all California counties.

$\%_{GCB\ use\ HHs}$ indicates the percentage of HHs using gas cooking appliances. Based on the entire RASS cohort, 7.6 percent of natural gas-fueled HHs report cooking with their gas burner less than once per week. Since we cannot know the actual frequency of their cooking, for the purpose of our analysis, we treat these homes as never-cookers. Therefore, we assume 92.4 percent of all NG HHs in a given county use GCBs to prepare at least one meal per week.

The number of LNG HHs that use GCBs ($N_{LNG\ HHs}$) is estimated by multiplying Eq. 7 by an estimate of the percentage of HHs in a given county that receive LNG ($\%_{LNG\ HHs}$),

$$N_{LNG\ HHs} = N_{GCB\ HHs} \times \%_{LNG\ HHs} \quad (8)$$

where, $\%_{LNG\ HHs}$ is derived for each SoCal county assuming the projected distribution of LNG within the current natural gas infrastructure in California (Scenario 7 from Sospedra et al. 2011). Assumptions for $\%_{LNG\ HHs}$ are provided in Table 19, below. As seen from Table 19, LNG currently can reach nearly all gas-fueled residences in San Diego County and nearly a third of HHs in Riverside County. Liquefied natural gas is distributed to a much more limited extent to other SoCal counties.

In Table 19, we also summarize the number of total HHs in the county ($N_{county\ HHs}$) and provide estimates of the number of GCB HHs and LNG HHs. We also provide the distribution of RASS HHs that use GCBs during a typical week among each of the six SoCal counties.

These estimates suggest that LNG may reach as many as 20 percent of all HHs with gas appliances in the six-county SoCal region, with distribution focused in San Diego and Riverside counties. The exposure model can be run with homes from specific counties. However, as presented below in the Quality Assurance section, achieving stable population statistics for pollutant concentration outputs requires a sample size of a few thousand, and larger numbers are needed for exceedance-based output metrics. To conduct county-specific analysis therefore would require a resampling of the homes from a given county. We take instead the approach of conducting all analyses for the full SoCal RASS cohort of GCB-using homes. These results can be used to determine exceedance rates per 1,000 homes receiving LNG. And those rates can then be used to estimate region-wide impacts, irrespective of the specific distribution pattern of LNG.

Table 19: Summary of Data, Assumptions, and Estimated Values Used to Characterize the Scale of LNG Impacts across the Six-County Southern California Region Based on Modeling of Households (HHs) from the 2003 RASS

SoCal County	N _{county HHs}	N _{GCB HHs}	%LNG HHs	N _{LNG HHs}	N _{RASS HHs}
Los Angeles	3,133,774	1,664,974	0.63%	10,489	3,143
Orange	935,287	496,918	0.38%	1,909	941
Riverside	506,218	268,953	35.0%	94,222	606
San Bernardino	528,594	280,842	1.8%	5,144	598
Ventura	243,234	129,231	0.0%	0	307
San Diego	994,677	528,472	100%	528,472	1,039
All counties	6,341,784	3,369,390		640,236	6,634

N_{county HHs} = number of total HHs in a county from the 2000 Census

N_{GCB HHs} = number of gas fueled HHs that use GCBs (estimated using Eqn. 7)

%LNG HHs = estimated percentage of HHs that receive LNG in a given county (based on Scenario 7 in Sospedra et al. 2011).

N_{LNG HHs} = number of HHs that receive LNG and use GCBs (estimated using Eqn. 8)

N_{RASS HHs} = number of RASS HHs included in GCB cohort

2.14 Quality Assurance

Prior to running the suite of modeling scenarios outlined in the Methods Section, we conducted an extensive set of model runs and analysis for Quality Assurance (QA). The objectives of the QA analysis were (1) to confirm that the model code is executing the calculations and algorithms as intended and documented in this report, (2) to explore the sample size required for stable output metrics, and (3) to assess whether overall results—i.e., the calculated time-varying and time-averaged concentration distributions resulting from cooking burner use—are in line with available measurements. Most of the results presented in this report and appendices were produced in May–June 2011 with the final validated model. Some results, e.g., for assessing samples sizes required for stable output, reflect draft versions of the model.

Results from quality assurance analyses are presented in Appendix H and summarized here. We first compared our assigned values for total cooking energy use—built up from assigned cooking times and fuel use rates for individual meals—to estimates from independent analysis of data from the RASS households. Our median and mean estimates were lower than RASS estimates, suggesting that cooking fuel use is not over-estimated in the exposure model. The maximum 1-hr concentrations calculated for each home with the full mass balance algorithm were checked against an approximation to confirm that the algorithm was working correctly. The model was found to be stable for all output metrics at sample sizes of a few thousand households; some metrics were stable with smaller sample sizes. Model outputs were found to be generally in the range of relevant measurements.

CHAPTER 3: Results and Discussion

Results are organized as follows.

Presented first are summary results for the model-calculated pollutant concentrations in homes and exposure concentrations for individuals living in homes that use gas cooking burners (GCBs) in the Southern California (SoCal) counties of San Diego, Riverside, San Bernardino, Ventura, Orange, and Los Angeles. This SoCal cohort comprises 6,634 households and 19,288 individuals. Results are presented by pollutant and averaging time in box and whisker plots to facilitate comparisons of distributional results by scenario. Results are presented for indoor concentrations arising solely from GCB use—for NO₂, CO, and HCHO—and also for GCB emissions combined with entry from outdoors, for NO₂ and CO. The current version of the exposure model does not incorporate HCHO from outdoors or from indoor sources other than GCBs. Tabular summary statistics are presented in Appendix I. We also present the fraction of homes and individuals who experience at least one occurrence of indoor levels exceeding an ambient air quality standard or other relevant guideline, as summarized in Table 1. As noted in the Methods section, in this report we refer to these cases as “exceedances.”

The following outline summarizes the metrics that are presented in the Results section.

- (1) One-week average indoor concentrations:
 - NO₂, CO, and HCHO attributable to GCB use
 - NO₂ and CO from GCB use and outdoor sources (GCB + outdoor)
- (2) Highest 1-hour indoor concentrations during the week of modeling:
 - NO₂, CO, and HCHO attributable to GCB use
 - NO₂ and CO from GCB use and outdoor sources (GCB + outdoor)
- (3) Highest 8-hr indoor concentrations during the week of modeling:
 - HCHO attributable to GCB use
 - CO from GCB use and outdoor sources (GCB + outdoor)

Using the SoCal cohort, we examine the sensitivity of calculated individual concentration distributions and exceedances on the specific values used for F_{prox} (see Table 18). The results are presented with figures (and corresponding tables found in Appendix I) that follow the same format used for the time-averaged concentrations.

Following the presentation of results for the entire SoCal cohort, we examine results specific to San Diego and Riverside counties. We intercompare household-level output metrics for the 1,039 San Diego HHs and for the 606 Riverside HHs that are part of the 6,634 SoCal HHs. Though these samples are too small to provide robust results for the individual counties, the general consistency of county-level results with regional results supports the use of the larger regional dataset to obtain results that are generally applicable to any distribution pattern of LNG within Southern California.

The final section was slated to be an assessment of incremental cancer risk associated with formaldehyde emissions from GCBs for homes using LNG in place of conventional NG.

However, since formaldehyde cancer risk derives from chronic exposure, and the increments of chronic exposure with LNG are negligible, the change in cancer risk is assessed to be minimal and below the level for which a formal analysis is warranted.

3.1 Household and Individual Exposure Concentrations for NO₂

This section presents simulation results for one-week, maximum 8-hr, and maximum 1-hr indoor NO₂ concentrations resulting solely from GCB emissions, then for GCB use combined with outdoor sources for the full SoCal cohort. Results are first presented for concentrations in the home, then for individuals. Distributions of concentrations are presented in figures as box and whisker plots; tabular results are presented in Appendix I. The fractions of households and individuals exceeding relevant health-based air quality standards are provided in tables.

Figure 6 below shows that the distribution of one-week indoor NO₂ concentrations across the population is much more affected by the season and ventilation conditions than by the fuel used. Considering only GCB emissions, the (a) sections of the figure and table show that concentrations calculated for winter with infiltration air exchange yields the lowest AERs and thus the highest indoor concentrations from GCB emissions. The (b) sections of the figure and table show that when outdoor sources are included, the winter empirical AER scenarios yield the highest concentrations. A comparison of (a) and (b) panels of the figure and corresponding numbers from the table indicate that, averaged over the week, entry with outdoor air accounts for roughly half to three-quarters of the NO₂ indoors at the sample median level. Logically, the relative contribution of NO₂ from outdoor sources increases for simulations that use empirical AERs, which are higher, relative to AER calculated based on infiltration only. Figure 6 shows that the annual CAAQS of 57 µg m⁻³ is not exceeded at the model-estimated 95th percentile concentration for any scenario.

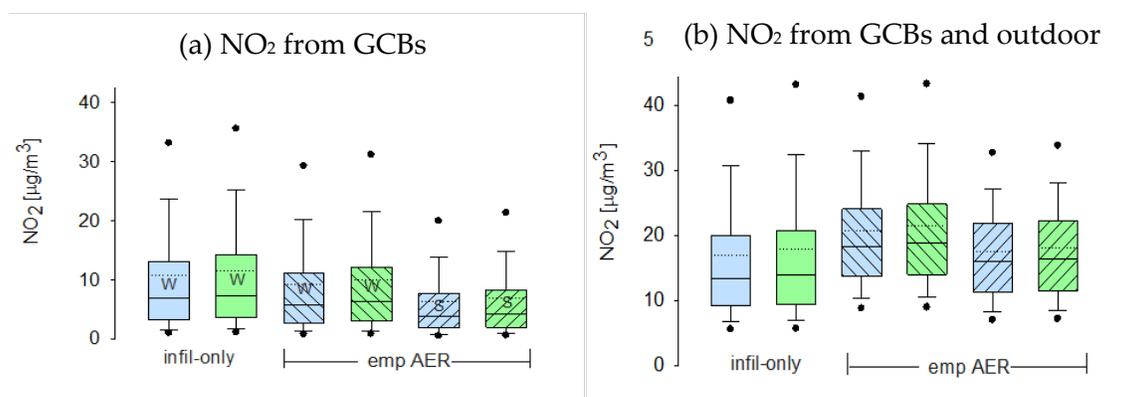


Figure 6: One-Week Average Indoor NO₂ Concentrations across 6634 SoCal HHs in Winter (W) Assuming Infiltration (Infil-Only) or Empirical AER (emp AER) Arising (a) Solely from GCB Emissions, and (b) from GCBs and Outdoor Sources

LNG use leads to an increase of 0.5 to 0.8 $\mu\text{g m}^{-3}$ in the sample mean and an increase of 0.3 to 0.5 $\mu\text{g m}^{-3}$ in the sample median across the modeled scenarios for GCB-only and GCB plus outdoor contributions averaged over the week. Sample mean levels increase by roughly 3–5 percent for GCB plus outdoor sources and by 7–8 percent for GCB contributions to indoor NO_2 .

Figure 7 presents results for maximum 8-hour indoor NO_2 arising from GCB use and outdoor sources. Sample median values for the SoCal cohort range from 32 to 43 $\mu\text{g m}^{-3}$ for conventional NG and from 33 to 45 $\mu\text{g m}^{-3}$ using LNG emission factors. Simulations of summer conditions yield the lowest concentrations overall and the two winter scenarios (using empirical AER or infiltration only) have similar values for central tendencies. Across the modeled scenarios, sample mean values with LNG were 3 to 4 $\mu\text{g m}^{-3}$ (5–8 percent) higher than with conventional NG. At the 75th percentile level, concentrations with LNG were 4 to 6 $\mu\text{g m}^{-3}$ (roughly 8 percent) higher than with conventional NG.

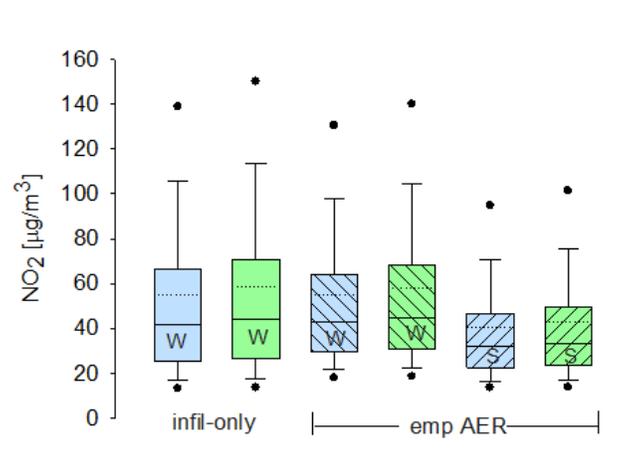


Figure 7: Maximum 8-hr Average Indoor NO_2 Concentrations across 6,634 SoCal HHs in Winter (W) and Summer (S) Assuming Infiltration (Infil-Only) and/or Empirical AER (emp AER) Arising from the Use of GCBs and Outdoor Sources

Summary statistics for 1-hr maximum NO_2 concentrations are presented in Figure 8. For all variations of season, AER and fuel, inclusion of outdoor sources leads to a 4–10 percent increase in the sample-mean value of 1-hr maximum NO_2 relative to the levels calculated considering only the contribution from GCBs. The relative contribution of outdoor sources is smaller for homes with higher emissions from GCBs and overall higher 1-hr indoor levels.

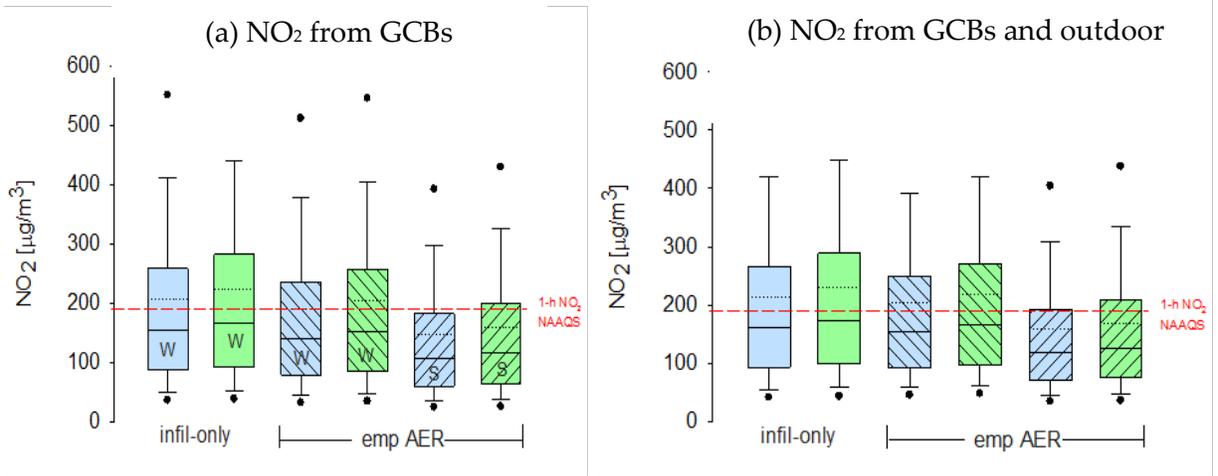


Figure 8: Maximum 1-hr Average Indoor NO₂ Concentrations across 6,634 SoCal HHs in Winter (W) and Summer (S) Assuming Infiltration (Infil-Only) and/or Empirical AER (emp AER) Arising from (a) GCBs and (b) GCBs and Outdoor Sources

Table 20 presents the fraction of households that exceeded the 1-hr NAAQS of 190 µg m⁻³ at any time during the one-week simulation. This table presents the exposure model prediction that, in the winter, roughly 40 percent of the households that use GCBs in this region will have indoor concentrations exceeding the outdoor air quality standard. Most of these acute exceedances would occur without any contribution from outdoor NO₂. Considering only GCB emissions with conventional natural gas and empirical AERs, 23 percent and 35 percent of the modeled homes had exceedances in summer and winter, respectively. Adding outdoor sources raises the exceedance rates to 26 percent and 38 percent, respectively. Considering GCB and outdoor sources, use of LNG is estimated to raise the number of exceedances from 38 percent to 42 percent in winter and from 26 percent to 29 percent in summer.

Table 20: Number of Homes with Concentrations Exceeding Health-Based Standards for NO₂^a per 1000 Southern California Homes That Use Gas Cooking Burners, by Modeling Scenario

Season	AER	Fuel	Homes Exceeding 1-hr NAAQS ^a per 1000 Homes that Use GCBs, Based Solely on GCB Emissions	Homes Exceeding 1-hr NAAQS ^a per 1000 Homes Based on GCB Emissions and Outdoor NO ₂
Winter	Infiltration	Base	393	413
		LNG	430	452
Winter	Empirical	Base	348	384
		LNG	384	421
Summer	Empirical	Base	233	256
		LNG	267	293

^a U.S. national ambient air quality standard of 190 µg m⁻³ averaged over 1 hour

We present below results for one-week and 1-hr maximum NO₂ exposure concentrations calculated for the 19,288 individual occupants of the 6,634 homes in the six-county SoCal RASS cohort. These results could differ from the household distributions primarily because they include the near-source (proximity factor) multipliers for cooks and small children nearby to

adult cooks. The individual calculations take into account periods when occupants leave the home and the results reflect the co-variance of more frequent cooking and emissions in homes with more occupants.

Figure 9 presents distributions of the modeled one-week time-integrated individual exposure concentrations for the six primary scenarios. Consistent with the household concentrations, distributions vary more by season and AER assumption than by fuel. Also consistent with the household results, the inclusion of outdoor sources causes the winter empirical AER scenario to have the highest exposure concentrations with summer empirical and winter infiltration scenarios having similar magnitude and spread. The 90th and 95th percentile concentrations are similar for the winter infiltration and winter empirical AER scenarios. Summary statistics are provided in tabular form in Appendix I. Liquefied natural gas use is estimated to raise median and mean exposure concentrations (from GCBs plus outdoor sources) by 0.4–0.6 $\mu\text{g m}^{-3}$ and by 0.6–0.9 $\mu\text{g m}^{-3}$ respectively; these represent increases of roughly 3–5 percent. The increases are of similar relative magnitude at the 75th percentile exposure concentrations.

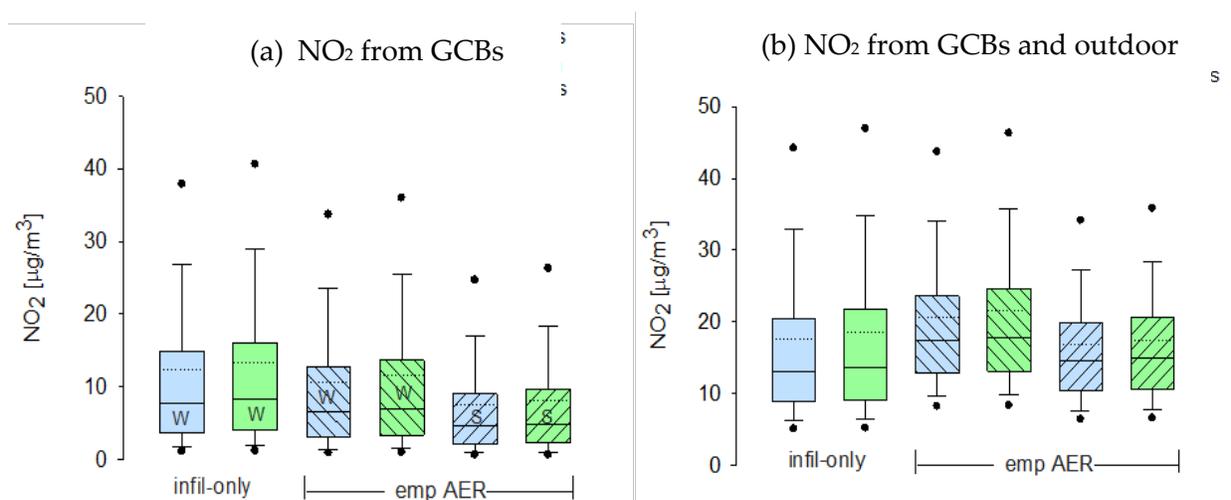


Figure 9: One-Week Average Indoor NO₂ Concentrations across Residents (N= 19,288) of SoCal HHs in Winter (W) and Summer (S) Assuming Infiltration (Infil-Only) and/or Empirical AER (emp AER) Arising from (a) GCBs and (b) GCBs and Outdoor Sources

Results for 8-hr maximum NO₂ concentrations are very similar to those presented for households in the previous subsection and are not shown.

Distributions of maximum 1-hr NO₂ individual exposure concentrations for the SoCal cohort are presented in Figure 10. As seen for household results, the contribution of outdoor sources raises only slightly the maximum 1-hr individual exposure concentrations relative to those resulting only from GCB emissions. Inclusion of outdoor sources leads to increases of 5–9 percent in the sample median and 3–6 percent in the sample mean across scenarios. A red line in each panel shows that a substantial fraction of the individuals in the cohort exceed the 1-hr NO₂ NAAQS.

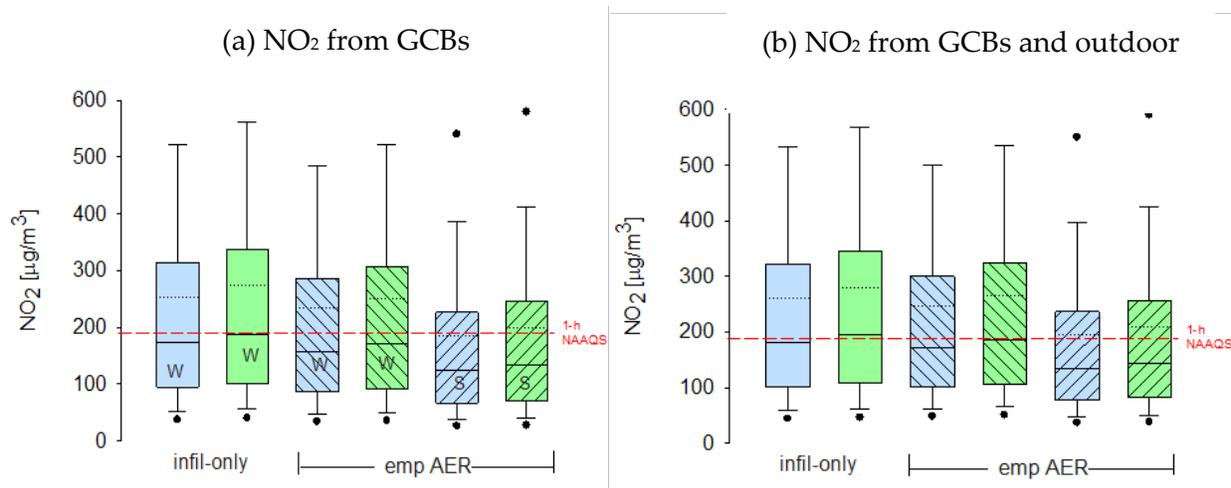


Figure 10: Maximum 1-hr Average Indoor NO₂ Concentrations across Residents (N = 19,288) of the SoCal RASS Cohort in Winter (W) and Summer (S) Assuming Infiltration (Infil-Only) and/or Empirical AER (emp AER) Arising from (a) GCBs and (b) GCBs and Outdoor Sources

Table 21 presents the fraction of individuals exposed to a 1-hr concentration that exceeds the NAAQS for NO₂. These results again show that the use of GCBs without venting – an important assumption of the model – can lead to exposure concentrations in homes that exceed target levels for outdoor air quality. Even without outdoor source contributions, GCB use is estimated to lead to exceedances of the 1-hr NO₂ standard in 31 percent of the cohort homes in summer and 42 percent in winter, assuming baseline NG emission factors. The effect of LNG is estimated to be small, increasing the exceedance rate by about 3 percent in absolute terms and by up to 10 percent in relative terms. Exceedance rates for individuals are a bit higher than those for households owing to the source proximity effect.

Table 21: Number of Individuals Exposed to Concentrations Exceeding 1-hr Standard for NO₂^a per 1000 Southern California Individuals Living in Homes That Use Gas Cooking Burners, by Modeling Scenario

Season	AER	Fuel	Individuals Exceeding 1-hr NAAQS, Based Solely on GCB Emissions	Individuals Exceeding 1-hr NAAQS Based on GCB Emissions and Outdoor NO ₂
Winter	Infiltration	Base	456	474
		LNG	491	509
Winter	Empirical	Base	416	451
		LNG	451	485
Summer	Empirical	Base	312	334
		LNG	344	369

^a U.S. national ambient air quality standard of 190 µg m⁻³ averaged over 1 hour

3.2 Household and Individual Exposure Concentrations for CO

This section presents results for the one-week average, maximum 8-hour and maximum 1-hour indoor CO concentrations resulting from GCBs and outdoor sources in the SoCal cohort.

Figure 11 shows that the distributions of one-week concentrations are substantially higher for the winter infiltration only scenario relative to winter or summer scenarios with empirical AERs. For both winter scenarios, CO from the outdoor air provides a substantial fraction of overall time-averaged CO inside. Taken from the other perspective, GCBs are seen to contribute roughly half of the total indoor CO during winter. Nevertheless, scenarios with LNG emission factors yield marginally higher household concentrations in most scenarios. These results suggest that GCB use can lead to discernible if small increases in chronic CO exposures in California homes, with the impacts greatest on homes that depend on infiltration air exchange in winter.

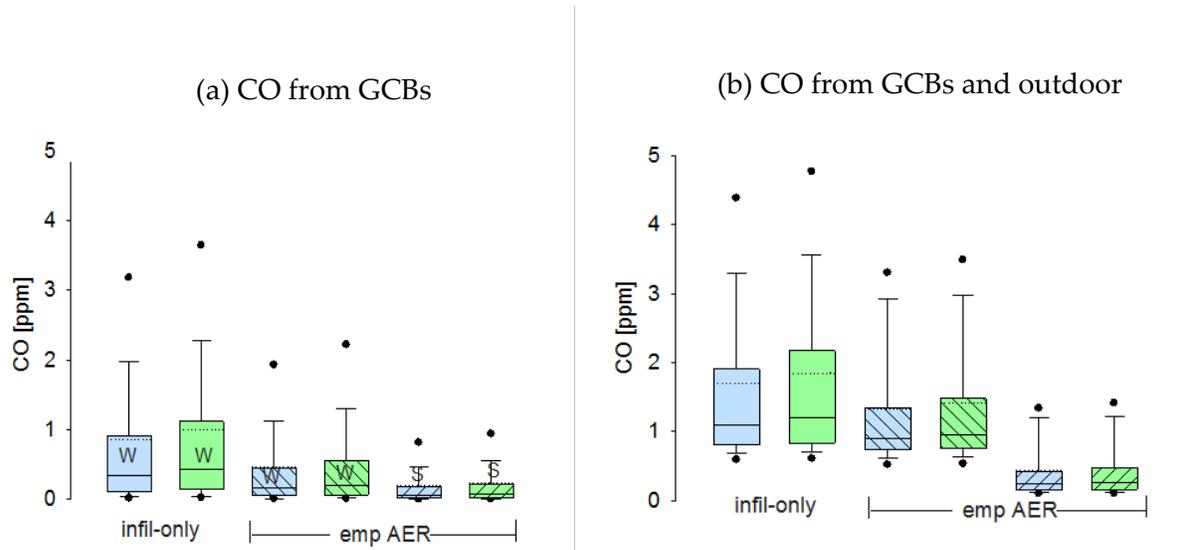


Figure 11: One-Week Average Indoor CO Concentrations across 6,634 SoCal HHs in Winter (W) and Summer (S) Assuming Infiltration (Infil-Only) or Empirical AER (emp AER) Arising from (a) GCBs and (b) GCBs and Outdoor Sources

Figure 12 presents summary results for the maximum 8-hour CO concentrations across the SoCal cohort of homes. Tabular results are again provided in Appendix I. Similar to the one-week averages shown above, the two winter scenarios again yield indoor concentrations that are substantially higher than in the summer. At the 75th percentile level, indoor concentrations increase by about 0.5 ppm for the winter empirical AER and by about 0.8 ppm for the winter infiltration AER scenarios.

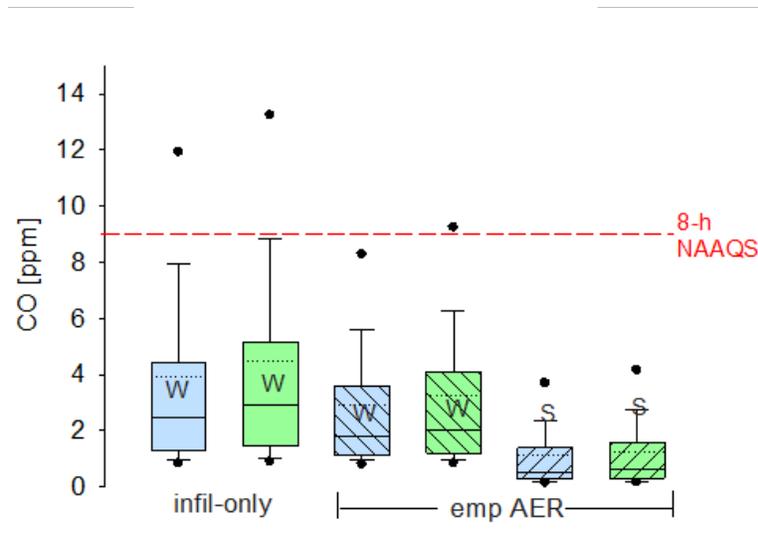


Figure 12: Maximum 8-hr Average Indoor CO Concentrations across 6,634 SoCal HHs in Winter (W) and Summer (S) Assuming Infiltration (Infil-Only) and/or Empirical AER (emp AER) Arising from the Use of GCBs and Outdoor Sources

Table 22 presents the fraction of homes with CO concentrations exceeding the NAAQS of 9 ppm averaged over an 8-hr exposure period. The table shows that there the variations by season and by air exchange estimation methodology are much larger than effects of changing fuels. With baseline fuels, the fraction of households exceeding the standard was 0.86 percent and 4.5 percent for summer and winter seasons using empirical air exchange distribution. Assuming only infiltration in winter raises the exceedance rate to 8.7 percent. Liquefied natural gas use increased these rates by 16–25 percent on a relative basis.

Table 22: Number of Homes with Concentrations Exceeding 8-hr Health-based Standard^a for CO per 1,000 Southern California Homes That Use Gas Cooking Burners, by Modeling Scenario

Season	AER	Fuel	Homes Exceeding 8-hr NAAQS per 1,000 Homes Based on GCB Emissions and Outdoor NO ₂
Winter	Infiltration	Base	87
		LNG	103
Winter	Empirical	Base	45
		LNG	56
Summer	Empirical	Base	8.6
		LNG	9.9

^a National ambient air quality standard of 9 ppm averaged over 8 hours

The distribution of maximum 1-hour indoor CO concentrations arising from the use of GCBs and outdoor sources is presented in Figure 13. For 1-hr maximum CO, the difference between NG and LNG sample-mean values for each winter scenario is of similar magnitude as the difference between the baseline NG values for the two scenarios, which are differentiated by air exchange rate method. Inclusion of outdoor CO causes an increase of 16–19 percent in the

highest 1-hr concentrations in homes relative to what would occur from GCBs only in the two winter scenarios. The shift from NG to LNG leads to increases of similar magnitude, considering as a base either the GCB only or GCBs and outdoor sources.

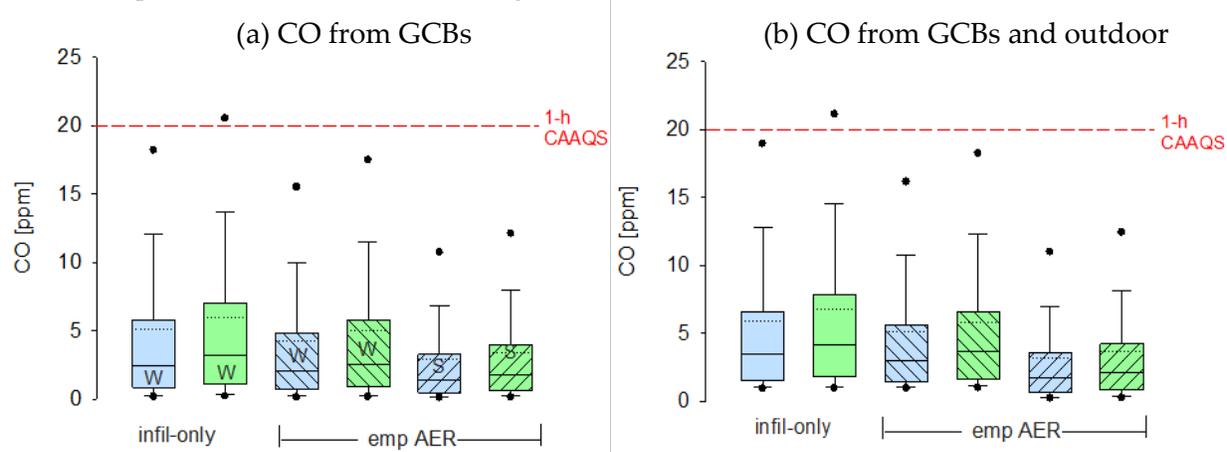


Figure 13: Maximum 1-hr Average Indoor CO Concentrations across 6,634 SoCal HHs in Winter (W) and Summer (S) Assuming Infiltration (Infil-Only) or Empirical AER (emp AER) Arising from (a) GCBs and (b) GCBs and Outdoor Sources

Table 23 indicates that a non-negligible fraction of homes in this cohort regularly exceeded the 1-hr CAAQS for CO. The rate of exceedances is about two to three times higher in winter than summer and LNG is estimated to have a small impact on this rate. As an example, running the model with empirical AERs predicts that 3.4 percent of homes will exceed the CAAQS for CO during a typical winter week with NG, and that number is predicted to increase to 4.1 percent with LNG.

Table 23: Number of Homes with Concentrations Exceeding Health-Based Standard^a for CO per 1,000 Southern California Homes That Use Gas Cooking Burners, by Modeling Scenario

Season	AER	Fuel	Homes Exceeding 1-hr CAAQS per 1,000 Homes that Use GCBs, Based Solely on GCB Emissions	Homes Exceeding 1-hr CAAQS per 1,000 Homes Based on GCB Emissions and Outdoor NO ₂
Winter	Infiltration	Base	43	46
		LNG	52	56
Winter	Empirical	Base	32	34
		LNG	40	41
Summer	Empirical	Base	17	17
		LNG	20	20

^a California ambient air quality standard of 20 ppm averaged over 1 hour

Figure 14 presents the distribution of weekly average indoor CO across all individuals in the SoCal cohort. Variations by season and air exchange rate method (infiltration or empirical) are much larger than variations by fuel. Tabular results are presented in Appendix I.

The model predicts CO exposure concentrations for most people that are non-zero but generally low, in the range of a few ppm or less. For the worst-case scenario of homes depending solely

on infiltration air exchange in the winter, chronic exposure concentrations for individuals are still lower than 5 ppm at the 95th percentile. Use of LNG instead of conventional NG leads to small increases in chronic CO exposures for all scenarios that were modeled.

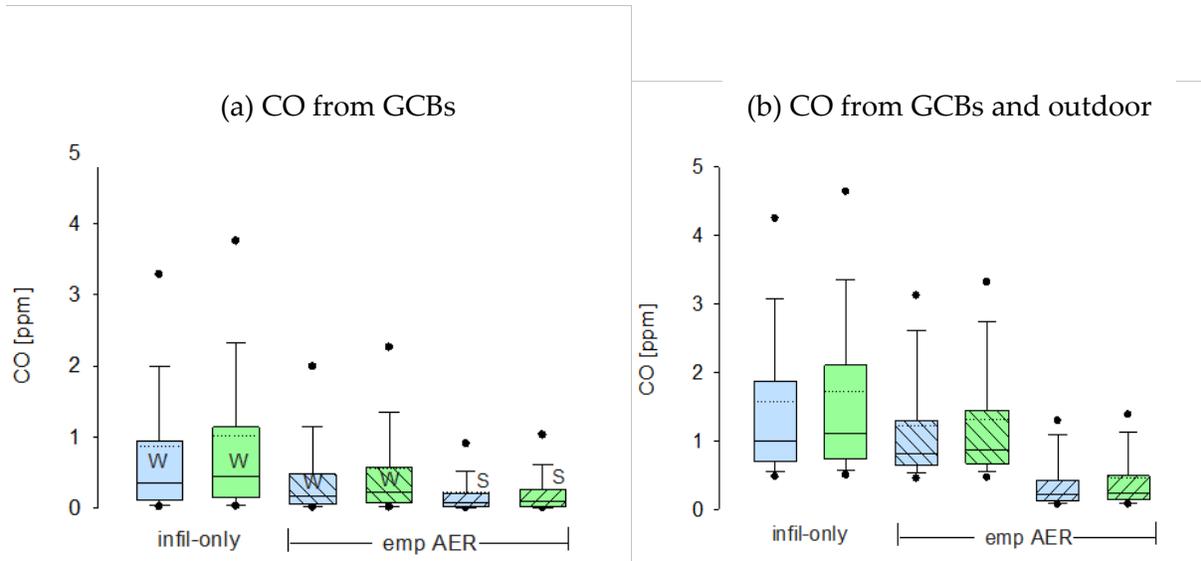


Figure 14: One-Week Average Indoor CO Concentrations across Residents (N = 19,288) of SoCal HHs in Winter (W) and Summer (S) Assuming Infiltration (Infil-Only) or Empirical AER (emp AER) Arising from (a) GCBs and (b) GCBs and Outdoor Sources

Figure 15 presents summary results for the calculated maximum 8-hour indoor CO arising from GCB use and outdoor sources across all individuals in the SoCal RASS cohort. The figure shows that the 8-hr national ambient air quality standard of 9 ppm is exceeded for a substantial fraction of individuals in both winter modeling scenarios.

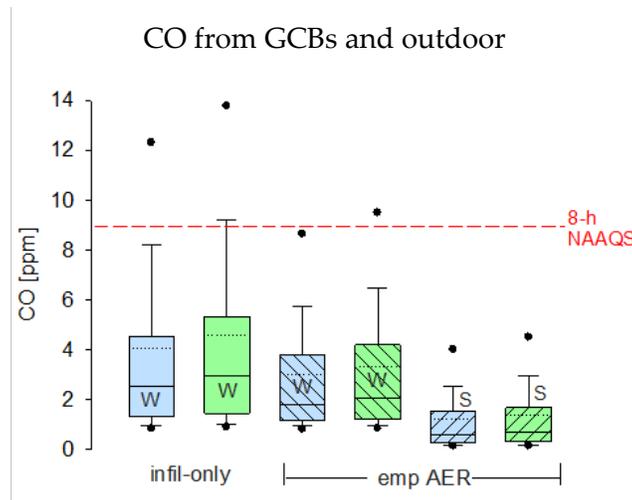


Figure 15: 8-hr Average Indoor CO Concentrations across Residents (N = 19,288) of SoCal HHs in Winter (W) and Summer (S) Assuming Infiltration (Infil-Only) or Empirical AER (emp AER) Arising from the Use of GCBs

Table 24 presents the number of individuals per 1,000 that the model predicts are exposed to CO levels that exceed the 8-hr national standard of 9 ppm. Results for individuals follow the same basic pattern by season and AER as the home concentrations. The impact of LNG is similar as well: exceedance rates increase by about 20 percent relative to their levels with baseline fuel.

Table 24: Number of Individuals Exposed to Concentrations Exceeding the 8-hr Standard for CO^a per 1,000 Southern California Individuals Living in Homes That Use Gas Cooking Burners, by Modeling Scenario

Season	AER	Fuel	Individuals Exceeding 8-hr NAAQS Based on GCB Emissions and Outdoor NO ₂
Winter	Infiltration	Base	93
		LNG	112
Winter	Empirical	Base	50
		LNG	60
Summer	Empirical	Base	12.2
		LNG	14.6

^a National ambient air quality standard of 9 ppm averaged over 8 hours

Figure 16 presents the distributions of modeled 1-hr maximum CO across the 19,288 individuals of the SoCal cohort. Similar to the 1-hr NO₂ results, the addition of outdoor pollutants to the CO emitted by GCBs is small. Also, while winter concentrations are still higher than summer, the seasonal difference is not as pronounced. Both of these trends occur because the short-term peaks are driven primarily by emissions and the size of the home. The higher air exchange rates extant in summer play less of a role as the averaging time is shortened.

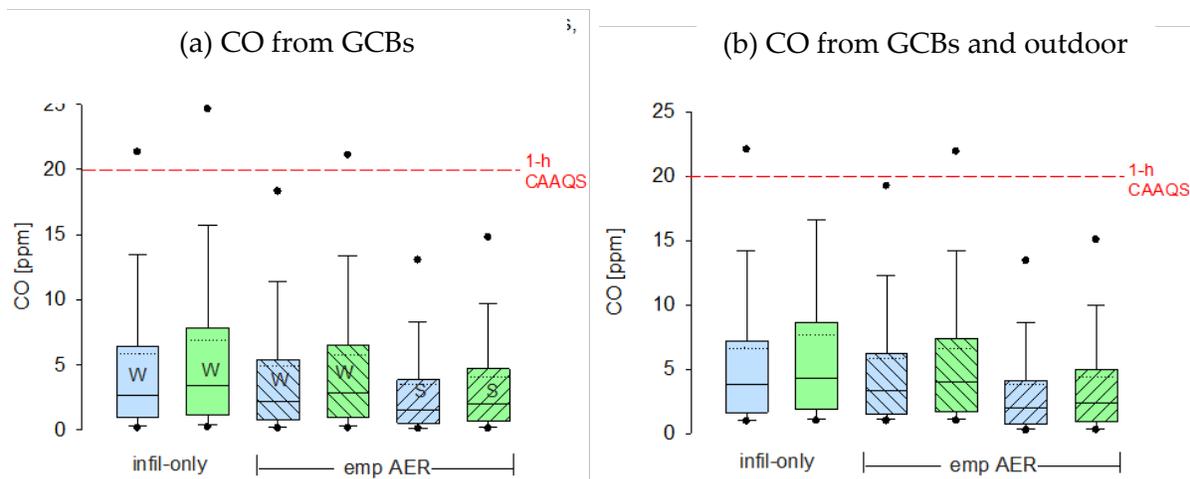


Figure 16: Maximum 1-hr Average Indoor CO Concentrations across Residents (N = 19,288) of SoCal HHs in Winter (W) and Summer (S) Assuming Infiltration (Infil-Only) and/or Empirical AER (emp AER) Arising from (a) GCBs and (b) GCBs and Outdoor Sources

Table 25 below presents the rate of exceedances of the 1-hr CAAQS for CO per 1,000 individuals included in the model. Owing again to the proximity effect, these numbers are higher than those presented for concentrations in the home. But it is interesting to note that the exceedance rates do not differ much when including outdoor CO or looking only at GCB emissions. The increase in exceedance rate when moving from baseline NG to LNG is substantial; exceedance rates with LNG are about 20 percent higher (in relative terms) than rates with baseline NG.

Table 25: Number of Individuals Exposed to Concentrations Exceeding 1-hr Standard for CO^a per 1,000 Southern California Individuals Living in Homes That Use Gas Cooking Burners, by Modeling Scenario

Season	AER	Fuel	Individuals Exceeding 1-hr CAAQS, Based Solely on GCB Emissions	Homes Exceeding 1-hr CAAQS per 1,000 Homes Based on GCB Emissions and Outdoor CO
Winter	Infiltration	Base	55	58
		LNG	66	71
Winter	Empirical	Base	43	46
		LNG	53	56
Summer	Empirical	Base	26	26
		LNG	30	31

^a California ambient air quality standard of 20 ppm averaged over 1 hour

3.3 Household and Individual Exposure Concentrations for HCHO

This section presents modeled household and individual exposure concentrations for HCHO emitted from gas cooking burner use in the six-county SoCal region. As noted previously, the modeling for HCHO considered only GCB use; outdoor and other indoors sources were not considered. Otherwise results are presented using figures with similar formats to those in previous sections.

Simulation results for the distributions of HCHO concentrations averaged over 1-hr, 8-hr, and one-week periods are presented in Figure 17 for households and Figure 18 for individuals; tabular results corresponding to these figures are presented in Appendix I. As seen for NO₂ and CO, the variations between scenarios is greater than the differences between results obtained with NG compared with LNG emissions factors. Overall, LNG use would lead to a small (relative to baseline) increase in household and individual exposure concentrations and the fraction of households and individuals exposed at concentrations exceeding guideline levels.

Considering concentrations in the home, GCB use with baseline NG is estimated to add about 0.5 and 1.4 $\mu\text{g m}^{-3}$ to the sample median of one-week concentrations in summer and winter, respectively. For homes dominated by infiltration in winter, the increment is about 2.9 $\mu\text{g m}^{-3}$. These winter levels are an order of magnitude lower than HCHO concentrations measured over multiple-day periods in homes, indicating that emissions from gas cooking burners are a small contributor to chronic exposures in homes. Use of LNG increases the sample mean of one-week concentrations by 0.1–0.2 $\mu\text{g m}^{-3}$; this amount is on the order of 1 percent of typical household HCHO levels. Higher concentrations are recorded for 8-hr and 1-hr acute exposure periods.

Median 1-hr concentrations in homes using conventional NG vary from 10.7 $\mu\text{g m}^{-3}$ during summer (empirical AER) to 19.6 $\mu\text{g m}^{-3}$ during winter, assuming infiltration-only air exchange. Sample means are a bit more than twice the median values.

Switching from NG to LNG causes an increase of roughly 7–9 percent in the sample median and an increase of 3–4 percent in sample mean household HCHO concentrations for both shorter term and one-week averaging times across almost all scenarios.

The fraction of homes with concentrations exceeding relevant guideline exposure levels is shown in Table 26. The fraction of households with at least one exceedance of the 1-hr Agency for Toxic Substances and Disease Registry (ATSDR) guideline level for HCHO was 11.8 percent for summer with empirical AER, was 18.7 percent for winter with empirical AER, and was 22.2 percent for winter infiltration air exchange simulated using conventional NG emission factors. When LNG emission factors were used, these exceedance rates increased to 12.4 percent, 19.6 percent, and 24.2 percent, respectively. On a relative basis, these exceedance rates are 9 percent, 5 percent, and 9 percent higher than the corresponding rates with conventional NG. The fraction of individuals exposed to concentrations exceeding relevant guideline exposure levels is shown in Table 27. The rates of individual exceedances were higher than those for households, owing to the proximity effect. For winter scenarios, individual exceedance rates were about 11–13 percent higher than exceedance rates on a household level. The effect of LNG on individual exceedances is of almost identical magnitude as the effect on households.

Table 26: Number of Homes with Concentrations Exceeding HCHO Guideline Levels per 1,000 Southern California Homes That Use Gas Cooking Burners, by Modeling Scenario

Season	AER	Fuel	Homes Exceeding 8-hr Guideline per 1,000 Homes Using GCBs	Homes Exceeding 1-hr Guideline per 1,000 Homes Using GCBs
Winter	Infiltration	Base	583	222
		LNG	603	242
Winter	Empirical	Base	399	187
		LNG	420	196
Summer	Empirical	Base	193	118
		LNG	207	124

Table 27: Number of Individuals Exposed to Concentrations Exceeding HCHO Guideline Levels per 1,000 Southern California Individuals Living in Homes That Use Gas Cooking Burners, by Modeling Scenario

Season	AER	Fuel	Individuals Exceeding 1-hr ASTDR Guideline for HCHO
Winter	Infiltration	Base	248
		LNG	268
Winter	Empirical	Base	210
		LNG	222
Summer	Empirical	Base	147
		LNG	152

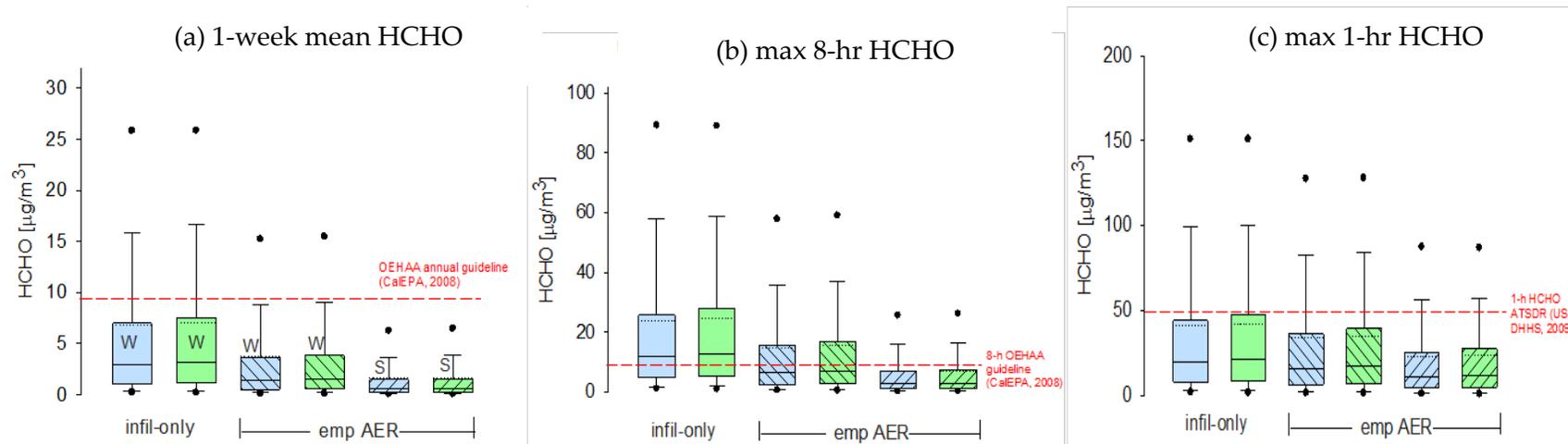


Figure 17: Distribution of Indoor HCHO, Including the (a) Average 1-Week, and (b) Maximum 8-hour, and (c) Maximum 1-hour Concentrations ($\mu\text{g}/\text{m}^3$) Arising from GCB Use, across 6,634 SoCal HHs in Winter (W) and Summer (S) Assuming Infiltration (Infil-Only) and Empirical AER (emp AER).

The (red) dashed line indicates applicable health-based standards (provided in Table 1).

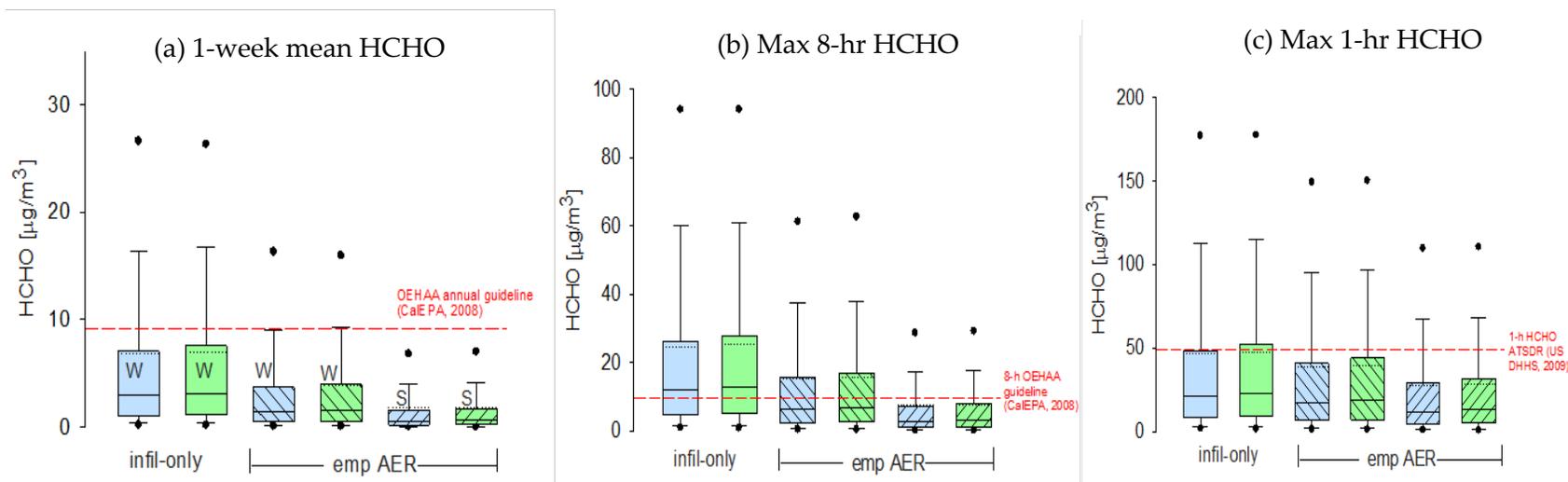


Figure 18: Distribution of Indoor HCHO Time-Averaged Concentrations, Including (a) Average 1-Week, and (b) Maximum 8-Hour, and (c) Maximum 1-Hour Concentrations ($\mu\text{g}/\text{m}^3$) Arising from the Use of GCBs across All 19,288 Residents of the SoCal RASS GCB Cohort in Winter (W) and Summer (S), and Assuming Infiltration (Infil-Only) and Empirical AER (emp AER).

The (red) dashed line indicates applicable health-based standards (provided in Table 1).

3.4 Sensitivity of Results to F_{prox} Values

To assess the sensitivity of model predictions to the specific values selected for the proximity multiplier, we ran simulations with alternate values of F_{prox} . Using the winter-empirical AER scenario, simulations were conducted for conventional NG and LNG with the following F_{prox} values:

- Baseline F_{prox} as defined in Table 16 (2.0 for an adult designated as the cook and 1.5 for any 0- to 5-year-old children, who are assumed to be in the same room as the cook)
- $F_{\text{prox}} = 1$ for all residents (no proximity effect)
- $F_{\text{prox}} = 2x$ baseline (4.0 for adult cook, 3.0 for 0- to 5-year-old children).

The same set of output metrics was calculated for these scenarios—defined by $F_{\text{prox}} \times$ values—as were calculated for all the scenarios described previously. Since F_{prox} only affects individual exposure concentrations, this section presents only the results for individuals. Figure 19 through Figure 21 present distributions of maximum 1-hour and one-week average exposure concentrations for individual residents for NO_2 , CO, and HCHO. Tabular results corresponding to these figures are provided in Appendix I (Tables I-14 to I-16).

These figures show that for each pollutant, the distribution of weekly average concentrations is substantially affected by the values selected for F_{prox} . Comparing simulations for conventional (baseline) natural gas, the median of the weekly average individual NO_2 concentrations varies from $5.7 \mu\text{g m}^{-3}$, when no proximity multipliers are used, to $7.6 \mu\text{g m}^{-3}$, when the highest values are used. For the same scenarios, the sample median of one-week average concentrations varies from 2.0 to 2.6 ppm for CO and from 1.3 to $1.5 \mu\text{g m}^{-3}$ for HCHO. Using LNG raises the median and mean one-week NO_2 by 7–9 percent, the median CO by 26–29 percent and the median HCHO by 13–21 percent across scenarios.

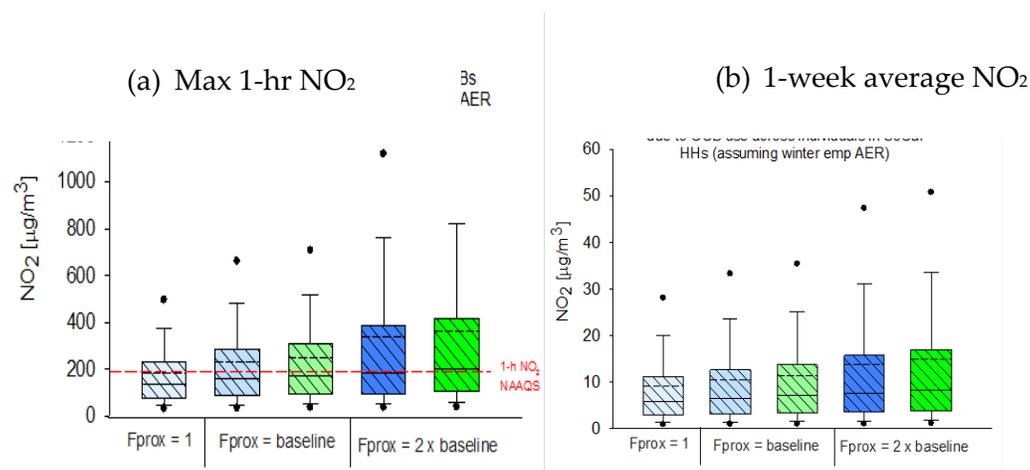


Figure 19: (a) Maximum 1-hr and (b) Average 1-Week Indoor NO_2 Concentrations ($\mu\text{g/m}^3$) Attributable to GCB Use across 19,288 Residents of 6,634 SoCal HHs under Varying Assumptions of F_{prox} (Baseline = 1.5 for Young Children and 2 for Cookers).

Blue indicates baseline natural gas; green shading indicates LNG. Winter empirical AER is assumed for all scenarios.

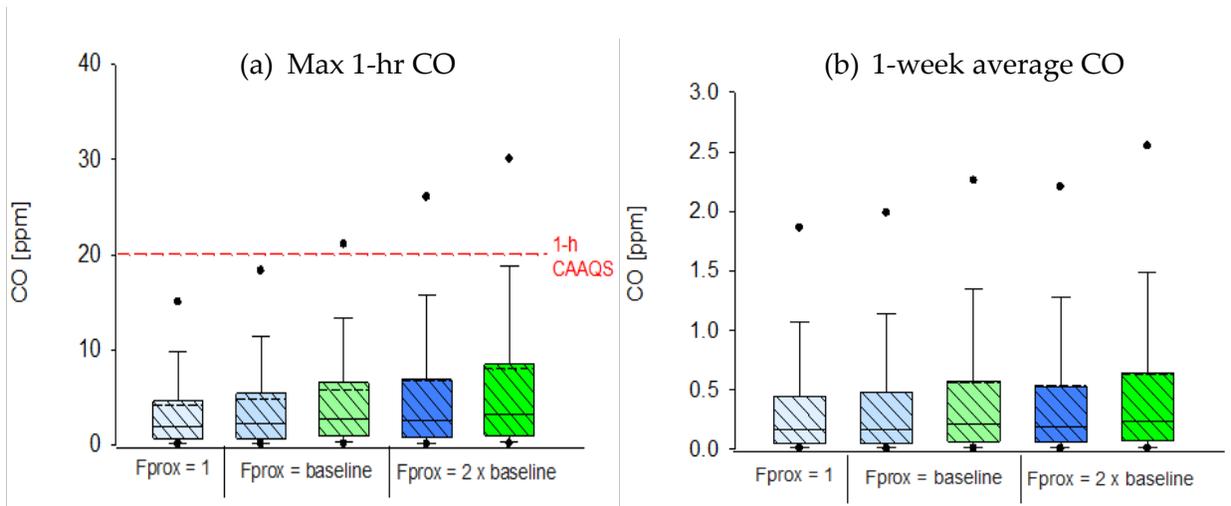


Figure 20: (a) Maximum 1-hr and (b) Average 1-Week Indoor CO Concentrations (ppm) Attributable to GCB Use across 19,288 Residents of 6,634 SoCal HHs under Varying Assumptions of F_{prox} (Baseline = 1.5 for Young Children and 2 for Cookers).

Blue indicates baseline natural gas; green shading indicates LNG. Winter empirical AER is assumed for all scenarios.

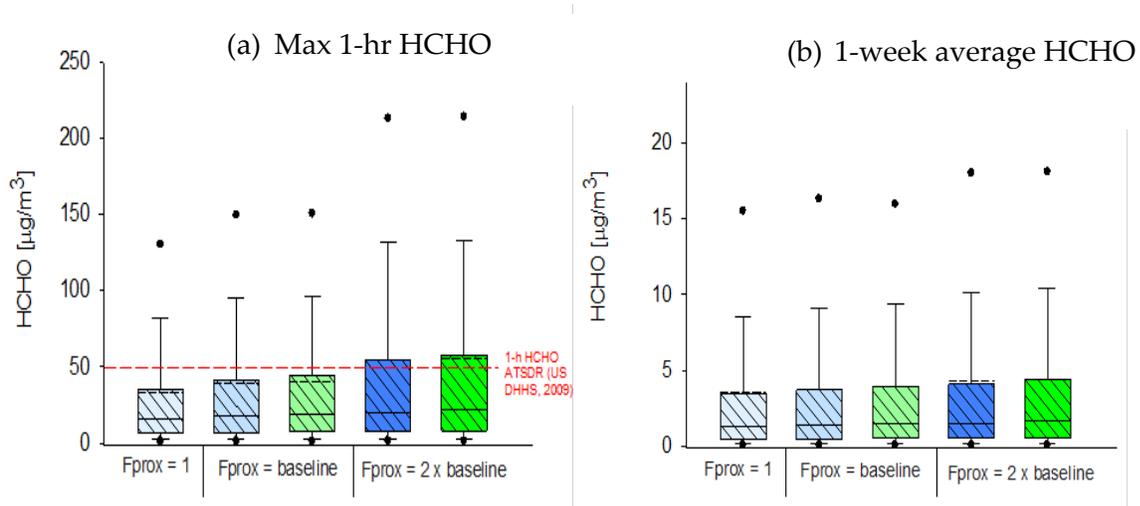


Figure 21: (a) Maximum 1-hr and (b) Average 1-Week Indoor HCHO Concentrations ($\mu\text{g}/\text{m}^3$) Attributable to GCB Use across 19,288 Residents of 6,634 SoCal HHs under Varying Assumptions of F_{prox} (Baseline = 1.5 for Young Children and 2 for Cookers).

Blue indicates baseline natural gas; green shading indicates LNG. Winter empirical AER is assumed for all scenarios.

3.5 Impacts for San Diego and Riverside, Compared with SoCal Region

This subsection compares the region-wide simulation results to results obtained for individual counties within the region. To do this we examine results for homes in San Diego and Riverside counties that were included in the full SoCal region-wide cohort. These results are presented with recognition that the number of San Diego homes is sufficient to yield robust results for concentration distributions but the rate of exceedances could change somewhat if the sample size were increased (as shown in the Quality Assurance section of Appendix H). The sample of Riverside homes is on the low side of what we assess as needed to reach stable concentration distributions, and is too small to provide stable results for exceedances. Comparisons between region-wide ($n = 6,634$) and specific county ($n = 1,039$ for San Diego and $n = 606$ for Riverside) results are therefore reasonably robust for concentration distributions. Comparisons of exceedance rates should be regarded as being approximate only, especially for Riverside.

The results shown in this section were produced with a beta-version of the model that used nominal rather than measured firing rates for oven burners. This version produced concentrations and exceedances that were slightly higher than the final results presented in previous sections. These differences should not affect the comparison between county- and region-level analysis.

We compare in Table 28 the time-averaged concentrations from simulations conducted for the full SoCal region to the same values calculated for the subset of households from San Diego and for the subset of households from Riverside. The increase in concentrations associated with LNG relative to the baseline, expressed as $\Delta \%$, is generally similar for all three groups across all the metrics shown (mean, median, and 25th and 75th percentiles for various averaging times). The $\Delta \%$ varies by less than two percentage points across the three groups for most summary statistics.

Table 29 presents the same comparison of results by county or region but includes the contribution of outdoor sources on indoor time time-averaged concentrations of NO_2 and CO . There is again a generally consistent effect of LNG on pollutant levels in all three geographic groups as $\Delta \%$ varies by less than 2 percentage points (absolute) for almost all the metrics across the three groups.

To further compare the county-level to region-level cohorts, we calculated for each relevant combination of pollutant and averaging period the number of homes (HHs) that have concentrations exceeding the health-based standards shown in Table 1. Table 30 presents the rate of such exceedances per 1,000 HHs for each acute pollutant standard; household exceedance rates are calculated (a) based solely on the pollutants contributed by GCB use and (b) for the combined contributions of GCB use and outdoor air. Again, results are presented for the full six-county SoCal cohort and separately for San Diego and Riverside homes. The exceedance rates for baseline gas and the changes with LNG vary somewhat among the three groups, but the exceedance rates are of similar magnitude.

These results suggest that the impacts of LNG would be similar if not precisely the same in particular counties as they would be for the broader region. Fractional changes to concentration distribution would be very small, while rates (per 1,000 HHs) at which standards are exceeded would vary substantially.

The purpose of this analysis was to assess whether it is necessary to present detailed results by county for the various simulations that were conducted. As described in the Methods section, simulations were conducted with two different approaches to assigning air exchange rates, for summer and winter seasons, and using pollutant emission factors relevant to baseline natural gas or LNG. As described in the Methods section, these simulations were run for the entire cohort of Southern California RASS homes that reported using a GCB. Simulations were run for all GCB-using homes in San Diego, Riverside, Orange, Ventura, Los Angeles, and San Bernardino counties. Results for individual counties can be extracted from the database of results if necessary. However, owing to the much larger number of homes, results for the full SoCal cohort are much more robust and stable from run to run than are results for any single county.

Table 28: Comparison of NO₂, CO, and HCHO Time-Averaged Concentrations Arising from GCB Use in Households across the Six-County SoCal Region (n = 6,634), San Diego (SD) County (n = 1,039), and Riverside County (n = 606). Δ % Indicates the Percent Increase Associated with LNG, Relative to Conventional NG (Base NG). All Scenarios Assume Winter AER.

NOTE: The numbers provided in this table were calculated using nominal, rather than measured, oven firing rates, resulting in slightly higher concentrations than shown elsewhere in report. These results are provided for purpose of comparing individual counties to SoCal region.

Pollutant metric	Emfacs	HHs in 6-county SoCal Region (n = 6,634)				SD HHs (n = 1,039)				Riverside HHs (n = 606)			
		mean	Median	25%	75%	mean	Median	25%	75%	mean	Median	25%	75%
NO₂ (µg/m³)													
Max 1-hr	Base NG	195	141	78	244	175	135	73	226	167	121	70	207
	LNG	210	152	84	264	190	149	80	245	179	134	75	225
	Δ %	7.7%	7.8%	7.7%	8.2%	8.6%	10.4%	9.6%	8.4%	7.2%	10.7%	7.1%	8.7%
1-week	Base NG	9.5	6.0	2.8	11.7	8.5	5.5	2.7	10.6	8.2	5.3	2.3	10.6
	LNG	10.3	6.4	3.0	12.6	9.1	5.9	2.9	11.5	8.8	5.7	2.5	11.4
	Δ %	8.4%	6.7%	7.1%	7.7%	7.1%	7.3%	7.4%	8.5%	7.3%	7.5%	8.7%	7.5%
CO (ppm)													
Max 1-hr	Base NG	4.6	2.0	0.7	5.0	4.4	1.9	0.73	4.8	3.9	1.7	0.63	4.4
	LNG	5.3	2.6	0.9	6.2	5.0	2.5	0.92	6.0	4.5	2.3	0.77	5.5
	Δ %	15.2%	30.0%	24.3%	24.0%	14.7%	30.9%	26.0%	25.0%	15.4%	33.5%	22.2%	25.0%
1-week	Base NG	0.50	0.17	0.051	0.47	0.46	0.15	0.055	0.44	0.42	0.14	0.042	0.39
	LNG	0.58	0.22	0.066	0.59	0.53	0.20	0.073	0.55	0.48	0.19	0.056	0.50
	Δ %	16.0%	29.4%	29.4%	25.5%	15.2%	33.3%	32.7%	25.0%	14.3%	35.7%	33.3%	28.2%
HCHO (µg/m³)													
Max 1-hr	Base NG	36.8	15.8	6.35	36.0	34.6	15.0	6.3	32.3	30.4	14.0	5.28	31.6
	LNG	37.6	16.7	6.66	39.6	35.8	16.0	6.91	35.2	31.0	15.1	5.57	33.0
	Δ %	2.2%	5.7%	4.9%	10.0%	3.5%	6.7%	9.7%	9.0%	2.0%	7.9%	5.5%	4.4%
Max 8-hr	Base NG	16.2	6.48	2.39	15.4	15.0	6.23	2.31	13.8	13.1	5.82	2.06	12.9
	LNG	16.6	6.81	2.55	16.5	15.5	6.49	2.53	15.5	13.4	6.23	2.23	13.5
	Δ %	2.5%	5.1%	6.7%	7.1%	3.3%	4.2%	9.5%	12.3%	2.3%	7.0%	8.3%	4.7%
1-week	Base NG	4.01	1.37	0.47	3.66	3.57	1.34	0.47	3.26	3.23	1.21	0.39	3.17
	LNG	4.12	1.48	0.49	3.87	3.71	1.47	0.51	3.51	3.31	1.30	0.45	3.35
	Δ %	2.7%	8.0%	4.3%	5.7%	3.9%	9.7%	8.5%	7.7%	2.5%	7.4%	15.4%	5.7%

Table 29: Comparison of NO₂, CO, and HCHO Time-Averaged Concentrations Arising from GCB Use and Outdoor Sources for RASS Households in the Six-County SoCal Region (n = 6,634), San Diego (SD) County (n = 1,039), and Riverside County (n = 606). Δ % Indicates the Percent Increase Associated with LNG, Relative to Conventional NG (Base NG). All scenarios Assume Winter AER.

NOTE: The numbers provided in this table were calculated using nominal, rather than measured, oven firing rates, resulting in slightly higher concentrations than those shown elsewhere in report. These results are provided for purpose of comparing individual counties to SoCal region.

Pollutant metric	Emfacs	HHs in 6-county SoCal Region				San Diego HHs				Riverside HHs			
		mean	Median	25%	75%	Mean	Median	25%	75%	mean	Median	25%	75%
NO₂ [μg/m³]													
Max 1 hr	Base NG	209	156	93	258	189	150	88	240	175	129	79	220
	LNG	224	167	99	279	204	163	94	259	187	141	84	236
	Δ %	7.2%	7.1%	6.5%	8.1%	7.9%	8.7%	6.8%	7.9%	6.9%	9.3%	6.3%	7.3%
Max 8-hr	Base NG	56.3	43.1	29.7	66.2	50.5	40.4	27.2	59.4	45.1	34.7	22.8	52.1
	LNG	59.5	45.4	31.0	70.5	53.5	42.9	28.3	63.7	47.8	36.6	23.6	55.3
	Δ %	5.7%	5.3%	4.4%	6.5%	5.9%	6.2%	4.0%	7.2%	6.0%	5.5%	3.5%	6.1%
1-week	Base NG	21.1	18.4	13.9	24.5	18.9	16.7	13.1	21.5	15.0	12.3	9.24	17.4
	LNG	21.8	18.8	14.2	25.5	19.5	17.1	13.4	22.7	15.6	12.7	9.47	18.2
	Δ %	3.3%	2.2%	2.2%	4.1%	3.2%	2.4%	2.3%	5.6%	4.0%	3.3%	2.5%	4.6%
CO [ppm]													
Max 1-hr	Base NG	5.45	3.05	1.45	5.79	5.06	2.49	1.41	5.35	4.34	2.16	1.07	4.86
	LNG	6.13	3.70	1.67	6.98	5.68	3.08	1.57	6.56	4.95	2.74	1.25	5.91
	Δ %	12.5%	21.3%	15.2%	20.6%	12.3%	23.7%	11.3%	22.6%	14.1%	26.9%	16.8%	21.6%
Max 8-hr	Base NG	3.1	1.8	1.16	3.77	2.86	1.71	1.24	2.88	2.2	1.23	0.76	2.3
	LNG	3.4	2.0	1.21	4.15	3.13	1.89	1.30	3.37	2.4	1.41	0.82	2.7
	Δ %	9.7%	11.1%	4.3%	10.1%	9.4%	10.5%	4.8%	17.0%	9.1%	14.6%	7.9%	17.4%
1-week	Base NG	1.36	0.91	0.74	1.40	1.29	0.98	0.88	1.26	0.91	0.64	0.54	0.88
	LNG	1.44	0.96	0.76	1.54	1.36	1.02	0.90	1.38	0.97	0.68	0.55	1.0
	Δ %	5.9%	5.5%	2.7%	10.0%	5.4%	4.1%	2.3%	9.5%	6.6%	6.3%	1.9%	13.6%

Table 30: Number of Households (per 1,000) with Concentrations Exceeding a Health-Based Pollutant Standard for Conventional Natural Gas and LNG Use in Gas Cooking Burners (GCBs) in Southern California^a

NOTE: The numbers provided in this table were calculated using nominal, rather than measured oven firing rates. These results are provided for purpose of comparing individual counties to SoCal region.

Time-averaged Pollutant Standards	Fuel	Per 1,000 SoCal HHs	Per 1,000 San Diego HHs	Per 1,000 Riverside HHs
(a) Indoor time averaged concentrations due to GCBs				
NO₂				
1-hr NAAQS (190 µg/m ³)	Base NG	360	326	287
	LNG	390	375	325
	+Δ	30	49	38
CO				
1-hr CAAQS (20 ppm)	Base NG	38	27	26
	LNG	44	29	33
	+Δ	6	2	7
HCHO				
1-hr ATSDR guidelines (49 µg/m ³)	Base NG	189	173	153
	LNG	201	188	172
	+Δ	12	15	19
8-hr OEHHA non-cancer REL (9 µg/m ³)	Base NG	189	173	153
	LNG	201	188	172
	+Δ	12	15	19
(b) Indoor time averaged concentrations due to GCBs and outdoor sources				
NO₂				
1-hr NAAQS (190 µg/m ³)	Base NG	397	366	310
	LNG	433	414	342
	+Δ	36	48	32
CO				
1-hr CAAQS (20 ppm)	Base NG	41	31	26
	LNG	49	31	36
	+Δ	8	0	10
8-hr NAAQS and CAAQS (9 ppm)	Base NG	41	31	26
	LNG	49	31	36
	+Δ	8	0	10

^a Results based on one week of wintertime simulations for all homes across six Southern California counties and for San Diego or Riverside homes in the cohort. Concentrations attributed to (a) GCBs and (b) GCBs plus outdoor sources. Simulations are based on empirical distribution of air exchange rates (AERs).

3.6 Formaldehyde Risk Assessment

To assess the effect of a switch to LNG on cumulative cancer risk from exposures related to cooking burner use, we first calculated the average change in one-week average exposure concentrations for the winter, infiltration air exchange scenario. This was selected as providing an upper bound estimate of the effect since concentrations are highest in this scenario. This corresponds to data shown in Figure 18. We multiplied this exposure concentration increment of $0.19 \mu\text{g m}^{-3}$ by the U.S. EPA's draft unit risk estimate of 1.1×10^{-4} per $\mu\text{g m}^{-3}$ over a 70-year lifetime exposure, then divided by 70 years (assumed lifetime for exposure) to calculate an annual excess cancer risk of 3×10^{-7} per year. This incremental risk is miniscule in comparison to the baseline cancer risk from HCHO exposures in homes – which is roughly two orders of magnitude higher – and is well below the most conservative threshold of concern of 1×10^{-6} . The actual increment of annual risk would be much lower than even the amount calculated above owing to lower exposure concentrations in the more broadly relevant empirical AER scenarios and considering that the winter AER scenarios represent only a fraction of annual exposures (see Figure 18 and Table I-13 in Appendix I for exposure concentrations during other scenarios). For example, the change in average one week HCHO concentration during summer with empirical AERs is estimated to be only $0.05 \mu\text{g m}^{-3}$ (Table I-13).

3.7 Comparisons between Simulation Results and Measurements

The results for this study were obtained using a physics-based model using parameters that are either specifically known for each home (e.g., home size, frequency of cooking) or assigned based on data that have been collected and related to home (e.g., air leakage or overall air exchange rates) or household (e.g., cooking times) characteristics. The calculated time-dependent and time-integrated concentrations should therefore be assumed to be roughly accurate. Nevertheless, it is desirable to compare the calculated concentration distributions to any available and relevant measurements.

Concentrations of carbon monoxide and nitrogen dioxide in homes have been measured in a number of studies; but comparisons between reported measurements and our modeling results must consider the following caveats. Our modeling study looked at only one indoor source – emissions from cooking burners – and results demonstrate that CO and NO₂ from outdoors can contribute a substantial fraction or even the majority of these pollutants even for many homes using gas cooking burners. The presence of any other indoor sources – including in order of likely impact, unvented combustion heaters, pilot lights for cooking and other unvented appliances, and smoking – and differences in outdoor concentrations will impact indoor measurements. Data are not consistently or uniformly presented with the full resolution that would be appropriate for direct comparison with our model results. With these physical phenomena and caveats in mind, we reviewed published data and summarize the most relevant comparative data below.

There have been several large indoor air quality field studies that include measurements of NO₂ or CO in California homes. Much of this work occurred during or prior to the early 1990s and publicly available reports do not always provide results resolved in a manner to allow relevant

comparisons to the simulation results presented in this report. For example, Wilson et al. (1993) report measurements of NO₂ and CO in 214 homes throughout California. They collected data on the appliances present and even on cooking. However, since they did not report measured NO₂ concentrations specific to homes with gas or electric appliances, we cannot readily use their results as a point of comparison here with one exception noted below (8-hr CO).

For time-integrated NO₂, Spengler et al. (1994) report measurements made in Los Angeles in the year 1988; concentrations were measured in samples collected outdoors and in bedrooms (indoors) of 482 homes and via personal samplers for 682 individuals living in those homes. The study analyzed results by various personal and household characteristics, including presence of gas cooking burners with and without pilots. They report personal exposures in homes with gas ranges as being 12 ppb (23 µg m⁻³) higher than in homes with electric ranges. The difference is 15 ppb (28 µg m⁻³) between homes with electric ranges and those with gas ranges with pilots. For homes with gas ranges without pilots, mean personal exposure concentrations were about 5 ppb (roughly 10 µg m⁻³) higher. Differences in homes with gas appliances with compared to without pilot lights was hypothesized to be partly associated with co-varying factors, namely the leakiness of the home.

Moving to studies outside of California, Schwab et al. (1994) reported measurements in Albuquerque, New Mexico, homes with gas cooking burners with pilot lights, gas cooking burners without pilot lights and all-electric homes. Differences between mean results from the first two groups of home suggest that the pilot burners contributed roughly 10–16 µg m⁻³ to indoor concentrations across several summer and winter seasons. Differences between homes with gas cooking without pilots and all electric homes were roughly 16–22 and 3.4–7.0 µg m⁻³ in winter and summer, respectively. Based on a subset of measurements reported by Neas et al. (1991) as shown in Table 31, NO₂ was higher in homes with unvented gas appliances compared to homes with electric appliances. The increments were 28–35 µg m⁻³ in winter and about 18 µg m⁻³ in summer. We selected from among the data reported by Neas et al. (1991) to focus on locations for which only a small minority of the gas appliance homes had kerosene heaters, but we note that many of these homes likely had pilot burners that continuously emit NO₂. Smoking occurred in a substantial fraction of both the all-electric homes and the homes with gas appliances. To the extent that the pilot burner results of Schwab can be applied to Neas et al., the incremental NO₂ attributable to gas cooking without pilot lights in the Neas et al. study appears to be of similar magnitude as the Schwab results. Berwick et al. (1984) report two-week integrated NO₂ measurements in homes in New Haven, Connecticut, with results resolved into homes that have gas cooking and a kerosene heater, only a kerosene heater, only gas cooking, and neither gas cooking nor kerosene (no source). Household concentrations of NO₂ averaged 31.4 µg m⁻³ in 13 homes with gas cooking and no kerosene compared with 5.9 µg m⁻³ in four homes with no source; this yields an estimated effect of gas cooking burners (potentially including pilot lights) of about 25 µg m⁻³ during the winter season in which measurements were made.

The relevant values to compare to these from our modeling results are those shown in Figure 6 and the corresponding table in Appendix I. Our model predicts mean indoor concentrations attributable to gas cooking burners of about 10 µg m⁻³ in winter and 6.5 µg m⁻³ in summer. These

results are of similar magnitude but at the lower end (especially for Winter) of the measured values reported by Spengler et al., Schwab et al., Neas et al. and Berwick et al.

For peak NO₂ following cooking burner use, we found very limited data in the literature. In a Netherlands-based study, Noy et al. (1990) report time-integrated measurements from passive samples collected over weeklong periods in homes and additional samples that were collected only during periods when an unvented gas appliance was used (peak values). For sampling in December, geometric mean, time-integrated concentrations of 30 and 24 µg m⁻³ were reported for the kitchens and living rooms of the 107 homes in the study. Peak concentrations in 67 of those homes ranged from 35 to 2500 µg m⁻³ in the kitchen and 19 to 1,180 µg m⁻³ in the living rooms. The average peak-to-time-integrated ratios were 5.5 for kitchens and 4.4 for living rooms. In a United Kingdom (UK) study, Ross et al. (1996) report maximum 1-hr and time-integrated measurement with a real-time analyzer for kitchens and living rooms in 12 homes. Maximum 1-hr concentrations in the living rooms and kitchens of homes with gas cooking were 190 to 1,100 µg m⁻³ in the kitchens and 92–560 µg m⁻³ in the living rooms. We provide these results with the very important caveat that cooking burners in the UK and the Netherlands may not have the same emission rates as those the United States. In a U.S. study conducted with one cooking appliance in a research home (Fortmann 2001), NO₂ concentrations of about 360 µg m⁻³ were measured throughout the home during a full-meal cooking event.

The measured values presented in the previous paragraph can be compared against the highest 1-hour concentrations shown in Figure 8. The simulation model used in this study predicts a mean value of highest 1-hr NO₂ concentrations of 200 µg m⁻³ across the sample cohort.

For CO, we found very limited data available for U.S. homes primarily affected by cooking burners and outdoor air. In Volume 3 of their report, Wilson et al. (1995) present results for the difference between indoor and outdoor maximum 8-hr CO (indoor-outdoor) by home, resolved by cooking burner type. Based on a small cumulative probability plot, the median values appear to be about 2.0, 1.2, and 1.0 ppm for homes with gas cooking burners with pilots, homes with gas cooking burners without pilots, and homes with electric cooking. At the 75th percentile, the difference between indoor-outdoor CO for homes with gas cooking without pilots and homes with electric cooking appears to be on the order of 1 ppm. These values are a bit lower than those found with the exposure model.

Taken as a group, these comparisons to relevant measurements reported in the literature demonstrate that the results of this modeling study are reasonable and generally consistent with the measurements.

Table 31: Summary Results for Selected Studies Reporting Measurements of Time-Integrated NO₂ in Homes

Location (Reference)	Season	Indoor Location	Mean (SD) NO ₂ [$\mu\text{g}/\text{m}^3$] in Homes w/Gas Sources, # Homes in Sample	Mean (SD) NO ₂ [$\mu\text{g}/\text{m}^3$] in Homes w/o Sources, # Homes in Sample	Sample Duration	Comments
Portage, Wisconsin (Neas et al. 1991)	Annual Winter Summer	Average of kitchen, activity room, and bedroom	32.3 37.8 29.1 N = 110 (52 w/smoking)	10.7 11.1 11.5 N = 194 (118 w/smoking)	2-week samples	Among 110 homes with sources: - 106 gas cooking - 10 kerosene heat
St. Louis, Missouri (Neas et al. 1991)	Annual Winter Summer	Average of kitchen, activity room, and bedroom	58.8 66.7 54.5 N = 208 (139 w/ smoking)	30.1 29.0 33.3 N = 69 (38 w/ smoking)	2-week samples	Among 208 homes with sources: - 205 gas cooking - 13 kerosene heat
Watertown, Massachusetts (Neas et al. 1991)	Annual Winter Summer	Average of kitchen, activity room, and bedroom	27.9 31.5 25.5 N = 162 (118 w/smoking)	12.5 10.2 15.9 N = 63 (42 w/smoking)	2-week samples	Among 162 homes with sources: - 162 gas cooking - 1 kerosene heat.

Albuquerque, New Mexico (Schwab et al. 1994)	Winter 88-89	Infant's bedrooms	53.7 (49.5) N = 144	14.8 (22.1) N = 127	2 weeks	Source data are homes w/gas cooking without pilots.
	Winter 89-90		52.1 (46.6) N = 240	13.7 (9.42) N = 183		
	Winter 90-91		39.2 (24.5) N = 155	11.8 (8.12) N = 92		
	Summer 1988		22.0 (11.6) N = 93	15.0 (9.61) N = 67		
	Summer 1989		17.0 (9.25) N = 209	13.8 (10.7) N = 183		
	Summer 1990		17.4 (8.54) N = 222	13.0 (7.28) N = 163		

CHAPTER 4: Conclusions and Recommendations

Exposure to pollutants emitted by natural gas cooking burners represents a substantial public health concern in California. The modeling results of this study indicate that when natural gas cooking burners are used without simultaneous task ventilation a substantial fraction of users will be exposed to pollutant concentrations that exceed health-based standards and guidelines. Modeling for Southern California suggests that among the population that lives in households that have and use gas cooking burners, roughly 40–45 percent will be routinely exposed to concentrations that exceed the U.S. national ambient air quality 1-hour standard for nitrogen dioxide, roughly 20–25 percent will be exposed to formaldehyde that exceeds guideline levels for acute exposure and roughly 4–6 percent will be exposed to acute CO above levels established for outdoor standards. Since the fundamental physical parameters are similar across the state, these results should be seen as broadly relevant to California homes with natural gas. In addition, since existing data suggests very low rates of task ventilation use during cooking, and since the key physical parameters that affect concentrations are similar throughout the state, the results of this study likely apply to the majority of homes with gas cooking burners throughout California. The switch from conventional natural gas to liquefied natural gas is projected to have a deleterious but small impact on concentrations, exposures, and health risk associated with use of natural gas cooking burners.

The hazard can be mitigated substantially through use of venting range hoods that capture cooking burner exhaust (as well as cooking-related pollutants) at the point of emissions and exhaust them to the outdoors. While many installed range hoods may capture only a fraction of the emitted pollutants, performance of most can be substantially improved by (1) starting the fans at or before the start of cooking, (2) leaving the fan on for at least a few minutes after cooking, and (3) preferentially cooking on back burners to improve pollutant capture.

This analysis quantifies the potential indoor exposure hazards associated with a switch from conventional natural gas to liquefied natural gas in Southern California. It also reveals that the use of natural gas-powered cooking burners without a kitchen exhaust fan commonly leads to indoor pollutant concentrations that exceed outdoor, health-based standards. The identification of this common hazard should help motivate action to mitigate these potentially harmful exposures and thus improve the health of Californians.

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GLOSSARY

ACH	air changes per hour
AER	air exchange rate
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATSDR	Agency for Toxic Substances and Disease Registry
Btu	British thermal unit
CAAQS	California Ambient Air Quality Standards
Cal/EPA	California Environmental Protection Agency
CARB	California Air Resources Board
CEC	California Energy Commission
CO	carbon monoxide
GCB	gas cooking burner
GM	geometric mean
GSD	geometric standard deviation
GTI	Gas Technology Institute
HCHO	formaldehyde
HH	household
LADWP	Los Angeles Department of Water and Power
LBNL	Lawrence Berkeley National Laboratory
LNG	liquefied natural gas
L/s-m ²	Liters per second per square meter
NAAQS	National Ambient Air Quality Standards
NG	natural gas
NHAPS	National Human Activity Patterns Survey
NL	normalized leakage
NO	nitrogen oxide
NO ₂	nitrogen dioxide
OEHHA	Office of Environmental Health Hazard Assessment
PG&E	Pacific Gas and Electric
PN	particle number
RASS	Residential Appliance Saturation Survey
REL	reference exposure level
SCE	Southern California Edison
scf	standard cubic foot
SD	standard deviation
SDG&E	San Diego Gas and Electric
SFDH	single-family detached home
SLAMS	State and Local Air Monitoring Site
UFP	ultrafine particles
URE	unit risk estimate
U.S. DHHS	United States Department of Health and Human Services

U.S. EPA	United States Environmental Protection Agency
WN	Wobbe number

APPENDIX A: Characteristics of 2003 Residential Appliance Saturation Survey Households Reporting Using Gas Cooking Burners during a Typical Week

This appendix presents summary statistics on the 10,499 households from the 2003 Residential Appliance Saturation Survey (RASS) who reported having a gas cooking burner and cooking at least one meal during a typical week. This group was regarded as the pool of respondents suitable for analysis of statewide LNG impacts on indoor pollutant concentrations. We compiled summary statistics for this group of respondents prior to making the decision to limit analysis to Southern California. The following characteristics of the statewide sample of homes reporting use of gas appliances are summarized in this appendix:

- Building type (Single-family detached (SFD), single-family attached (SFA), apartment/condo with 2–4 units, apartment/condo with 5+ units, mobile home, and “other”)
- Home living area (ft²)
- Home locations with respect to California Climate Zone
- Home age (year built)
- Household occupancy (number of residents)
- Highest education level attained by the head of household
- Ethnicity of head of household
- Primary language spoken in the RASS household

As can be seen from **Table A- 1**, the majority of RASS households with gas appliances are single-family detached homes (68 percent of all gas appliance households that reported building type). The second largest group of residences in the RASS are multi-family (5+ units) condominiums and apartments (12 percent). Single-family attached residences and 2–4 unit condos/apartments together make up another 11 percent of the residences, and approximately 3 percent of the gas appliance households live in mobile homes. However, approximately 11 percent of gas appliance households in the RASS provided no response as to their dwelling type.

Table A- 1. Building Type of RASS Households (HHs) with Gas Appliances

Building Type	No. of HHs	Proportion of HHs
SFD	6,385	60.8%
SFA	773	7.4%
Apt/Condo 2–4 Units	652	6.2%
Apt/Condo 5+ Units	1145	10.9%
Mobile home	260	2.5%
Other	112	1.1%
Non-response	1,172	11%

SFD = single-family detached

SFA = single-family attached (Townhouse, duplex, or row houses)

Home living area (in square feet, ft²) is associated with building type. Single-family detached residences tend to have a larger floor area relative to the other building types. The median living area over all gas cooking RASS households is 1,375 ft², the mean is 1,590 ft². **Table A-2** provides summary statistics on the living area of RASS households that use gas cooking appliances, by building type. These summary statistics are based on the “SQFT_A” RASS variable, which is the midpoint of the survey range responses to the “SQFT” variable. Specifically, “SQFT” is a categorical response variable for the square feet of living space (including bathrooms, foyers, and hallways and excluding garages, basements, and unheated porches). Respondents had the option to select from twelve categories of “SQFT,” ranging from “less than 250” to “greater than 5,000” square feet, in addition to a non-response option.

Note, in instances where a response to “SQFT” was missing (coded as “97” in the RASS data file), the California Energy Commission (Energy Commission) implemented a “plugging” routine (described on p. 109 of 417 in CEC 2004) to obtain the “final plugged data” (based on a “conditional means process”) where “SQFT” is interpolated based on household features. In addition to interpolating missing survey data on square feet of living area, the “conditional means process” was also used to interpolate missing survey data on income, household size, and the age of home.

Table A-2. Summary Statistics of Living area (ft²) of All RASS Households with a Gas Cooking Appliance, by Building Type

Building Type	Arithmetic Mean (ft ²)	Median (ft ²)	Standard Deviation
SFD	1,807	1,750	813
SFA	1,229	1,125	496
Apt/Condo 2–4 Units	1,017	875	562
Apt/Condo 5+ Units	895	875	465
Mobile home	1,264	1,375	429
Other	1,317	1,125	992
“no response”	1,743	1,750	802
All households	1,590	1,375	817

SFD = single-family detached

SFA = single-family attached (Townhouse, duplex, or row house)

Gas cooking appliance households in the RASS are distributed across the sixteen building climate zones defined by the Energy Commission (**Table A- 3**). We investigated the possibility of developing empirical air exchange rate distributions by climate zone but determined that the data were sufficient to resolve the state into only two geographic areas: Northern and Southern California.

Table A- 3. Distribution of RASS Gas Appliance Cooking Households by California Energy Commission Building Climate Zone

CEC Climate Zone	Household Count	Proportion (%)
1	90	0.9
2	266	2.5
3	1494	14.2
4	448	4.3
5	195	1.9
6	1582	15.1
7	955	9.1
8	1177	11.2
9	1621	15.4
10	890	8.5
11	262	2.5
12	512	4.9
13	513	4.9
14	350	3.3
15	107	1.0
16	37	0.4

As can be seen by **Table A-4**, the majority of households (68.4 percent) that use gas cooking appliances live in homes built before 1979. Slightly less than 10 percent of households using gas cooking appliances live in homes built after 1995. The rest of the RASS households that use gas cooking appliances live in homes built between 1980–1995 (approximately 22 percent of households).

Table A-4. Distribution of the Year the Residence Was Built Across All Gas Appliance Cooking RASS Households (HHs)

Year Built	HH Count	% of Total RASS HHs	Census 2000 HH count (%)
before 1950	2110	20.1	~20
1951–1979	5074	48.3	~50
1980–1995	2289	21.8	~24
>1995	1026	9.8	6

Building type and size is associated with household occupancy. Across the RASS HH cohort, single-family detached residences tend to have between 2–4 occupants, while single-family attached residences, mobile homes, and all condo/apartment units tend to have 1–2 occupants. The distribution of household occupancy among the gas cooking appliance household in the RASS, by building type, is provided graphically in Figure A-1(a-e).

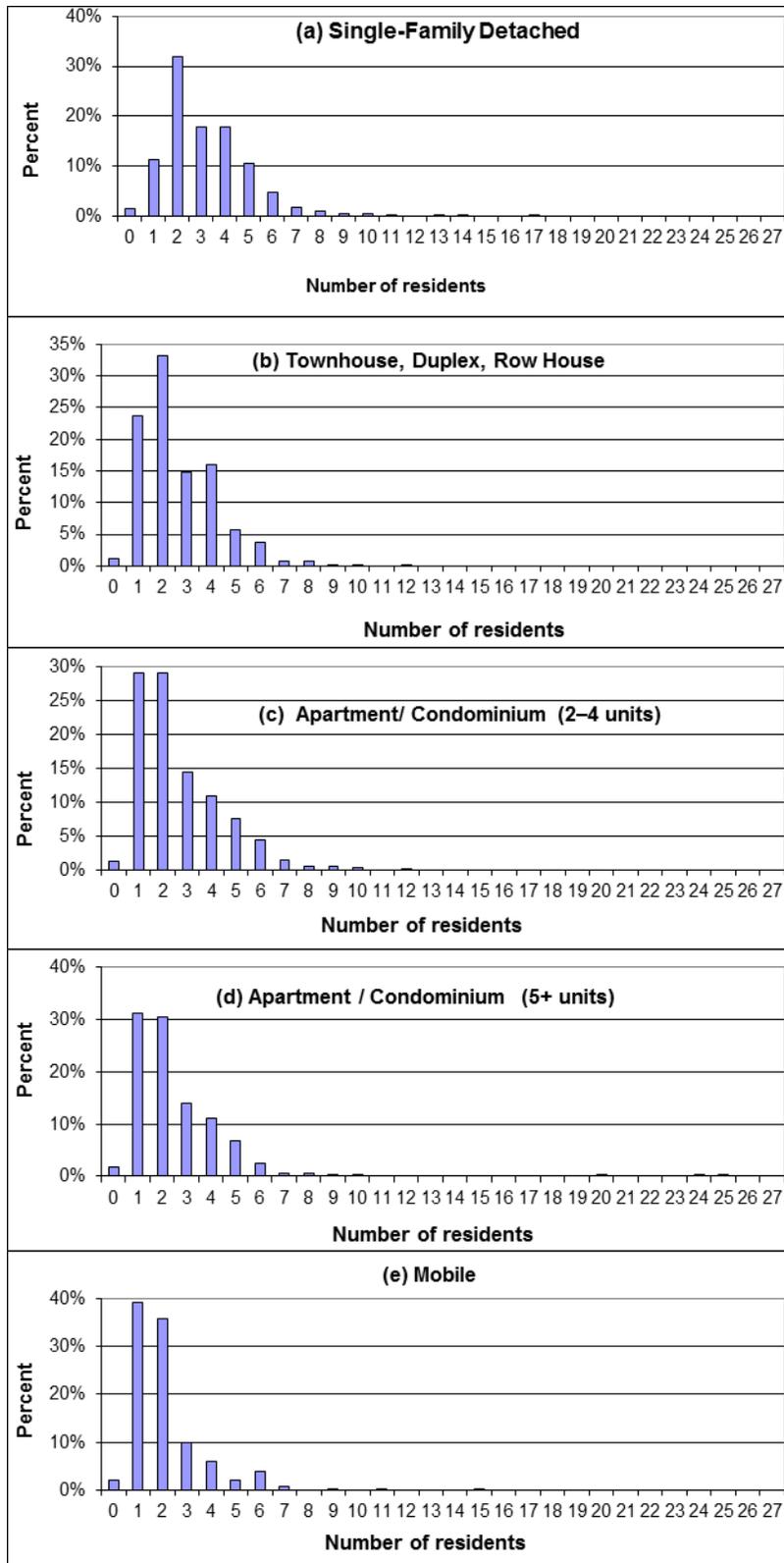


Figure A-1 (a-e). Distribution of Number of Occupants in RASS Households That Use GCBs by Building Type, (A) Single-Family Detached; (B) Townhome, Duplex, or Row Home; (C) Apartment/Condominium (2-4 Units); (D) Apartment/Condominium (5+ Units), and (E) Mobile Home

Among the gas cooking appliance RASS household, the highest education level of the head of the household is summarized in **Table A-5**. Less than 10 percent of these HHs did not complete college and over 20 percent have a postgraduate degree.

Table A-5. The Distribution of the Highest Education Level Attained by the Head of Household Among RASS Households That Report Using a Gas Cooking Appliance

Highest education level attained by head of household	Count	Proportion of all respondents (%)
Elementary	267	2.5
Some high school	486	4.6
High School Graduate	1238	11.8
Some college/trade/vocational school	3102	29.5
College Graduate	2999	28.6
Postgraduate degree	2118	20.2
No response	289	2.8

The distribution in the ethnicity of the head of household among the RASS gas appliance cooking households is summarized in **Table A- 6**. The majority of RASS households have a head of household that is of Caucasian descent.

Table A- 6. Ethnicity of Head of Household Among Gas Appliance Cooking RASS Households

Ethnicity of Head of Household	Count	Proportion of all respondents (%)
Caucasian	6728	64
Hispanic/Latino	1649	15.7
Asian/Pacific Islander	871	8.3
African American	545	5.2
American Indian	166	1.6
Other	243	2.3
No response	297	2.8

Lastly, the primary language spoken in the gas cooking appliance RASS households was English (9,119 households). Spanish was primarily spoken in 327 households, and an Asian language in 731 households. The remaining gas cooking households either responded as speaking an “other” language (108 households), or did not respond (214 households).

APPENDIX B: Supplemental Information Related to Air Exchange Rate

Infiltration-only AER

Based on the analyses of Chan et al. (2003, Final Report), Table B- 1 summarizes the distribution of normalized leakage area from conventional single-family detached homes that are not participants of a low-income or energy efficiency program, by floor area and year built.

Table B- 1. The GM, GSD, and Median NL of Conventional Houses by Floor Area and Year House Built (Chan et al. 2003- FINAL). Conventional houses are not low-income and are not participating in an energy-efficiency program.

Floor Area	Year Built	GM	GSD
< 93 m ²	Before 1950	1.09	1.84
	1950–1979	0.98	1.92
	1980–1995	0.49	1.62
	After 1995	0.33	1.36
93 – 139 m ²	Before 1950	1.14	1.78
	1950–1979	0.82	1.73
	1980–1995	0.44	1.74
	After 1995	0.34	1.45
140-185 m ²	Before 1950	0.74	1.76
	1950–1979	0.51	1.68
	1980–1995	0.41	1.79
	After 1995	0.28	1.57
186-232 m ²	Before 1950	0.55	1.49
	1950–1979	0.40	1.49
	1980–1995	0.35	1.59
	After 1995	0.25	1.64
>232 m ²	Before 1950	0.53	1.41
	1950–1979	0.37	1.40
	1980–1995	0.29	1.67
	After 1995	0.18	1.68

Empirical AER

We located previous studies reporting AER in winter and non-winter (i.e., summer, spring, and fall) throughout California. Summary statistics and additional information, including home age, location (i.e., northern or southern California) and AER measurement method of the full suite of these studies is provided in the **Table B- 2** (for winter) and **Table B-3** (for non-winter seasons).

Table B- 2. Studies Reporting Measurements of Air Exchange Rate (AER, [ACH]) in California Homes in Winter. Bolded values are based on analysis of available raw data. Entries sorted by the year the homes were built.

Year Home Built	No. homes (measurements)	AM (SD)	GM	AER Measurement Method	Additional Notes on Home Characteristics	Reference
Southern California						
Pre - 1984	192		0.42 ^b		Each home had a forced air furnace	Wilson et al. (1986)
Pre- 1985	371	0.58 (0.47)	0.45 ^b			Wilson et al. (1986) ^a
1965– 1987	13		0.29 ^b	1 week PFT	Located in Los Angeles County	Wilson et al. (2003)
Pre- 1990	112	0.66 (0.5)	0.53	48-hr PFT	PG&E, SoCalGas, and SDG&E utility districts	Wilson et al. (1993)
Pre- 1991	40	0.79 (0.57)	0.47 ^b		Each home had a forced air furnace	Wilson et al. (1986) ^d
Pre- 2002	47	0.78 (0.50)	0.65	48-hr PMCH tracer	Located in Los Angeles county	RIOPA (AER, 2010)
2002	37	0.17 (0.07)	0.16; 0.17^b	1-week PFT		Wilson et al. (2003)
Pre- 2004	40	1.36 (1.17)			Located in inner-city LA; 68% of homes are SFA or SFD.	Sax et al. (2004)
Northern California						
Pre- 1990	171	0.44 (0.23)	0.38	48-hr PFT	PG&E, SoCalGas, and SDG&E utility districts	Wilson et al. (1993)
Pre- 1993	130	0.65 (0.41)	n/a		Homes located in Placerville and Roseville	Sheldon et al. (1993) ^a
	137	0.63 (0.36)	n/a			
Northern and Southern California						
Post- 1995	44	0.25 (0.13)	0.22	24-hr PFT		Offermann et al. (2009)

AM = arithmetic mean; SD = Standard deviation; GM = geometric mean

^a as referenced in Table C1 of CARB (1998)

^b GM is approximated from the reported median

^c as cited in Table 7-15 of Koontz et al. (1998). Note this is assumed lognormal, and input to the CPIEM.

^d as cited in Wilson et al. (2003).

Table B- 3. Studies Reporting Air Exchange Rates (AERs, [ACH]) in California Homes in Non-winter Seasons. Bolded values are based on analysis of available raw data. Entries sorted by the year the homes were built.

Year Home Built	Number of Homes (Measurements)	AM (SD)	GM	AER Measurement Method	Additional Notes on Home Characteristics	Reference
Summer – Southern California						
Pre-1984	426	1.51 (1.47)	1.08 ^b			Wilson et al. (1986) ^a
Pre-1991	43 (90)	2.83 (2.54)	n/a		Located in Los Angeles County	Wallace et al. (1991) TEAM ^c
Summer I – Northern and Southern California combined						
Pre-1975	29	0.7 (0.52)			Central and Southern California	ADM (1990) ^a
Post-1995	62 (182)	0.82 (1.31)	0.44	24-h PFT	Northern and Southern California ^d	Offermann (2009)
Fall – Southern California						
Pre-1994	175	1.25 (1.03)	1.0 ^b			PTEAM (Ozkaynak et al. 1994) ^a
Pre-2000	35	2.45 (2.22)			Inner-city LA homes; 68% of homes SFA or SFD.	Sax et al. (2004)
Spring – Southern California						
Pre-1984	571	0.78 (0.63)	0.62 ^b			Wilson et al. (1986) ^a
All non-winter – Southern California						
Pre -2002	137 135 ^e	1.50 (2.09) 1.28 (0.98)	1.01 0.97	48-h PMCH tracer	Located in Los Angeles	RIOPA (AER, 2010)

^a as referenced in Table C1 of CARB (1998).

^b GM is approximated from the reported median

^c as cited in Table 7-15 of Koontz et al. (1998). Note this is assumed lognormal, and input to CPIEM.

^d Five homes that were each > 1550 ft² had measured AER of 6.47, 5.34, 5.18, 4.28, and 3.17.

^e removed two highest AER (16.7334 ACH in House ID "CA080", and 16.4806 ACH in "CA 00310")

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APPENDIX C: Cooktop and Oven Burner Use

Home and household characteristics data in RASS, such as building type, number of household occupants, and ethnicity have been found to correlate with cooking frequency. The next section summarizes the research and analysis on:

- Building type and cooktop and/or oven use Frequency
- Household Occupancy and Frequency of Cooktop and/or oven burner use
- Ethnicity and frequency of cooktop and/or oven burner use
- NHAPS food preparation time-activity plots
- LBNL web-based cooking activity survey

Building Type and Cooktop and/or Oven Use Frequency

As can be seen in **Table C-1** to **Table C-4**, the frequency of cooktop and/or oven use for a given meal is relatively consistent across building types, with the exception of dinner (**Table C-3**) among the “often” category (i.e., 5–7 times per week), with over 47 percent of single-family detached households in this category, and only 37 percent of mobile home households. Additionally, nearly 14 percent of all mobile home households responded that they “never” use their range or oven for “other” cooking, but over 32 percent of all apartment/condo (5+ units) households responded likewise (**Table C-4**).

Table C-1. Distribution of RASS Responses by Building Type, to the Question “During a Typical Week, How Often Do You Use Your Range or Oven for Breakfast?”

Survey Response	Single-Family Detached	Townhouse, Duplex, Row House	Apt Condo 2–4 Units	Apt Condo 5+ Units	Mobile Home	Other
NEVER	20.3%	23.6%	26.6%	25.0%	19.2%	17.7%
RARELY (<1 per week)	21.2%	21.8%	17.3%	20.8%	22.9%	16.3%
OCCASIONALLY (1-2 times per week)	23.2%	23.6%	17.5%	16.5%	18.9%	15.1%
SOMETIMES (3–4 times per week)	12.7%	10.4%	11.9%	11.2%	11.1%	12.5%
OFTEN (5–7 times per week)	17.3%	14.8%	19.7%	20.7%	16.8%	13.7%
NO RESPONSE	5.5%	5.9%	7.0%	5.8%	11.1%	24.7%

Table C-2. Distribution of RASS Responses by Building Type to the Question “During a Typical Week, How Often Do You Use Your Range or Oven for Lunch?”

Survey Response	Single-Family Detached	Townhouse, Duplex, Row House	Apt Condo 2-4 Units	Apt Condo 5+ Units	Mobile Home	Other
NEVER	27.3%	28.7%	32.4%	31.4%	20.5%	18.4%
RARELY (<1 per week)	26.6%	25.8%	18.8%	21.8%	28.7%	16.5%
OCCASIONALLY (1-2 times per week)	18.6%	16.8%	15.1%	18.2%	14.6%	16.3%
SOMETIMES (3-4 times per week)	10.0%	9.0%	8.9%	10.0%	8.5%	9.0%
OFTEN (5-7 times per week)	9.4%	9.9%	13.5%	12.2%	8.7%	11.4%
NO RESPONSE	8.1%	9.8%	11.2%	6.5%	19.0%	28.4%

Table C-3. Distribution of RASS Responses by Building Type to the Question “During a Typical Week, How Often Do You Use Your Range or Oven for Dinner?”

Survey Response	Single-Family Detached	Townhouse, Duplex, Row House	Apt Condo 2-4 Units	Apt Condo 5+ Units	Mobile Home	Other
NEVER	2.0%	5.0%	5.1%	4.4%	5.2%	3.1%
RARELY (<1 per week)	7.1%	7.0%	13.8%	9.6%	12.6%	8.6%
OCCASIONALLY (1-2 times per week)	13.3%	19.0%	14.8%	15.5%	19.1%	15.3%
SOMETIMES (3-4 times per week)	27.6%	26.1%	23.8%	28.1%	20.8%	26.0%
OFTEN (5-7 times per week)	47.4%	39.8%	38.2%	40.3%	37.2%	29.4%
NO RESPONSE	2.5%	3.1%	4.2%	2.2%	5.0%	17.7%

Table C-4. Distribution of RASS Responses by Building Type to the Question “During a Typical Week, How Often Do You Use Your Range or Oven for Other?”

Survey Response	Single-Family Detached	Townhouse, Duplex, Row House	Apt Condo 2-4 Units	Apt Condo 5+ Units	Mobile Home	Other
NEVER	25.6%	25.2%	35.1%	32.2%	13.7%	10.9%
RARELY (<1 per week)	14.5%	14.3%	11.0%	15.6%	10.1%	6.4%
OCCASIONALLY (1-2 times per week)	9.4%	8.5%	8.8%	9.6%	7.0%	5.0%
SOMETIMES (3-4 times per week)	3.2%	2.7%	2.2%	3.9%	3.6%	4.5%
OFTEN (5-7 times per week)	2.5%	1.8%	1.3%	2.3%	2.5%	5.5%
NO RESPONSE	44.7%	47.5%	41.7%	36.3%	63.1%	67.8%

Household Occupancy and Frequency of Cooktop and/or Oven Burner Use

The distribution in cooking frequency by household occupancy varies more than by building type, especially with respect to the frequency of range or oven use to cook dinner cooking frequency. **Table C-5** to **Table C-8** present the RASS responses to cooking frequency by household occupancy. We can see from these tables that as household occupancy increases, there is a general trend of increased frequency of use of oven or range to prepare breakfast, lunch, and dinner (but not for the “other” cooking type category). This is particularly evident in the “often”, i.e., 5-7 times per week, oven or range use category. Nearly 57 percent of all five or more person households report using their range and/or oven frequently (5-7 times per week) to cook dinner, while only 24 percent of one-person households report doing so (**Table C-7**).

Table C-5. Distribution of RASS Responses by Household Occupancy (One, Two, Three, Four, or Five or More Occupants) to the Question “During a Typical Week, How Often Do You Use Your Range or Oven for Breakfast?”

Survey Response	One	Two	Three	Four	Five or more
NEVER	28.9%	21.6%	22.3%	20.6%	14.2%
RARELY (<1 per week)	21.9%	23.8%	21.3%	20.9%	12.8%
OCCASIONALLY (1-2 times per week)	16.8%	19.7%	23.2%	24.6%	22.7%
SOMETIMES (3-4 times per week)	8.8%	11.6%	12.3%	11.7%	17.2%
OFTEN (5-7 times per week)	15.9%	16.4%	16.1%	17.3%	26.2%
NO RESPONSE	7.7%	6.9%	4.8%	4.9%	6.9%

Table C- 6. Distribution of RASS Responses by Household Occupancy (One, Two, Three, Four, or Five or More Occupants) to the Question “During a Typical Week, How Often Do You Use Your Range or Oven for Lunch?”

Survey Response	One	Two	Three	Four	Five or more
NEVER	33.4%	28.4%	29.2%	26.4%	20.7%
RARELY (<1 per week)	25.8%	27.5%	26.5%	25.3%	16.6%
OCCASIONALLY (1–2 times per week)	15.5%	18.2%	19.9%	19.7%	16.9%
SOMETIMES (3–4 times per week)	5.8%	8.7%	8.9%	11.6%	14.6%
OFTEN (5–7 times per week)	6.3%	7.0%	9.0%	10.2%	22.5%
NO RESPONSE	13.2%	10.1%	6.6%	6.8%	8.8%

Table C- 7. Distribution of RASS Responses by Household Occupancy (One, Two, Three, Four, or Five or More Occupants) to the Question “During a Typical Week, How Often Do You Use Your Range or Oven for Dinner?”

Survey Response	One	Two	Three	Four	Five or more
NEVER	6.6%	2.4%	2.1%	1.2%	3.0%
RARELY (<1 per week)	15.0%	8.1%	6.5%	5.7%	6.0%
OCCASIONALLY (1–2 times per week)	23.1%	15.3%	12.3%	10.9%	8.9%
SOMETIMES (3–4 times per week)	26.6%	29.6%	29.0%	25.7%	21.3%
OFTEN (5–7 times per week)	24.1%	42.6%	48.6%	53.9%	56.8%
NO RESPONSE	4.6%	2.1%	1.6%	2.6%	3.9%

Table C- 8. Distribution of RASS Responses by Household Occupancy (One, Two, Three, Four, or Five or More Occupants) to the Question “During a Typical Week, How Often Do You Use Your Range or Oven for Other?”

Survey Response	One	Two	Three	Four	Five or more
NEVER	26.5%	23.8%	27.0%	25.2%	30.3%
RARELY (<1 per week)	13.1%	13.3%	16.0%	13.3%	15.4%
OCCASIONALLY (1–2 times per week)	6.5%	9.2%	9.0%	11.2%	10.0%
SOMETIMES (3–4 times per week)	2.0%	2.6%	4.1%	4.7%	3.7%
OFTEN (5–7 times per week)	1.7%	2.0%	1.8%	2.1%	4.7%
NO RESPONSE	50.2%	49.0%	42.1%	43.5%	35.9%

Ethnicity and Frequency of Cooktop and/or Oven Burner Use

Cooking activity also varies with ethnicity. Based on analysis of all RASS households, we have found the following:

- More White/Caucasian households tend to “never cook breakfast using their range and/or oven,” relative to other ethnicities. Hispanic/Latin households tend to cook breakfast more frequently than other ethnicities (**Table C- 9**).
- More White/Caucasian households tend to “never cook lunch using their range and/or oven,” relative to other ethnicities. This difference is most apparent between the 34 percent of Black/African American respondents who reported “never” using their range/oven to cook lunch compared with 55 percent for White/Caucasian households. Hispanic/Latin and Asian/Pacific Islander households tend to cook lunch most frequently (5–7 times per week) using their range/oven, relative to other ethnicities—approximately 15 percent of all Hispanic/Latin and Asian/Pacific Islander households cook lunch 5–7 times per week but, fewer than 8 percent of White/Caucasian and American Indian/Alaskan and Black/African American Households frequently use a gas appliance to cook lunch (**Table C- 10**).
- Almost 16 percent of all Hispanic/Latin households report “never” using their range or oven to cook dinner. More Asian/Pacific Islanders cook dinner most frequently (5–7 times per week), relative to other ethnic groups (**Table C- 11**).

Table C- 9. Frequency of Range/Oven Use to Cook Breakfast in a Typical Week for Respondents Who Identified the “Head of Household #1” with the Following Ethnicities

Ethnicity	Never	1–2 times	3–4 times	5–7 times
Hispanic/Latin	32.8%	19.1%	12.7%	21.8%
White/Caucasian	44.5%	21.7%	10.5%	15.1%
Black/African American	30.1%	26.4%	15.1%	18.9%
Asian/Pacific Island	40.4%	16.9%	12.0%	18.8%
American Indian/Alaskan	35.8%	25.9%	11.8%	17.8%

Table C- 10. Frequency of Range/Oven Use to Cook Lunch in a Typical Week for Respondents Who Identified the “Head of Household #1” with the Following Ethnicities

Ethnicity	Never	1–2 times	3–4 times	5–7 times
Hispanic/Latin	37.2%	16.7%	11.2%	15.5%
White/Caucasian	54.8%	19.0%	8.3%	5.6%
Black/African American	43.8%	18.5%	10.3%	7.8%
Asian/Pacific Island	34.4%	23.4%	14.4%	15.3%
American Indian/Alaskan	46.7%	19.1%	11.2%	7.1%

Table C- 11. Frequency of Range/Oven Use to Cook Dinner in a Typical Week for Respondents Who Identified the “Head of Household #1” with the Following Ethnicities

Ethnicity	Never	1–2 times	3–4 times	5–7 times
Hispanic/Latin	15.9%	12.5%	22.0%	41.5%
White/Caucasian	9.3%	15.5%	30.3%	41.9%
Black/African American	9.0%	18.6%	32.1%	36.0%
Asian/Pacific Island	14.0%	12.3%	22.2%	47.5%
American Indian/Alaskan	6.5%	16.5%	31.1%	42.6%

Note: “never” includes “rarely” (<1/week) responses

National Human Activity Pattern Survey (NHAPS) Time-activity Plots: Food Preparation

The following figures present weekday and weekend time-activity profiles of food preparation times, based on raw data collected from questionnaire data of adult (19–64 years old; **Figure C-1**) and senior (65+ years old; **Figure C-2**) from the *National Human Activity Pattern Survey*.

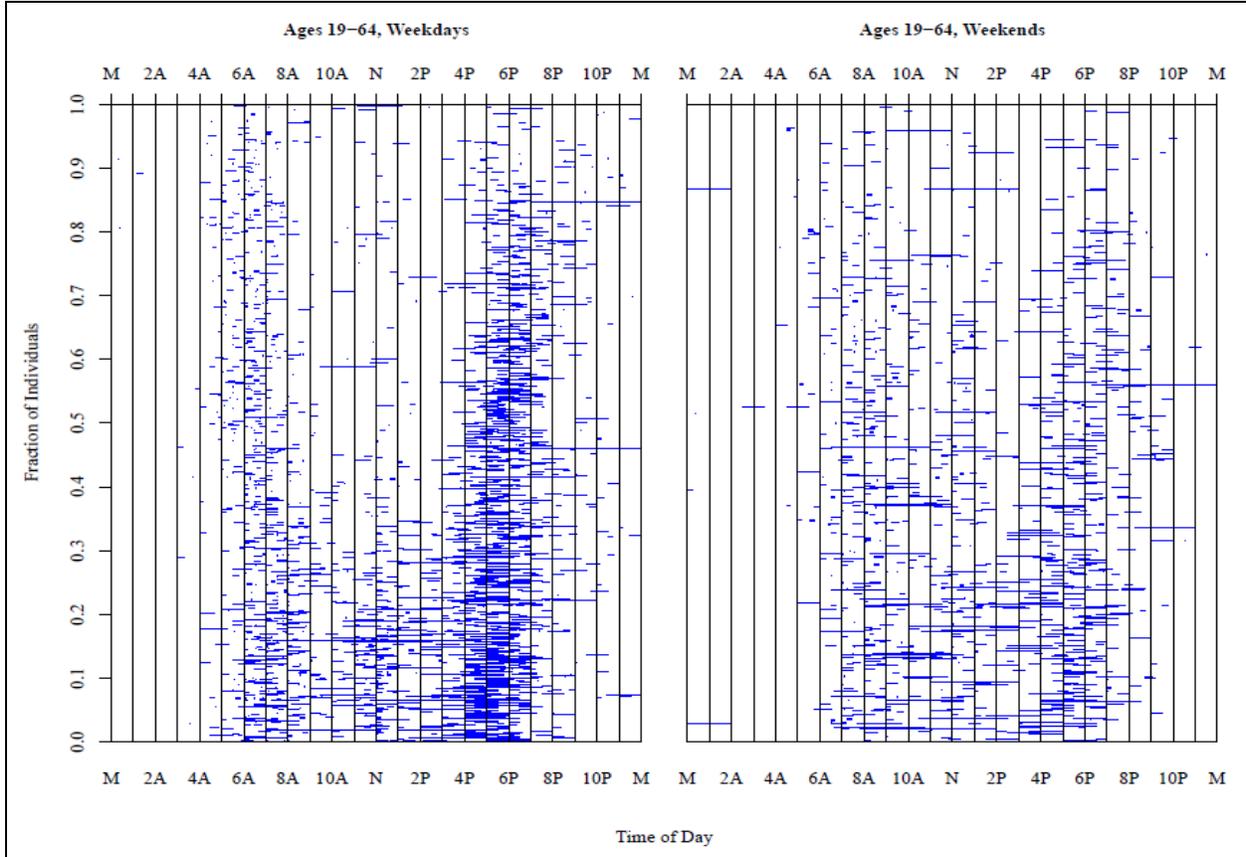


Figure C-1. Food Preparation Activity Profiles for 19- to 64-year-olds in the NHAPS

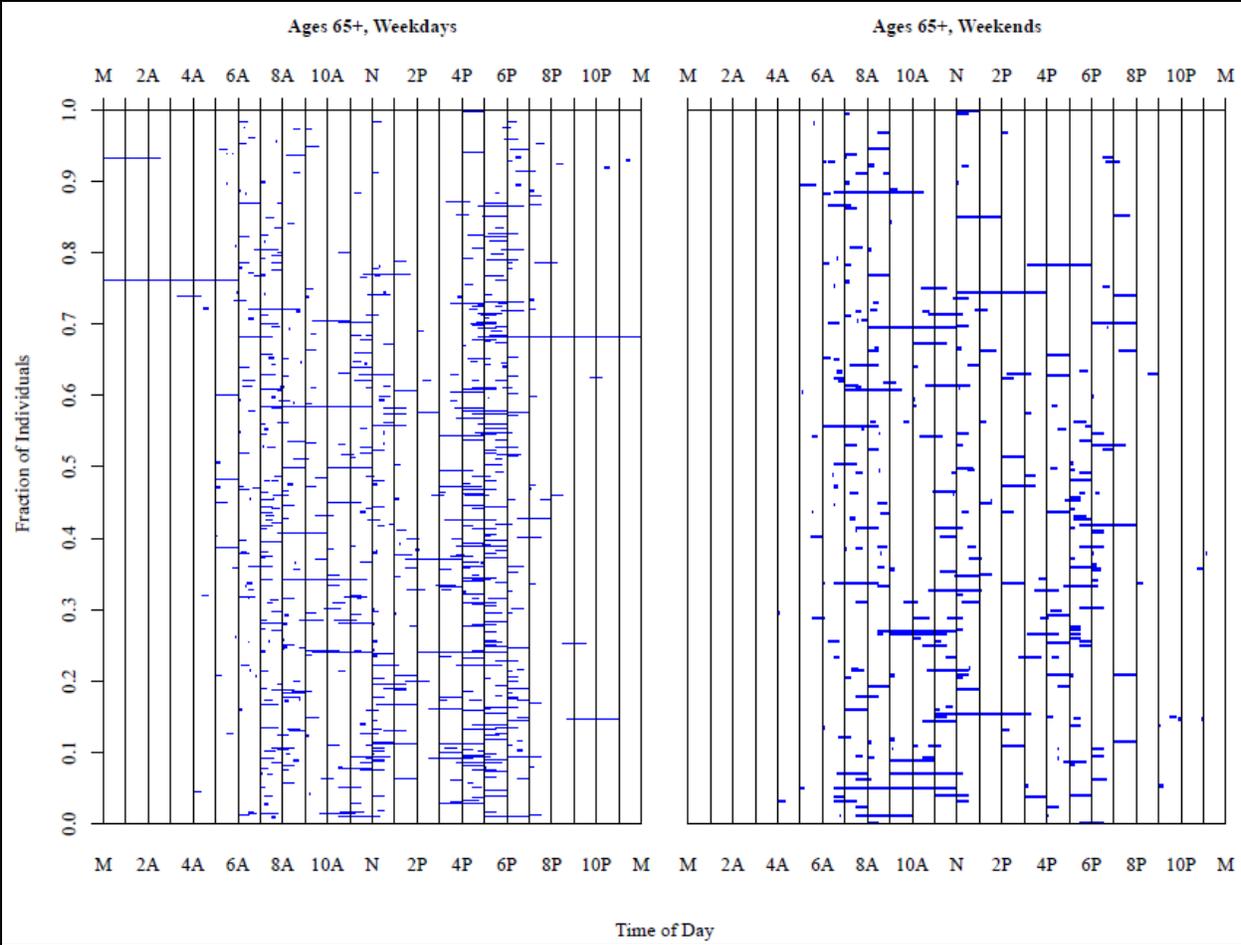


Figure C-2. Food Preparation Activity Profiles for 65+-year-olds in the NHAPS

APPENDIX D: LBNL Web-based Cooking Survey

Household Cooking Patterns

1. Consent to Participate in Household Cooking Activity Survey

*** 1. The purpose of this survey is to collect data on household cooking activity. Your responses will be used to characterize cooking-related pollutant exposures and to relate these exposures to household characteristics. This research is being conducted by Lawrence Berkeley National Laboratory and is funded by the California Energy Commission.**

Participation in this research survey is voluntary. No incentive is being offered and there is no penalty for choosing not to participate or to stop participating at any time. You will have the option at the end of the survey of whether to 1) submit your responses, or 2) stop the survey and your responses will not be used.

Participation involves completing an online survey that will take 5-10 minutes.

The survey tool was designed to be anonymous and confidential. Data will be stored in a password protected electronic format and the survey does not request personally identifiable information. IP addresses of responders will be retained solely for the purpose of screening out replicates. The results of this study will be used for scientific research purposes only.

If you have any questions about the research study, please contact Agnes Lobscheid at 510-486-6945, or ablobscheid@lbl.gov. This research has been reviewed according to the Lawrence Berkeley National Laboratory Institutional Review Board procedures for research involving human subjects.

ELECTRONIC CONSENT: Please select your choice below.

Clicking on the "agree" button below indicates that:

- you have read the above information
- you voluntarily agree to participate
- you are at least 18 years of age

If you do not wish to participate in the research study, please decline participation by clicking on the "disagree" button.

Household Cooking Patterns

- agree
 disagree

2. Stove/Cooktop and Conventional Oven (not microwave oven) Characteristics

This survey will ask questions about your COOKTOP and OVEN. The COOKTOP, sometimes called a stove top, refers to the gas burners or electric heating elements at counter level. OVEN questions refer only to gas or electric conventional (standard) ovens; they do NOT include microwaves.

This Section asks about the type of COOKTOP and OVEN in your residence. If you have both gas and electric conventional ovens, provide information for the one that is used most often.

1. What is the fuel for your Cooktop and Conventional Oven?

	natural gas	electric	other
COOKTOP	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
OVEN	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

2. How old is your Cooktop and Conventional Oven?

	0-4 years	5-9 years	10-14 years	15-19 years	20+ years
COOKTOP	<input type="radio"/>				
OVEN	<input type="radio"/>				

3. TYPICAL WEEK'S COOKING ACTIVITY

1. In a typical week, on how many days do you or anyone in your household, use your COOKTOP for the following cooking events?

	Never	1-2	3-4	5-6	every day
Breakfast	<input type="radio"/>				
Lunch	<input type="radio"/>				
Dinner	<input type="radio"/>				
Other- snacks or other food preparation	<input type="radio"/>				

2. In a typical week, on how many days do you and/or anyone in your household, use your CONVENTIONAL OVEN for the following cooking events?

	Never	1-2	3-4	5-6	every day
Breakfast	<input type="radio"/>				
Lunch	<input type="radio"/>				
Dinner	<input type="radio"/>				
Other- snacks or other food preparation	<input type="radio"/>				

Household Cooking Patterns

4. Cooking Activity OVER THE PAST 24 HOURS

The next two questions refer to ALL cooking activity in your home OVER THE PAST 24 HOURS. For cooking times, please provide the best estimate in the pull-down menus, of the number of minutes YOU OR ANYONE in your household spent using the Cooktop and/or Oven.

1. Thinking about Breakfast, Lunch, Dinner, and Other Cooking OVER THE PAST 24 HOURS, how many

	minutes was COOKTOP used?	COOKTOP burners were used?	minutes was OVEN used?	people at home (including you) when cooking occurred?
Breakfast	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Lunch	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Dinner	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Other (snacks and other food preparation)	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>

2. Please select whether or not the following statements apply to the Breakfast, Lunch and Dinner cooking activities in your home OVER the PAST 24 HOURS.

	Breakfast	Lunch	Dinner
Cooking Activity was on a weekday	<input type="text"/>	<input type="text"/>	<input type="text"/>
Kitchen exhaust fan was on	<input type="text"/>	<input type="text"/>	<input type="text"/>
Window(s) opened during cooking	<input type="text"/>	<input type="text"/>	<input type="text"/>
Food was stir-fried	<input type="text"/>	<input type="text"/>	<input type="text"/>
Food was pan-fried	<input type="text"/>	<input type="text"/>	<input type="text"/>
Liquid was boiled	<input type="text"/>	<input type="text"/>	<input type="text"/>
Food was simmered	<input type="text"/>	<input type="text"/>	<input type="text"/>
Oven used on BAKE setting	<input type="text"/>	<input type="text"/>	<input type="text"/>
Oven used on BROIL setting	<input type="text"/>	<input type="text"/>	<input type="text"/>

5. Household characteristics.

The information you provide to us on the next four questions will allow us to assess cooking-related exposures based on household characteristics.

Household Cooking Patterns

1. How many people, including yourself, currently reside in your household?

- 1
- 2
- 3
- 4
- 5+
- decline to state

2. Please indicate the number of household residents that are in the following age categories.

	0	1	2	3	4	5+	decline to state
0-17 years old	<input type="radio"/>						
18-65 years old	<input type="radio"/>						
over 65 years old	<input type="radio"/>						

3. Which of the following ethnicities are represented by member(s) of your household?

- American Indian, Alaska Native
- Asian or Pacific Islander
- Black, African American
- Hispanic/Latino
- White, Caucasian
- Other
- decline to state

4. What type of building does your household reside in?

- single-family detached
- townhome/duplex
- 2-4 unit condo or apartment
- apartment/condo with more than 5 units
- mobile home
- decline to state

Household Cooking Patterns

6. Submit your response

1. Please select one of the following.

- Submit my responses
- Stop survey and do not use my responses

7. Your responses have been submitted!

Thank you for your participation!

If you have any questions about this study, please contact

Agnes Lobscheid at 510-486-6945 or ablobscheid@lbl.gov
or
Brett Singer at 510-486-4779 or BCSinger@lbl.gov

8. Stop Survey

The survey has ended. If you provided any responses, they will not be used.

If you have any questions about the survey, please contact

Agnes Lobscheid at 510 486 6945 or ablobscheid@lbl.gov
or
Brett Singer at 510 486 4779 or BCSinger@lbl.gov

9.

The survey has ended. Please exit the browser.

APPENDIX E: Cooktop and Oven Burner Emission Factors

Table E- 1. Emission Factors for Cooktop Burners. Each row represents one set of cooktop burners, based on Table 34 (CO), Table 38 (NO₂), Table 42 (HCHO), and Table 45 (NO_x) of Singer et al. (2009). Baseline emission factors were measured with PG&E line gas. Change in emission factors with LNG calculated from results of experiments with simulated LNG blends having higher Wobbe numbers (WN). Change expressed as mean (lower and upper bounds of 95% confidence interval) per increase in fuel WN of 25 Btu/scf. Bolded values were changes in emissions factors that were statistically significant (p<0.05). Details provided in Singer et al. (2009).

ID	Age (yrs)	CO		NO ₂		HCHO		NO	
		EF _{PG&E} [ng/J]	ΔCO/Δ25WN (95% CI)	EF _{PG&E} [ng/J]	ΔNO ₂ /Δ25WN (95% CI)	EF _{PG&E} [ng/J]	ΔHCHO/Δ25WN (95% CI)	EF _{PG&E} [ng/J]	ΔNO/Δ25WN (95% CI)
CT01	12	11	1 (0, 3)	6.7	0.5 (0.2, 0.8)	0.31	0.05 (0.03, 0.08)	24.8	0.03 (-0.46, 0.53)
CT02	9	29	2 (0, 3)	8.5	0.24 (0.01, 0.47)	0.55	0.04 (-0.29, 0.38)	28.7	0.20 (-0.82, 1.21)
CT03	6	231	34 (21, 48)	12.1	1.2 (0.7, 1.7)	1.00	0.31 (0.22, 0.40)	22.8	-0.44 (-1.21, 0.33)
CT05	5	87	-1 (-2, 1)	11.2	0.2 (-0.3, 0.6)	0.67	0.01 (-0.13, 0.15)	30.8	0.78 (0.65, 0.92)
CT06	11	13	6 (3, 8)	5.0	0.0 (-0.2, 0.2)	0.12	0.00 (-0.06, 0.06)	33.5	0.34 (-0.18, 0.86)
CT07	13	59	5 (2, 7)	7.3	0.4 (0.2, 0.7)	0.44	0.08 (0.03, 0.13)	27.0	-0.26 (-0.44, -0.09)
CT08	16	7	1 (0, 1)	6.7	0.1 (-0.1, 0.3)	0.09	0.00 (-0.02, 0.02)	26.8	0.13 (-0.38, 0.64)
CT09	2	823	24 (11, 37)	17.7	0.1 (-0.1, 0.4)	4.67	0.00 (-0.28, 0.27)	7.25	-0.42 (-0.76, -0.08)
CT10	12	57	8 (6, 9)	9.6	-0.1 (-0.9, 0.8)	1.15	-0.16 (-0.45, 0.13)	26.6	0.24 (-0.77, 1.26)
CT11	8	107	12 (6, 19)	7.6	0.2 (-0.1, 0.4)	0.31	-0.02 (-0.09, 0.05)	22.1	0.17 (-0.17, 0.51)
CT12	17	123	25 (16, 33)	10.2	0.6 (0.1, 1.0)	0.81	0.04 (-0.06, 0.13)	24.3	-0.89 (-1.08, -0.70)
CT13	6	48	13 (10, 16)	7.1	0.4 (0.0, 0.8)	0.10	0.01 (-0.07, 0.10)	27.8	-0.14 (-0.55, 0.28)

Table E- 2. Emission Factors for Oven Burners. Each row represents one oven burner, based on Table 34 (CO), Table 38 (NO₂), Table 42 (HCHO), and Table 45 (NO_x) of Singer et al. (2009). Baseline emission factors were measured with PG&E line gas. Change in emission factors with LNG calculated from results of experiments with simulated LNG blends having higher Wobbe numbers (WN). Change expressed as mean (lower and upper bounds of 95% confidence interval) per increase in fuel WN of 25 Btu/scf. Bolded values were changes in emissions factors that were statistically significant (p<0.05). Details provided in Singer et al. (2009).

Oven ID	Age (yrs)	CO		NO ₂		HCHO		NO	
		EF _{PG&E} [ng/J]	ΔCO/Δ25WN (95% CI)	EF _{PG&E} [ng/J]	ΔNO ₂ /Δ25WN (95% CI)	EF _{PG&E} [ng/J]	ΔHCHO/Δ25WN (95% CI)	EF _{PG&E} [ng/J]	ΔNO/Δ25WN (95% CI)
OV01	12	16	3 (2,4)	3.8	0.1 (-0.2, 0.5)	0.49	-0.01 (-, -)	32.1	0.4(-0.4,1.2)
OV02	9	99	17 (-3, 37)	7.5	0.7 (0.3, 1.1)	0.38	0.02 (-0.02, 0.07)	26.8	-1.4 (-3.7, 0.9)
OV03	6	61	28 (23, 33)	5.1	0.4 (0.2, 0.6)	0.46	-0.01 (-0.19, 0.16)	32.1	-1.6 (-3.8, 0.5)
OV05	5	163	20 (17, 22)	13.9	0.1 (-0.1, 0.3)	0.43	0.05 (-0.02, 0.12)	17.5	-1.1 (-1.6, -0.6)
OV06	11	124	6 (3, 9)	8.1	0.0 (-0.1, 0.1)	1.01	-0.01 (-0.13, 0.12)	24.9	0.4 (-0.8, 1.7)
OV07	13	156	5 (2, 7)	6.1	0.3 (0.1, 0.4)	0.57	0.02 (-0.10, 0.14)	25.6	-1.3 (-1.7, -0.9)
OV08	16	108	16 (9, 24)	5.5	0.3 (0.1, 0.5)	2.98	-0.31 (-0.94, 0.32)	27.8	-1.9 (-2.8, -1.0)
OV09	2	174	17 (3, 31)	11.3	0.0 (-0.1, 0.1)	0.60	-0.03 (-0.48, 0.43)	16.1	-2.0 (-3.1, -0.9)
OV10	12	58	7 (6, 9)	4.4	0.5 (0.4, 0.6)	0.32	0.00 (-0.03, 0.02)	28.5	-1.0 (-1.4, -0.6)
OV11	8	528	-37(-62,-12)	13.2	0.2 (-0.2, 0.5)	5.51	-0.10 (-0.69, 0.48)	27.3	0.6 (-0.5, 1.8)
OV12	17	36	3 (2, 4)	5.6	0.3 (0.1, 0.4)	0.25	0.00 (-0.02, 0.01)	28.9	-1.3 (-1.9, -0.7)
OV13	6	70	16 (13, 20)	6.3	1.2 (0.8, 1.6)	0.33	0.03 (0.03, 0.04)	33.4	-3.0 (-3.7, -2.3)

Reference

Singer, B. C., M. G. Apte, D. R. Black, T. Hotchi, D. Lucas, M. M. Lunden, A. G. Mirer, M. Spears, and D. P. Sullivan (2009). *Natural Gas Variability in California: Environmental Impacts and Device Performance: Experimental Evaluation of Pollutant Emissions from Residential Appliances*. California Energy Commission Report CEC-500-2009-099. Lawrence Berkeley National Laboratory Report LBNL-2897E. December 2009.

APPENDIX F: Outdoor Air Concentrations

Hourly averaged ambient concentrations of NO₂ and CO were obtained from monitoring stations distributed across the state of California. The raw hourly data from 2008 from these monitoring stations was provided to us via electronic files, sent by Dwight Oda, of the California Air Resource Board. The most recent year that a complete set of June and December concentrations was available was 2008.

Each monitoring station has a unique nine-digit monitor code made up of the following digits:

- First two digits = state Federal Information Processing Standard (FIPS) code (“06” for California)
- Next three digits = county FIPS code
- Last four digits = actual U.S. EPA monitoring code

Additional information on each of the monitors can be found based on the unique monitor code from the U.S. EPA’s AIRData website (U.S. EPA 2010b).

Table F-1 provides the AIRData Site ID and locations (latitude and longitude) of the selected NO₂ (and NO), and CO monitoring sites in California.

Table F-1. Site ID and Location of NO₂ (and NO) and CO Monitoring Sites throughout California

AIRdata NO ₂ (and NO) Site ID	CO Alternative Site	County	Other Counties represented by the NO ₂ and CO site	latitude	longitude
60010009		Alameda		37.74306	-122.17
60070002		Butte	Trinity, Shasta, Siskiyou, Modoc, Lassen, Pluman, Sierra, Glen, and Tehama	39.7575	-121.842
60133001		Contra Costa		38.02917	-121.902
60190008		Fresno	Kings, Inyo, Madera, Mariposa, Mono	36.78139	-119.772
60231004		Humboldt	Del Norte	40.77694	-124.178
60250006		Imperial		32.67778	-115.39
60290014	60290010	Kern		35.35611	-119.04
60372005		Los Angeles		34.1326	-118.127
60410001		Marin		37.9725	-122.519
60450009		Mendocino		39.40306	-123.349
60470003	Stanislaus	Merced		37.28167	-120.434
60531003		Monterey		36.69683	-121.636

60550003		Napa	Lake	38.31083	-122.295
60570005	no CO	Nevada	Alpine	39.23444	-121.056
60590007		Orange		33.83062	-117.938
60610006	no CO	Placer		38.74583	-121.265
60650012	60658001	Riverside		33.92086	-116.858
60670006		Sacramento	El Dorado, Amador	38.61417	-121.367
60710306		San Bernardino		34.51	-117.331
60730003	60731010	San Diego		32.79119	-116.942
60750005		San Francisco		37.766	-122.399
60771002		San Joaquin	Calaveras, Tuolumne	37.95083	-121.268
60798001	Santa Barbara	San Louis Obispo		35.49139	-120.668
60811001		San Mateo		37.4829	-122.203
60832004		Santa Barbara		34.63782	-120.458
60850005		Santa Clara		37.3485	-121.895
60870003		Santa Cruz		37.01194	-122.193
60950004		Solano		38.1027	-122.238
60970003		Sonoma		38.4435	-122.71
60990006		Stanislaus		37.48833	-120.836
61010003	Butte county	Sutter	Yuba	39.13889	-121.618
61072002	Kern county	Tulare		36.33222	-119.29
61112002	Santa Barbara	Ventura		34.2775	-118.685
61130004	Napa county	Yolo	Colusa	38.53333	-121.775

APPENDIX G: Technical Documentation on Exposure Model Structure

Brief Summary: A modular simulation model has been written to predict in-home pollutant concentrations and exposures due to fuel-based emissions from residential cookstoves using liquid natural gas (LNG) and located in the State of California. The model input data are based on the results of the 2002–2003 California Statewide Residential Appliance Saturation Survey (RASS), which is a statewide survey ($n = 20,000+$) of appliance use and cooking activity (California Energy Commission 2004)

Execution: A master simulation function (**sim.master**) is used to control execution of the model. This master function calls modular functions of the model as necessary. Generally, model execution consists of the following simple steps: (1) run **sim.master** with all.inputs=TRUE to generate stochastic and deterministic inputs for every subject, (2) after inputs are calculated, run **sim.master** with $n=<\text{number of households}>$ to deterministically simulate pollutant concentrations and exposures for a set of any number of households without having to re-calculate the inputs—specifying a custom format and content of the simulation output for each run. Rerunning the simulation with the same inputs will give the identical output results. The characteristics of a given run can be specified by giving different parameter values to **sim.master**, e.g., `sim.master(parameter1=value1, parameter2=value2)`. The recognized input parameters are given in **Table G-1**.

Technical Details: The model was implemented in the R programming environment (<http://www.r-project.org>). The raw RASS response data are used as the foundation for all household-level inputs, since they contain representative statewide data for California home geography, occupant demographics, size, construction type, age, cooking frequency, etc. Building on the RASS responses, the model generates appropriate input profiles so that concentrations and exposures can be simulated for a week-long study period on a minute-by-minute basis. Individual R functions handle the production of different classes of model inputs (cooking start times and duration, emission factors, occupancy, building characteristics, etc.). Each function uses theoretical methods and/or empirical data from a variety of sources to produce appropriate inputs. The main loop in the **sim.master** function takes all of the data inputs produced by the other functions, cycles through each household, and, using a single-zone indoor air quality model, simulates concentration and exposure profiles, which are then processed into different output metrics.

Table G-2 below contains a description of each modular function of the simulation model. Note that functions are generally classified as follows: “control” (controls the calculation); “main loop” (called inside main simulation loop to generate per-subject runtime data); “inputs” (called

to generate simulation inputs for all subjects which are saved and attached to foundational RASS inputs).

Table G- 4 below contains all of the household-level and individual-level output variables.

Figure G- 1 illustrates the structure and execution of the simulation model.

Table G-1. Input Parameters for the sim.master Function

No.	Name	Description	Default Value	Values
1	<i>name</i>	<i>Name tag for a simulation run</i>	-	<i>Any string</i>
2	<i>n</i>	<i>Number or index of houses to simulate</i>	<i><no. of qualifying RASS subjects></i>	
3	<i>pollutant</i>	<i>Pollutant(s) to simulate for each house</i>	<i>c("NO2", "NO", "CO", "HCHO")</i>	<i>"NO2", "NO", "CO", "HCHO"</i>
4	<i>county</i>	<i>California county(ies) to simulate</i>	NULL	<i>Any CA county name in Sentence Case</i>
5	<i>season</i>	<i>Season of the year to simulate</i>	<i>"Summer"</i>	<i>"Summer", "Winter"</i>
6	<i>emissions</i>	<i>Use baseline or new (LNG) emission factors</i>	<i>"Base"</i>	<i>"Base", "New"</i>
7	<i>window.flow</i>	<i>Additional flow to add to each house [m³/h]</i>	0	<i>Any positive number</i>
8	<i>burner.rating</i>	<i>Fixed burner rating to use, e.g., 7 kBtu, otherwise assigns based on actual ratings</i>	NULL	<i>Any positive number</i>
9	<i>randomize</i>	<i>Whether to select random individuals or sequential</i>	FALSE	<i>TRUE, FALSE</i>
10	<i>all.inputs</i>	<i>Whether to rerun ALL inputs or not</i>	FALSE	<i>TRUE, FALSE</i>
11	<i>cook.times</i>	<i>Rerun cooking time inputs</i>	FALSE	<i>TRUE, FALSE</i>
12	<i>meal.activity</i>	<i>Rerun meal activity inputs</i>	FALSE	<i>TRUE, FALSE</i>
13	<i>energy.use</i>	<i>Rerun energy use inputs</i>	FALSE	<i>TRUE, FALSE</i>
14	<i>outdoor.conc</i>	<i>Rerun outdoor concentration inputs</i>	FALSE	<i>TRUE, FALSE</i>
15	<i>geography</i>	<i>Rerun geography inputs</i>	FALSE	<i>TRUE, FALSE</i>
16	<i>building</i>	<i>Rerun building characteristic inputs</i>	FALSE	<i>TRUE, FALSE</i>
17	<i>occupancy</i>	<i>Rerun occupancy inputs</i>	FALSE	<i>TRUE, FALSE</i>
18	<i>smokers</i>	<i>Rerun smoker inputs</i>	FALSE	<i>TRUE, FALSE</i>
19	<i>plot</i>	<i>Whether to generate plots for each house</i>	FALSE	<i>TRUE, FALSE</i>
20	<i>plot.avg</i>	<i>Whether to create moving avg plots</i>	FALSE	<i>TRUE, FALSE</i>
21	<i>plot.file</i>	<i>Name to use for PDF plot file</i>	<i>outputPlots.pdf</i>	<i>Any valid filename string</i>
22	<i>log</i>	<i>Whether to plot as semi-log</i>	TRUE	<i>TRUE, FALSE</i>
23	<i>debug</i>	<i>Whether to generate debugging output</i>	FALSE	<i>TRUE, FALSE</i>
24	<i>houseOutputFile</i>	<i>Base name to use for household-level output CSV file</i>	<i>simOutputHouse.csv</i>	<i>Any valid filename string</i>
25	<i>individualOutputFile</i>	<i>Base name to use for individual-level output CSV file</i>	<i>simOutputIndividuals.csv</i>	<i>Any valid filename string</i>
26	<i>save.csv.each.iter</i>	<i>Whether to update CSV file each sim iteration</i>	TRUE	<i>TRUE, FALSE</i>
27	<i>save.output.in.workspace</i>	<i>Whether to save output to R workspace</i>	FALSE	<i>TRUE, FALSE</i>

Table G-2. List of All R functions Used in the Exposure Simulation Model. “All Households” = function processes all households at once; “One Household” = function processes a single household at a time (called inside main sim.master loop).

Function	Input	Output	Details
sim.master (control)	No. of subjects (Integer); Process Inputs Y/N? (Logical)	Processed Inputs (Dataframes); Model output metrics (Dataframe)	Function optionally processes all inputs by calling other function and generates all model outputs by looping over each subject
sim.output (main loop)	<i>One Household:</i> Subject ID, Subject Concentration Profile; Days of Simulation, Meal Time-Activity; Subject Exposure Profiles	No. People; No. Days; No. Meals Cooked; Mean/Max House Conc.; Min/Max Mean Subject Exposures (Dataframe)	Function takes raw minute-by-minute simulation results for the occupants of the current home and returns a data frame record of output metrics
sim.cooking.time (inputs)	<i>All Households:</i> Ages, Day of Week	Time Cooking Starts by Meal Type in units of Minutes after Midnight (MAM) (Dataframe)	Function takes ages and days of week for all occupants of subject homes and returns the times each type of meal starts. Based on LBL survey.
sim.cooking.duration (inputs)	<i>All Households:</i> Ages	Duration of cooking for each meal (Dataframe)	Function takes ages for occupants of all subject homes and returns duration of cooking for each meal. Based on LBL survey
sim.meal.days (inputs)	<i>All Households:</i> Subject ID; Per Week Frequencies for Breakfast, Lunch, and Dinner	Meal Activity Profile by Day of Week (Time-activity data object)	Function takes RASS data on frequency of cooking for each type of meal and simulates which days of the week the subject prepares each meal
sim.energy.use (inputs)	<i>All Households:</i> N o. of Subjects; Burner Type	Energy Use in Joules/min (Dataframe)	Function returns the energy used per minute by a given type of burner. Based on units used in LBL study.
sim.cook.profile (main loop)	<i>One Household:</i> Meals Per Day by Type; Simulation Days. Prep Starting Times and Duration for Weekdays and Weekends	Profile of meal preparation times (Time-activity data object)	Functions returns minute-by-minute time-activity profile encoding times that each meal type is prepared
sim.emissions (inputs)	<i>All Households:</i> No. of Subjects; Pollutant Name; Burner Type; Burn Type	Emissions Data in ng/Joule: Baseline; Confidence Intervals, Delta; New Estimate	Functions returns emission factor in ng/J from cook stoves estimating increase in emissions with new fuel. Based on LBL study that provided confidence intervals for emissions from 13 stoves.
sim.air.exchange (inputs)	<i>All Households:</i> No. of Subjects	Whole-House Air Exchange Rate (air changes per hour)	
sim.occupancy (inputs)	<i>All Households:</i> Ages; Day of Week	Leave and Return Times for all Occupants in Minutes after Midnight (MAM) (Dataframe)	Function takes lists of ages for all homes and their occupants and day of week and returns a data frame of times that each occupant leaves the home and returns; Based on NHAPS.
sim.outdoor.conc (main loop)	<i>One Household:</i> Times; Pollutant Name	Pollutant Concentration Profile	Function returns outdoor pollutant concentrations for specified times.

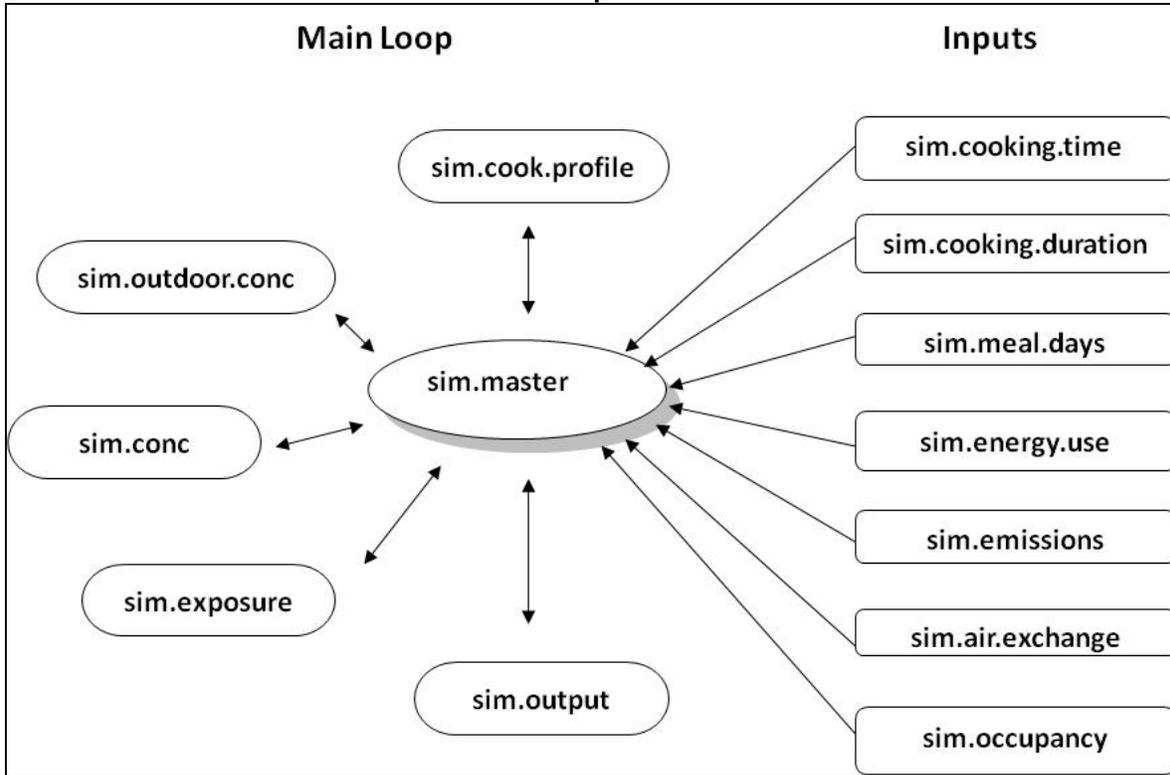
Table G-3. (continued)

Function	Input	Output	Details
sim.conc (main loop)	<i>One Household: Simulation Times; Emissions Profile; House Volume, Air Change Rate, Pollutant Deposition Rate, Outdoor Concentrations</i>	Home Concentration Profile for Given Pollutant	Function uses a single-zone mass balance model to simulate minute-by-minute profiles of pollutant concentrations
sim.exposure (main loop)	<i>One Household: Occupant Occupancy by Day of Week; House Concentration Profile; Simulation Times; Simulation Days of Week</i>	Exposure Profile for each Occupant of the Current Home	Function takes data on each household occupant's time spent at home and the simulated house pollutant concentrations, and generates a minute-by-minute exposure profile for each occupant
sim.geography (inputs)	<i>All Households: Zipcodes</i>	A dataframe with county and climate zone variables corresponding to each zip code	Uses database for climate zones from California Energy Commission
sim.oven.burn (inputs)	<i>All Households: Oven Unit ID, Oven Cooking Time (min)</i>	Estimated oven burn times for each oven unit	Uses empirical formula: $\text{Offset} + \text{Factor} * (\text{CookDuration} - \text{Offset})$
sim.cook (inputs)	<i>One Household: Ages of people in the household</i>	Returns index of 'ages' vector of selected cook	Randomly selects an adult as cook - senior 65+ first, 19-64 second; Assigns NA if no adult/senior available to cook

Table G- 4. List of all Output Metrics (Both Household-level and Individual-level) Shown for NO₂; Same Variable Names for Other Pollutants with NO₂ Replaced by NO, CO, or HCHO

No.	Output Variable Name	Description
1	id	RASS id for the household
2	idx	Incremental integer index for the house
3	no.days	No. of days in the simulation
4	no.meals	No. of meals cooked in the house for the simulation
5	IDX	[<u>Individual file only</u>] Individual index, resets for each house
6	Cook	[<u>Individual file only</u>] Designates cook in house; values = [0, 1]
7	Age	[<u>Individual file only</u>] Designates age of individual (categorical)
8	avgOverallIndoorNO2ug.m3	Overall average concentration due to <u>indoor sources only</u>
9	max1IndoorNO2ug.m3	Maximum 1-min concentration due to <u>indoor sources only</u>
10	avgOverallNO2ug.m3	Overall average house concentration
11	max1NO2ug.m3	Maximum 1 min house concentration
12	maxByDayNO2ug.m3	Maximum daily 24-hour average
13	maxWhichDayNO2ug.m3	Day of week where maximum daily average occurred
14	max15NO2ug.m3	15-min maximum concentration
15	max60NO2ug.m3	60-min maximum concentration
16	max480NO2ug.m3	480-min maximum concentration
17	max60IndoorNO2ug.m3	60-min maximum concentration due to <u>indoor sources only</u>
18	maxExAcute15NO2ug.m3	Maximum 15-min concentration exceeding standard
19	maxExInter60NO2ug.m3	Maximum 60-min concentration exceeding standard
20	maxExInter480NO2ug.m3	Maximum 480-min concentration exceeding standard
21	maxExPEL480NO2ug.m3	Maximum 480-min concentration exceeding PEL standard
22	maxExInter60IndoorNO2ug.m3	Maximum 60-min concentration exceeding standard due to <u>indoor sources only</u>
23	whichMaxExInter60NO2ug.m3	Minute of the week (0:10080) where maximum 60-min exceedance occurred
24	todMaxExInter60NO2ug.m3	Time-of-day to nearest hour (0:23) where maximum 60-min exceedance occurred
25	daysExAcute15NO2ug.m3	No. days 15-min standard was exceeded
26	daysExInter60NO2ug.m3	No. days 60-min standard was exceeded
27	daysExInter480NO2ug.m3	No. days 480-min standard was exceeded
28	daysExPEL480NO2ug.m3	No. days 480-min PEL standard was exceeded
29	daysExInter60IndoorNO2ug.m3	No. days 60-min standard was exceed for <u>indoor sources only</u>
30	noExAcute15NO2ug.m3	No. events 15-min standard was exceeded
31	noExInter60NO2ug.m3	No. events 60-min standard was exceeded
32	noExInter480NO2ug.m3	No. events 480-min standard was exceeded
33	noExPEL480NO2ug.m3	No. events 480-min PEL standard was exceeded
34	noExInter60IndoorNO2ug.m3	No. events 60-min standard was exceeded for <u>indoor sources only</u>
35	noDinnerExInter60NO2ug.m3	No events 60-min standard was exceeded between 5pm and 8pm (dinner hours)

Figure G- 1. Chart Showing the Relationships Between the Modular Elements of the Simulation Model. The sim.master function controls the overall execution of the model. Input functions provide foundation-level data to the model which are saved for all households at once and used for repeated runs. The main loop functions are called for one household at a time and used to generate dynamic concentration and exposure profiles for each household occupant and a data frame of output metrics.



Reference

CEC (2004). *California Statewide Residential Appliance Saturation Study. Final Report. Prepared by KEMA-XENERGY, Itron, RoperASW.* June 2004. 400-04-009. Available at: http://www.energy.ca.gov/reports/400-04-009/2004-08-17_400-04-009ALL.PDF.

APPENDIX H: Quality Assurance Analysis Results

Prior to running the suite of modeling scenarios outlined in the Methods Section, we conducted an extensive set of model runs and analysis for Quality Assurance (QA). The objectives of the QA analysis were (1) to confirm that the model code is executing the calculations and algorithms as intended and documented in this report, (2) to explore the sample size required for stable output metrics, and (3) to assess whether overall results—i.e., the calculated time-varying and time-averaged concentration distributions resulting from cooking burner use—are in line with available measurements.

The QA analysis started in October 2010 and continued through February 2011. Most of the results presented in this section were produced with a mostly validated version of the model from February 2011; this version incorporates updates and fixes that address issues or opportunities for improvement identified in the QA analysis. A final adjustment was made to the model in May 2011 to switch from nominal to measured firing rates for the oven burners. This change was large and important for OV11, which was the oven with highest emission rates of CO, NO₂, and HCHO. Final results in most sections of the main report use the measured, rather than nominal oven firing rates. The exception is the comparison between county-specific and SoCal regional results. This is noted in the main report in the comparison section.

QA of Estimate of Energy Use

We first evaluated the modeled estimate of total energy use (in joules, J) associated with gas cooking burner (GCB) use for each household (HH). The total energy use was calculated from the assumed cooktop or nominal oven firing rates described previously and the time of use over the week of modeled cooking activity. As can be seen from **Figure H-1** for modeling across the HHs located in the six-county SoCal region, the central tendencies and upper percentiles of energy use associated with GCBs generally increase as the number of cooked meals increases.

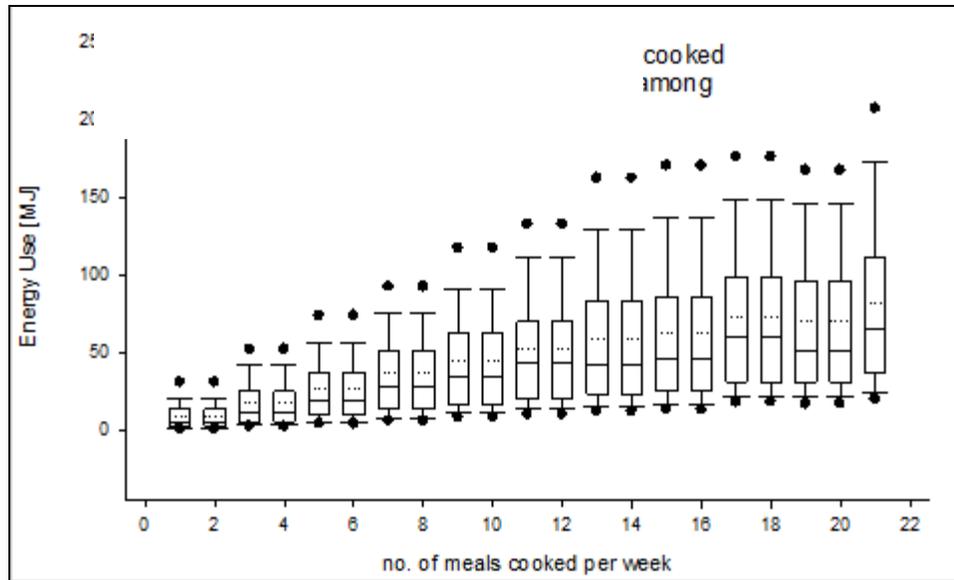


Figure H-1. Calculated Energy Use [MJ/week] by Gas Cooking Burners in Households Across the six-county SoCal Region (N = 6634 HHs)

For 1,000 HHs from the SoCal cohort, we compared the exposure model estimates of energy use for each HH that used GCBs with the RASS “unit energy consumption” (UEC) estimates for “range and/or oven” use for HHs with gas appliances (grng_use) (CEC 2004). As **Table H-1** summarizes, summary statistics on cooking energy use calculated for RASS UECs and those resulting from the cooking activity algorithm of the exposure model are similar. Interestingly, the median estimated by RASS is a bit more than twice that calculated in the exposure model. Whereas the RASS UEC estimate is derived from a top-down apportionment of actual energy use in the home, the exposure model estimate is a bottom-up calculation based on data and some assumptions about cooking activities. That the two median estimates resulting from such different methodologies are within a factor of two is reassuring. These results also bolster the case that the exposure model is not overestimating cooking activity; it may in fact be understating use of cooking burners.

Table H-1. Comparison between the RASS UEC for Gas Range and/or Oven Use with the Exposure Model Predicted Energy Use Due to GCBs over a Typical Week. Energy use is presented in units of MJ/wk.

	Exposure model	RASS UEC
Mean	60	74
Median	44	73
Min	0.74	0.46
Max	337	250

For individual households, the ratio of the RASS UECs to our energy use estimates varies over a wide range (from 0.0125 to 147) with the median value of 1.44 indicating the RASS estimating UECs higher than those used in the exposure model. This wide range of ratios points to the larger uncertainty of calculating this parameter for individual households, but the value of the

median again provides support for the central tendency estimates of both approaches, and should increase confidence that the exposure model is not overestimating cooking burner use.

QA on Fprox Assumptions

We checked that the model correctly incorporated the intended values of Fprox in calculating exposure concentrations for individual adults designated as cooks and for small children assumed to be under their care and thus nearby. To do this, we evaluated the ratio of the individual (resident) to household maximum 1-hr concentration for adult cooks, senior cooks, young children (0–5 years old), children 6–18 years old, and non-cooker adults and seniors that resided in a random subsample of 200 SoCal HHs (501 individuals).

Taking into account cooking time and the time-activity patterns of each archetypal individual, the ratios of all 6–18 year-olds and senior and adult non-cookers are always unity; this reflects the results that the maximum 1-hr concentrations are always associated with dinner cooking since all archetypal activity patterns have the people at home for dinner and remaining at home after dinner. **Table H-2** summarizes the ratio of individual to HH maximum 1-hr indoor concentrations due to GCB use for cooks (adults and seniors) and for young children (0–5 years old). The ratios appear reasonable, with the maximum never exceeding the Fprox assumption. The finding that central tendencies of individual to HH 1-hr maximum concentrations are much lower than the Fprox values of 2.0 for cooks and 1.5 for young children is attributable to the fact that most cooking times are less than 1 hour. This result supports the fact that the Fprox algorithm is working as intended and the proximity effect alters the exposure distribution less than Fprox values might suggest.

Table H-2. Summary Statistics of Ratio of the Individual to Household Max 1-hr Concentrations for Individuals with Fprox > 1. Analysis was Performed on a Subset of 200 SoCal Households

	0–5 year olds (n=31)			Adult cooks (n = 137)			Senior Cookers (n = 61)		
	NO ₂	CO	HCHO	NO ₂	CO	HCHO	NO ₂	CO	HCHO
GM	1.25	1.15	1.15	1.53	1.36	1.36	1.50	1.33	1.32
GSD	1.08	1.06	1.06	1.16	1.16	1.16	1.15	1.14	1.14
Median	1.25	1.16	1.16	1.54	1.34	1.34	1.46	1.27	1.27
Mean	1.26	1.15	1.15	1.55	1.38	1.37	1.51	1.34	1.33
Min	1.13	1.05	1.05	1.14	1.09	1.09	1.12	1.08	1.08
Max	1.46	1.30	1.30	2.00	1.95	1.95	2.00	1.99	1.94

QA on Output Metrics

The following QA analysis was performed on the output metrics for each generation (i.e., following any substantial update or revision) of the exposure model code. To check that the model accurately calculated time-resolved concentrations following each emission event, we applied the following simplified mass balance equation to estimate short-term peak concentrations expected to result from cooking burner use in each home.

$$C_{in} = \frac{E}{V (1+(v_{dep}+AER_{emp}) \times del t)}$$

In this equation, E [µg] is the total mass of pollutant emitted assuming two cooktop burners and oven use for the specific cooking duration assigned to dinner in the home being checked; V is the volume of the residence [m³]; v_{dep} is the deposition rate (hr⁻¹, relevant to NO₂ only); AER_{emp} is the winter empirical AER; and del t = 1 hour. The denominator accounts for dilution of the emitted mass in the volume of air present in the house at the start of cooking plus the additional air that enters the home during the next 1 hour. Deposition has the same functional form as air exchange removal and is treated in this equation as effectively adding to dilution. In the approximate calculation, emissions are biased high because it includes oven use for all HHs; whereas, the exposure model assigns oven use for dinner in only half of the cases.

Table H-3 below shows that the population statistics for the approximated peak 1-hr indoor concentrations resulting from dinner cooking are consistent with the population statistics for the maximum 1-hr concentrations for CO, NO₂, and HCHO calculated with the exposure model.

Table H-3 presents summary statistics from this calculation.

Table H-3. Summary Statistics for Maximum 1-hr Concentrations in Each Household from Approximate Calculation Compared with the Exposure Model Predictions for HCHO and NO₂ Across All 6,634 Households in the SoCal GCB Cohort

Pollutant, Max 1-hr estimation method	Median	Mean (arithmetic)	Min	Max
HCHO [µg/m³]				
Approximation	16.3	39.9	0.58	1502
Exposure Model	15.8	36.8	0.12	1683
NO ₂ [µg/m³]				
Approximation	123	173	3.8	2529
Exposure Model	141	195	4.7	3465
CO [ppm]				
Approximation	1.9	3.8	0.02	146
Exposure Model	2.0	4.6	0.01	241

QA of Conventional NG and LNG Emission Factor Assignment

We confirmed that the exposure model was randomly selecting conventional baseline emission factors and applying the increments for LNG as described in the *Pollutant Emission Factors* section.

We confirmed random baseline emission factor selection by saving in the input file the values selected for each burner and checking that equal numbers of each burner were selected. This check was applied to the calculated emission rate—the product of emission factor and firing rate—as this was the value saved in the data file that serves as input to the exposure model.

The distribution of LNG emission rates associated with each conventional (baseline) natural gas emission rate [$\mu\text{g}/\text{min}$] included in the exposure model across all the RASS HHs that use GCBs, is presented in **Figure H-2** and **Figure H-3** for NO_2 and CO, respectively, for each (a) cooktop and (b) oven unit. We can see from these figures that the incremental change in LNG emission factors relative to conventional natural gas is taken into account. The incremental change over baseline (conventional) natural gas is consistent with a 50 WN change, as calculated by Equation 5 in main report. On average, the LNG emission rates are slightly higher than the conventional natural gas emission rates. But, based on the measured emission factors, for some cooktop and oven units the average ratio of the LNG/conventional NG emission rate can be the same, or slightly less than unity (e.g., CT10 for NO_2 , and CT05 and OV11 for CO).

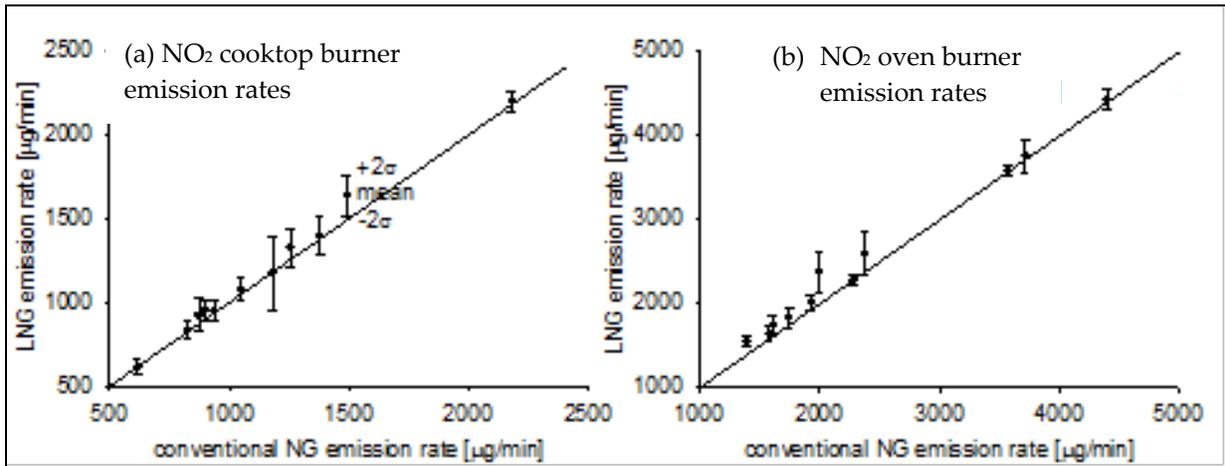


Figure H-2. NO_2 Conventional (Baseline) Natural Gas and LNG Emission Rates from (a) Cooktops and (b) Oven Burners. Uncertainty bars represent 2 standard deviations.

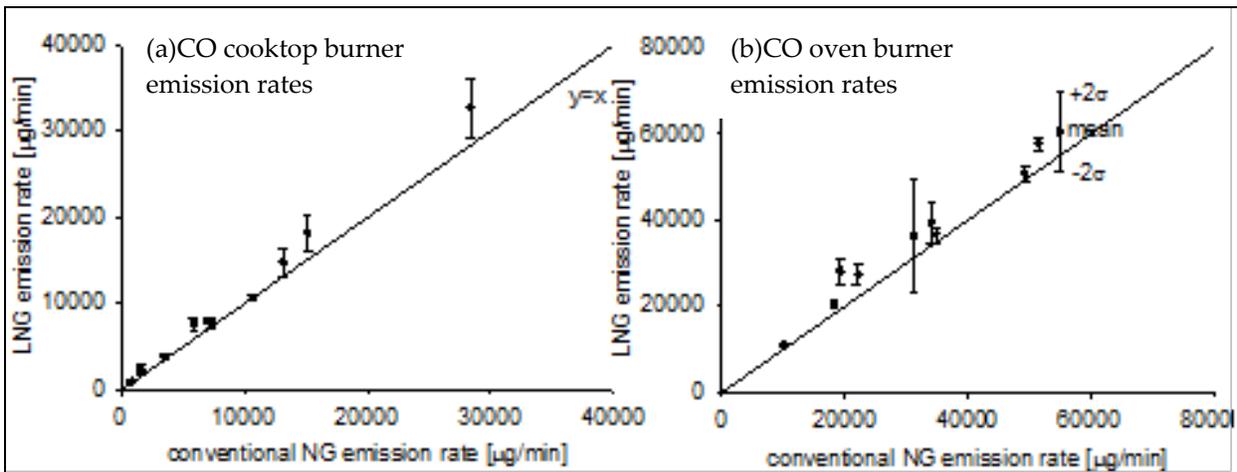


Figure H-3. CO Conventional (Baseline) Natural Gas and LNG Emission Rates from (a) Cooktops and (b) Oven Burners. Uncertainty bars represent 2 standard deviations.

QA Analysis of Sample Size Required for Stable Output Metrics

We assessed both the inter-run variability in the output metrics and also the number of households needed to reach stability in both the time-averaged output concentrations and exceedance-based output metrics.

First, we assessed the inter-run variability of the exceedance-based and time-averaged concentration metrics among the RASS GCB-using households in San Diego (N = 1,039 HHs). We ran five sets of simulations; each set included one run with baseline and one with LNG emission factors, with all other inputs held constant for the paired runs. For each set of runs, the oven and cooktop units were randomly reassigned. The following inputs were also resampled from lognormal distributions and assigned as described above in the Methods:

- Meal-specific duration of cooktop and/or oven use.
- Conventional (baseline) natural gas emission factors.
- Winter AER based on the distribution of winter empirical AERs.

Liquefied natural gas emission factors were recalculated following resampling of baseline emission factors. Concentration metrics were calculated for the 1,039 San Diego households included in each model run.

Table H- 4 presents sample mean values for 1-hr maximum and 1-week average concentrations of NO₂, CO, and HCHO, assuming GCBs are the only source contributing to indoor levels.

Table H- 4 shows that the sample-mean concentrations are generally consistent across runs. For both households and individuals, the maximum 1-hr concentrations are within 10 percent of each other for baseline NG and for LNG, for all pollutants. Sample-mean values for 1-week concentrations tend to vary more, up to 20 percent between runs for formaldehyde. Even for cases of larger run-to-run variations, the running mean values very stable after three or at most four runs. Differences between LNG and baseline NG can vary more in relative terms when the differences are small. For example, 1-week HCHO results for HHs vary from 3.25 to 3.82 for NG and from 3.37 to 3.85 for LNG; NG to LNG differences vary from 0.03 to 0.12 across the model runs. These results suggest that results obtained from simulations including only the 1,039 San Diego HHs sampled one time would vary between model runs; resampling through multiple runs or using the larger SoCal cohort of homes is warranted.

Table H- 4. Sample-mean Values for Maximum 1-hour and 1-week Average Indoor Concentrations of (a) NO₂, (b) CO, and (c) HCHO Resulting from GCB Use in San Diego Households. Results from the five sets of runs using all 1,039 San Diego RASS households (2,879 individuals) that use GCBs.

Emission factors and model run	Results for households 1-hr max.		Results for households 1-week avg.		Results for individuals, by run	
	By run	Cumulative	By run	Cumulative	1-hr Max.	1-week Avg.
	(a) NO ₂ [µg/m ³]					

Conventional NG						
NG - 1st run	175	174.8	8.5	8.46	210	9.6
NG - 2nd run	176	175.4	8.3	8.39	215	9.5
NG - 3rd run	172	174.2	8.3	8.35	213	9.7
NG - 4th run	180	175.8	8.9	8.49	220	10.1
NG - 5th run	175	175.7	8.5	8.48	212	9.8
LNG						
LNG - 1st run	189	188.7	9.1	9.12	227	10.4
LNG - 2nd run	190	189.5	9.0	9.07	233	10.3
LNG - 3rd run	186	188.2	8.9	9.02	229	10.5
LNG - 4th run	194	189.6	9.6	9.16	237	10.9
LNG - 5th run	190	189.6	9.1	9.15	230	10.6
(b) CO [ppm]						
Conventional NG						
1st run	4.07	4.07	0.45	0.45	4.67	0.47
2nd run	3.87	3.97	0.39	0.42	4.44	0.39
3rd run	3.94	3.96	0.43	0.42	4.70	0.45
4th run	4.26	4.03	0.46	0.43	4.98	0.48
5th run	4.36	4.10	0.46	0.44	4.75	0.45
LNG						
1st run	4.69	4.69	0.52	0.52	5.39	0.53
2nd run	4.47	4.58	0.46	0.49	5.16	0.46
3rd run	4.54	4.57	0.49	0.49	5.39	0.52
4th run	4.95	4.66	0.54	0.50	5.78	0.56
5th run	4.99	4.72	0.53	0.51	5.48	0.52
(c) HCHO [$\mu\text{g}/\text{m}^3$]						
Conventional NG						
1st run	34.1	34.07	3.79	3.79	38.5	3.82
2nd run	32.3	33.19	3.25	3.52	36.9	3.22
3rd run	33.0	33.13	3.63	3.56	40.6	3.98
4th run	36.1	33.87	3.82	3.62	41.7	3.96
5th run	34.6	34.02	3.57	3.61	38.4	3.55
LNG						
1st run	34.5	34.49	3.85	3.85	39.1	3.89
2nd run	32.8	33.63	3.37	3.59	37.5	3.30
3rd run	34.0	33.75	3.71	3.65	41.4	4.08
4th run	36.0	34.31	3.85	3.69	41.7	3.99
5th run	35.8	34.61	3.71	3.70	39.7	3.69

For exceedance-based metrics with either fuel, and especially for differences in exceedance rates between paired model runs with baseline NG and LNG fuels, there can be much greater variation between each set of model runs. As can be seen from **Table H-5**, the extra number of households in which GCB use exceeds a standard with LNG vs. baseline NG ranges from 33 to 51 (per 1,039 HHs) for the 1-hr NO₂ standard, from 2 to 11 for the 1-hr CO standard, and from 0 to 10 for the 8-hr CO standard. The number of additional households estimated to exceed 1-hr and 8-hr HCHO standards with LNG use can range from 1 to 18 per 1,039 SD gas HHs between model runs.

Table H-5. Results of Five Model Runs for 1,039 San Diego Households (HHs) That Use GCBs, the Number with Indoor Concentrations Exceeding a Pollutant Standard. Base exceedances for simulations with conventional NG; additional number of HHs exceeding a standard (+Δ) with LNG.

Model Run	NO ₂ 1-hr (GCB only)		CO 1-hr (GCB only)		CO 8-hr (GCB +outdoor)		HCHO 1-hr (GCB only) ^a	
	No. of HHs	(+Δ)	No. of HHs	(+Δ)	No. of HHs	(+Δ)	No. of HHs	(+Δ)
Run 1	332	35	35	4	38	5	170	9
Run 2	333	40	32	5	35	9	172	10
Run 3	340	36	31	5	33	4	176	18
Run 4	336	33	38	11	40	10	203	1
Run 5	339	51	28	2	32	0	180	15

^a Same number of households with an exceedance of 8-hr HCHO standard

To further explore the number of households necessary for the exposure model to provide a stable set of output metrics, we ran the model for a randomly selected subset of 3,000 HHs selected from the six-county SoCal homes that use GCBs (N=6,634 HHs). Each home had an opportunity to be selected only once in each run, i.e., randomly selected without replacement. We assumed GCBs as the only source of indoor concentrations and winter empirical AER. We tracked the running sample-mean of the maximum 1-hour and 1-week concentration and “exceedance-based” output metrics to identify where each of these outputs becomes stable for this sample. For this analysis, baseline NG and LNG runs are not paired; i.e., the model sampled households in a different order for an NG run relative to an LNG run. As the sample size increases toward the total pool of 6,634, there should be more overlap between the sampled groups. But the order in which they were sampled will still differ. It is important to note that this is different from the simulation approach used to obtain the primary results presented in the main paper; most results were obtained by running the entire cohort of available sample

As seen in **Figure H-4**, the number of HHs within the RASS SoCal gas cooking burner cohort needed to reach stability in the CO and HCHO maximum 1-hr pollutant concentrations is under 1,000. For NO₂ the sample mean for each fuel is still varying by a few percent over the last 1,000 of the 3,000 households included. The difference in maximum 1-hr concentrations associated with LNG relative to conventional NG is stable after roughly 1,500 HHs for CO and HCHO. The corresponding plots for individuals (**Figure H- 5**) show that sample-mean concentrations and differences in sample-means between NG and LNG are relatively stable after about 2,000

individuals for CO and HCHO; whereas, NO₂ again continues to vary through the entire sample.

Sample-means for 1-week concentration metrics and the difference between the LNG and conventional NG runs also becomes stable starting at about 1,000 households **Figure H-6**). Sample-mean 1-week concentrations are stable after about 2,000 individuals have been sampled **(Figure H-7)**.

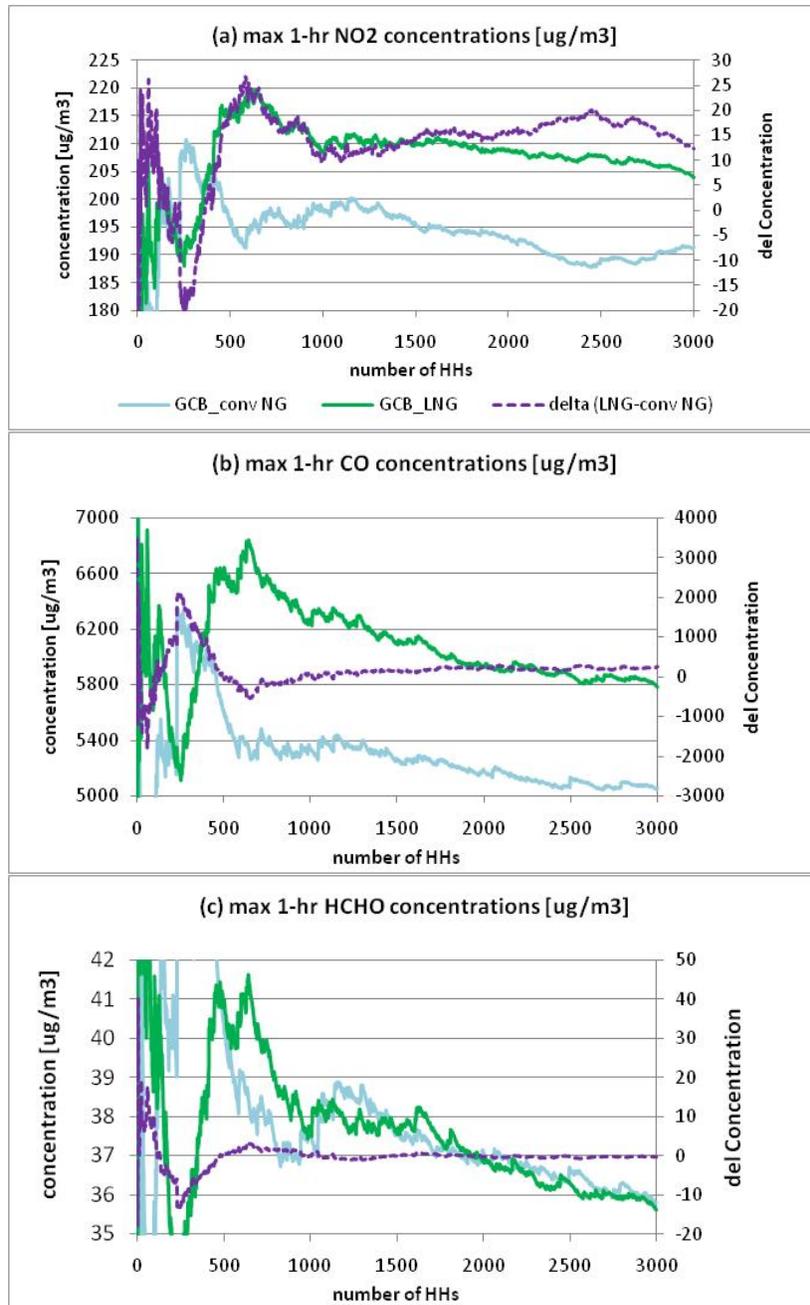


Figure H-4. Sample-mean of 1-hour Maximum (a) NO₂, (b) CO, and (HCHO) Concentrations Across 3,000 Randomly Sampled Households (HHs) Among the RASS SoCal Gas Cooking Burner Cohort. The difference (delta) in the 1-hour concentrations assuming LNG, relative to conventional NG emission factors is also shown (purple dashed line).

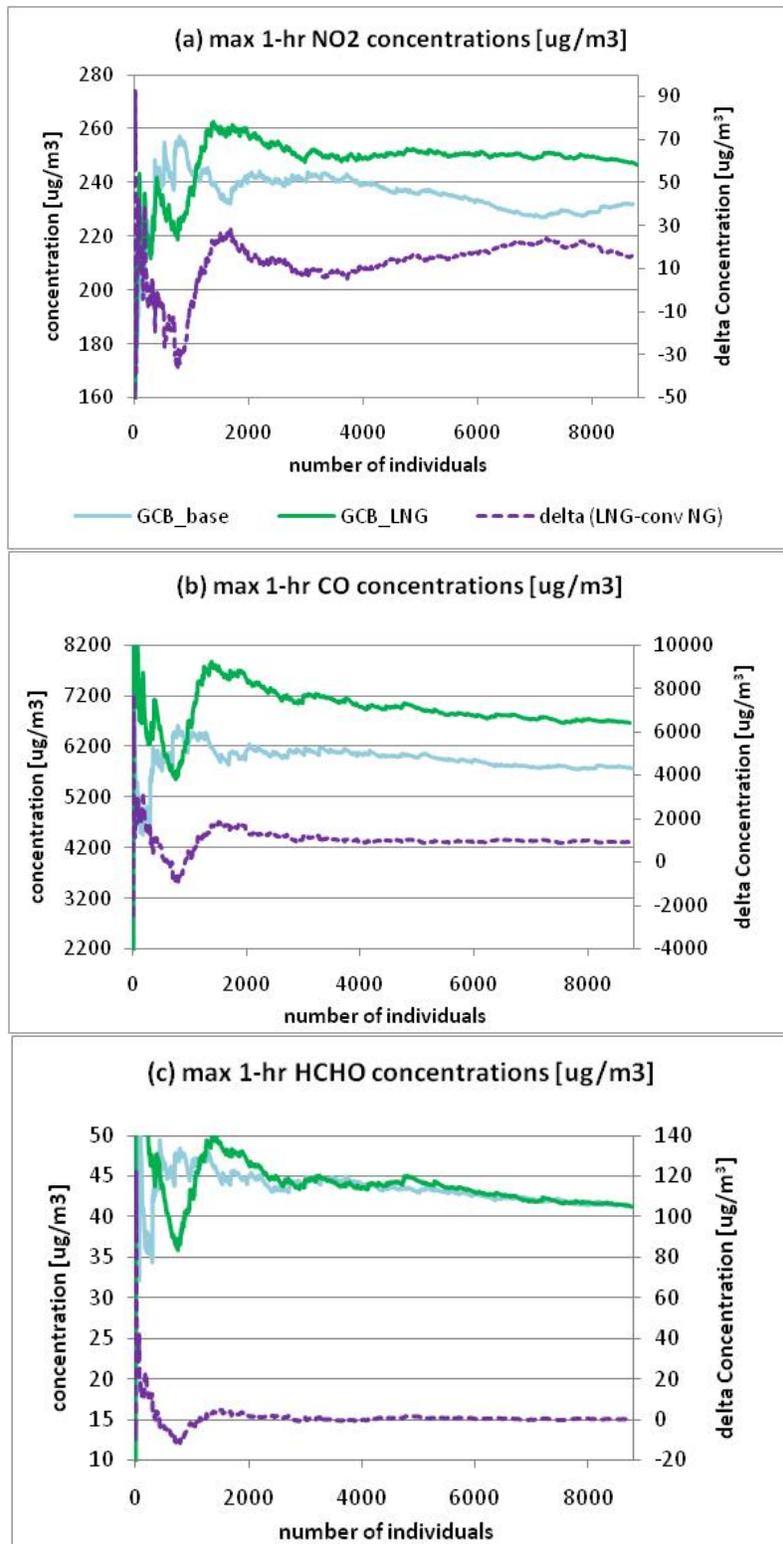


Figure H- 5. Sample-mean of 1-hour Maximum (a) NO₂, (b) CO, and (HCHO) Concentrations Across 8,738 Individuals Residing in 3,000 Randomly Sampled Households Among the RASS SoCal Gas Cooking Burner Cohort. The difference (delta) in the 1-hour concentrations assuming LNG, relative to conventional NG emission factors, is also shown (purple dashed line).

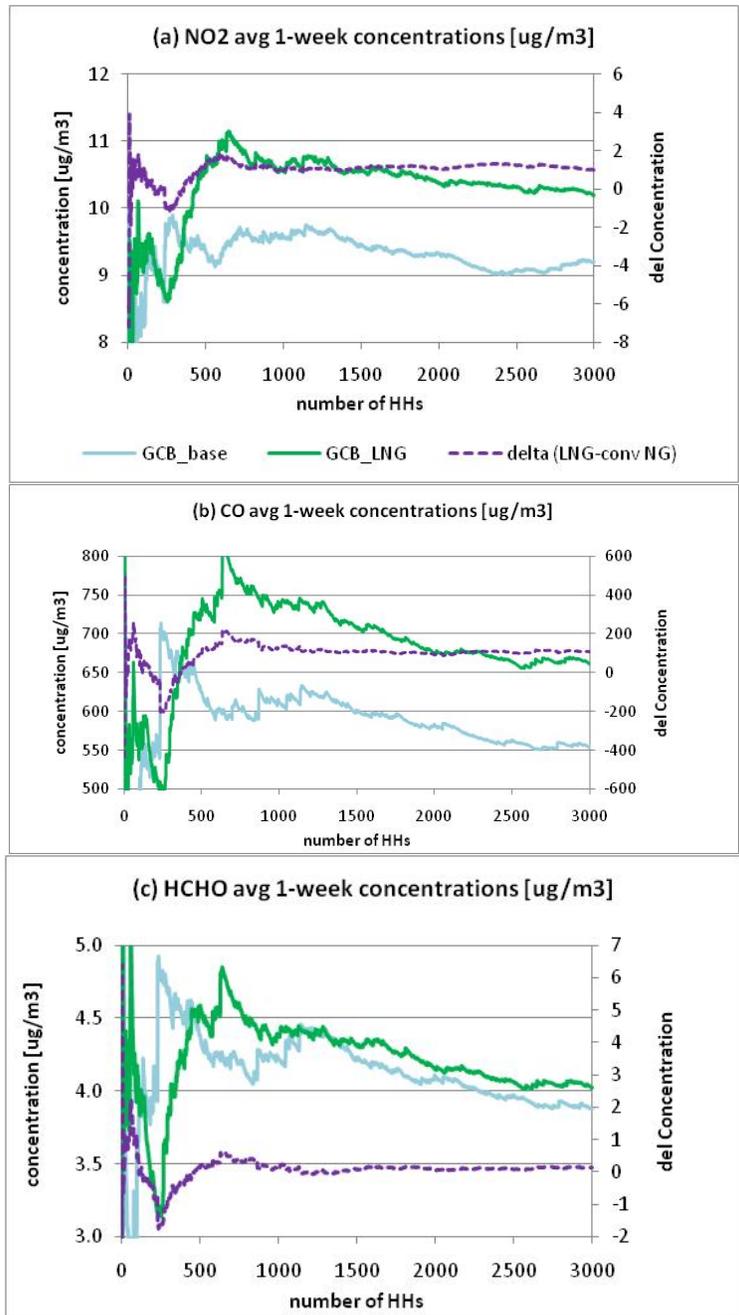


Figure H- 6. Sample-mean of 1-week (a) NO₂, (b) CO, and (HCHO) Concentrations Across 3,000 Randomly Sampled Households (HHs) Among the RASS SoCal Gas Cooking Burner Cohort. The difference (delta) in the 1-hour concentrations assuming LNG, relative to conventional NG emission factors, is also shown (purple dashed line).

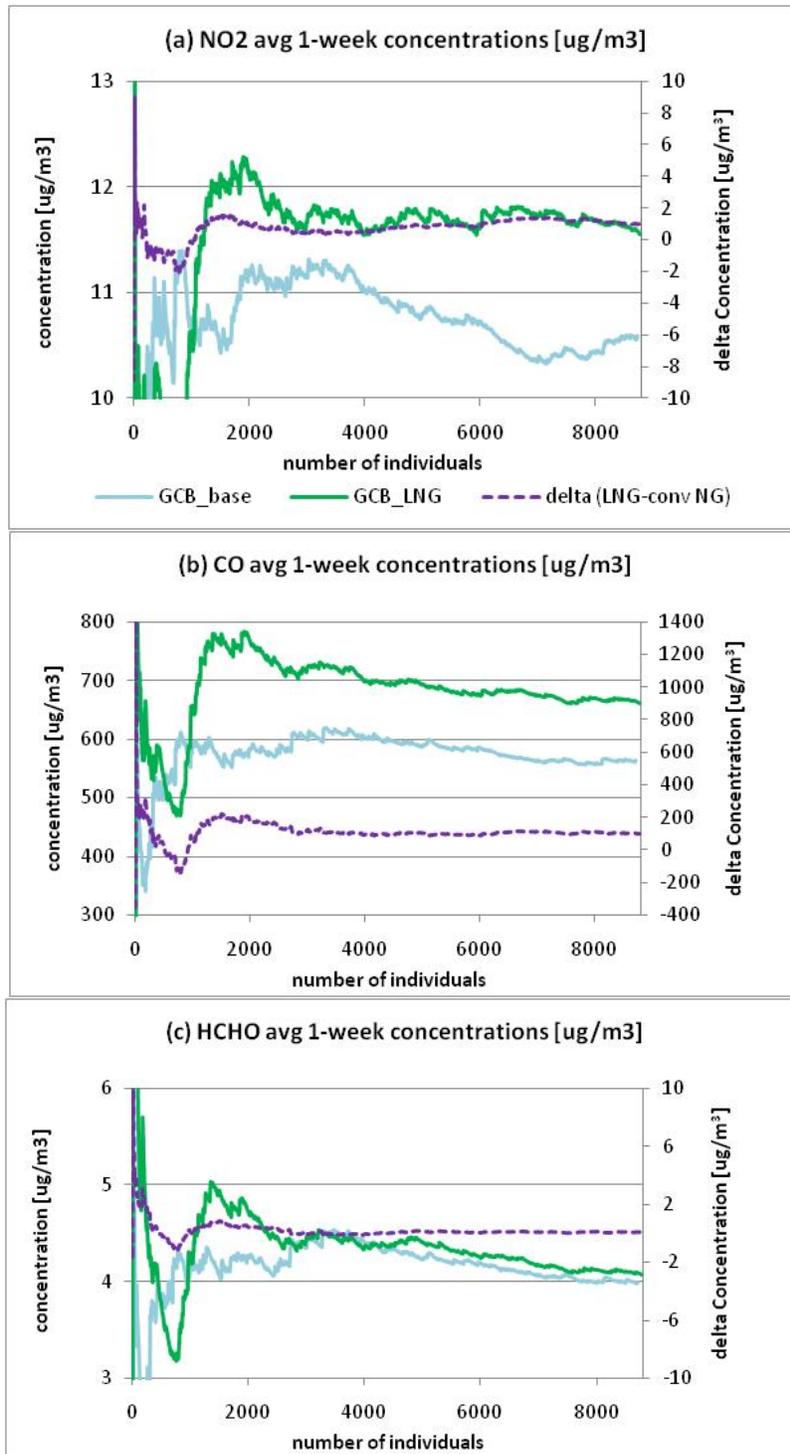


Figure H- 7. Sample Mean of 1-week (a) NO₂, (b) CO, and (HCHO) Concentrations Across 8,738 Individuals Residing in 3,000 Randomly Sampled Households Among the RASS SoCal Gas Cooking Burner Cohort. The difference (delta) in the 1-hour concentrations assuming LNG, relative to conventional NG emission factors is also shown (purple dashed line).

Results for exceedances of the 1-hr health-based standard are shown in **Figure H-8** for households and **Figure H-9** for individuals. Results are again provided for (a) NO₂, (b) CO, and (c) HCHO, assuming conventional natural gas or liquefied natural gas. Stability of the exceedance fraction (# with at least one exceedance of the 1-hr health based standard divided by total number of modeled homes) is achieved for sample sizes of 1,000 or less in most of the cases shown. The individual exceedance rate for NO₂ is consistent between roughly 1,500 and 3,500, then increases slightly.

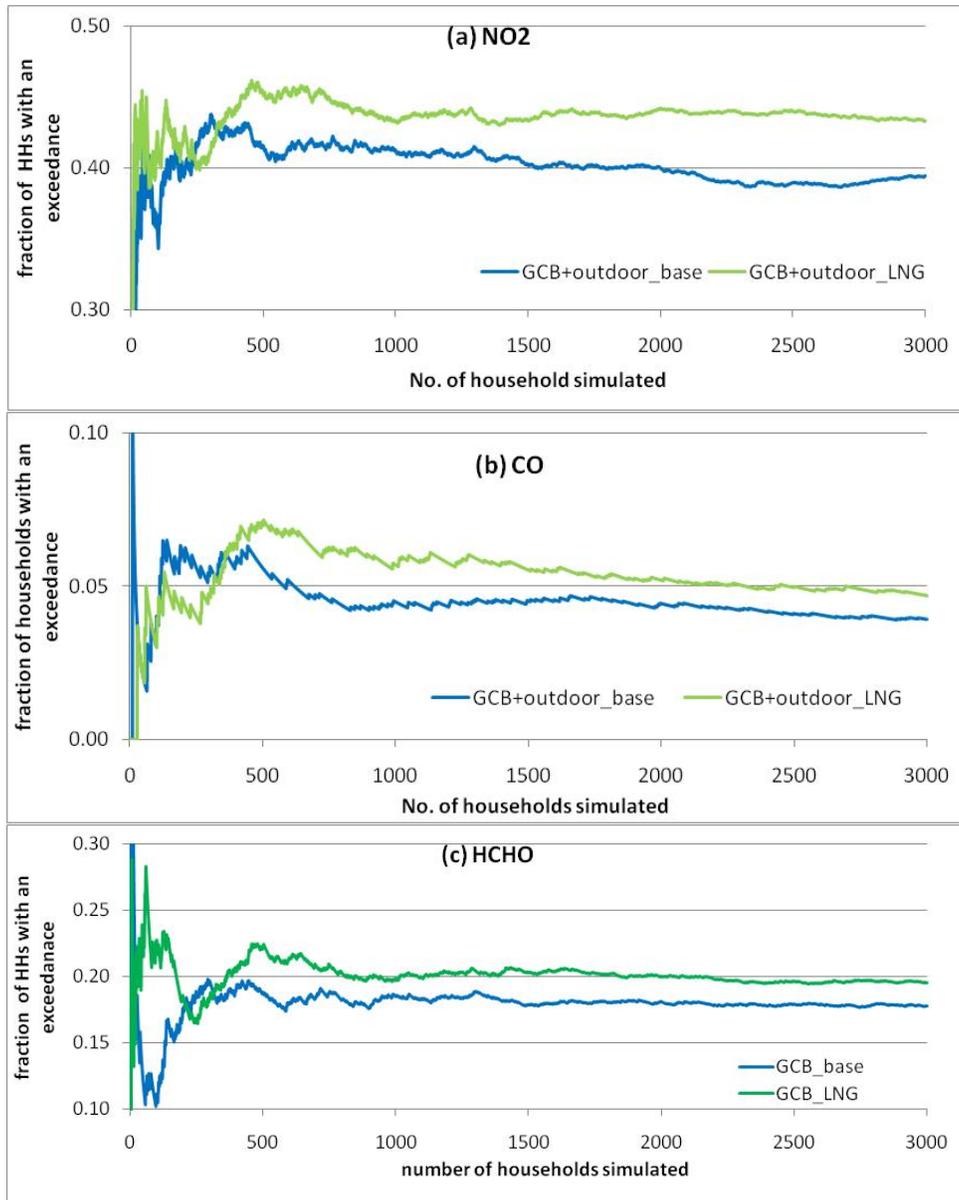


Figure H- 8. Fraction of Households (HHs) with Concentrations Exceeding the 1-hr Health-based Standard for (a) NO₂ (NAAQS of 190 µg/m³), (b) CO (CAAQS of 20 ppm), and (c) HCHO (ATSDR guideline of 50 µg/m³) Across a Random Sample of 3,000 households among the RASS SoCal Gas Cooking Burner cohort

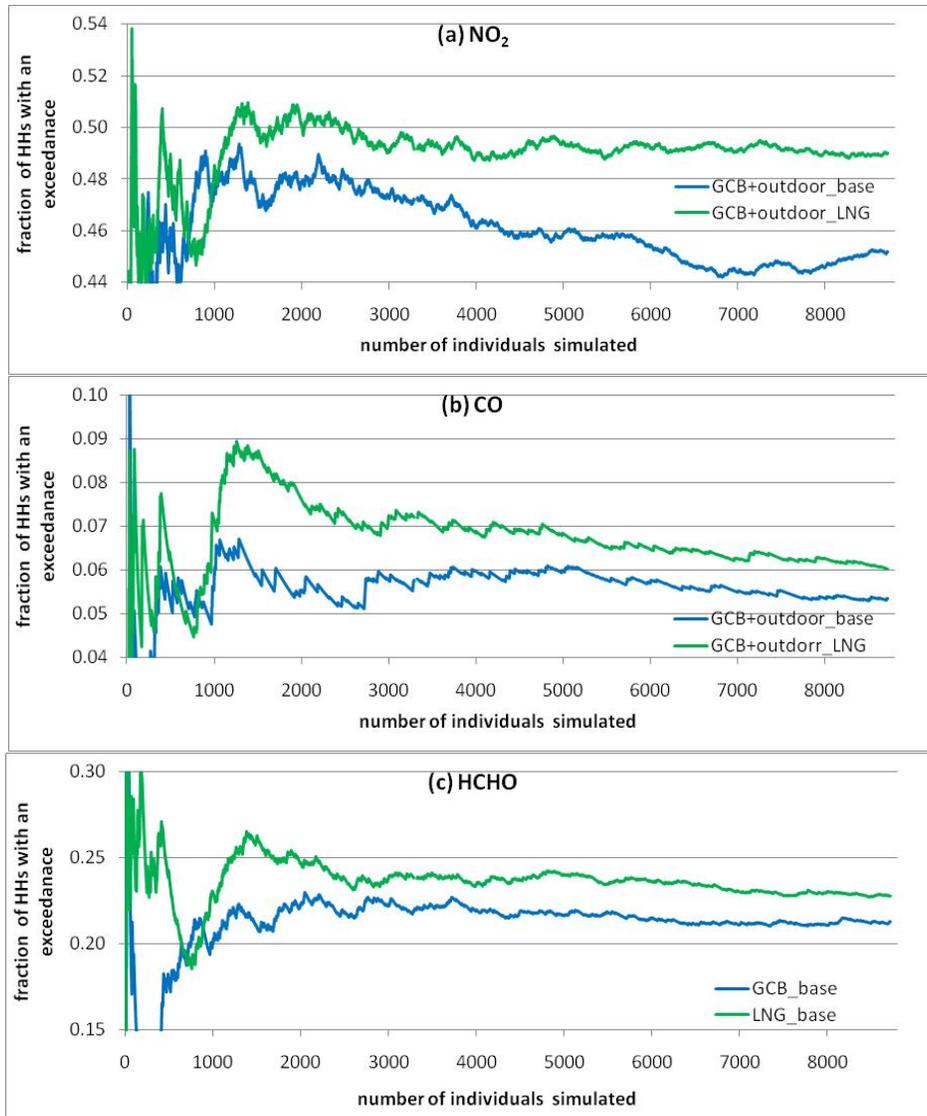


Figure H- 9. Fraction of Individuals Exposed to Concentrations Exceeding a 1-hr Health-based Standard for (a) NO₂ (NAAQS of 190 µg/m³), (b) CO (CAAQS of 20 ppm), and (c) HCHO (ATSDR Guideline of 50 µg/m³) Across a Random Sample of 3,000 Households Among the RASS SoCal Gas Cooking Burner cohort

The results presented above indicate that, when randomly sampling from the SoCal cohort of households, robust and stable results can be obtained for population-mean indoor pollutant concentrations with sample sizes of roughly 1,000 to 1,500 households for CO and HCHO; whereas, more households may be needed for very precise determination of increments for NO₂. Similar numbers of households are needed for precise and robust results for individual exceedances. The primary results presented in the report were obtained by running the model for each scenario using the entire cohort, with all parameters other than pollutant emission factors (conventional NG or LNG) held constant; this enables much more precise and robust results to be obtained.

Reference

CEC (2004). *California Statewide Residential Appliance Saturation Study. Final Report. Prepared by KEMA-XENERGY, Itron, RoperASW.* June 2004. 400-04-009. Available at:
http://www.energy.ca.gov/reports/400-04-009/2004-08-17_400-04-009ALL.PDF.

APPENDIX I: Tabular Model Results for Southern California

Table I-1. Summary Statistics for Modeled 1-week Indoor NO₂ Concentrations Attributable to (a) GCBs and (b) GCBs and Outdoor Sources, Across 6,634 HHs in the 6-county SoCal Region

Season	AER	Fuel	Mean	Std Dev	Median	25th %	75th %
(a) Indoor NO₂ due to GCBs							
Winter	Infiltration	Base	10.8	14	6.8	3.3	13
		LNG	11.6	15	7.7	3.6	14
Winter	Empirical	Base	9.3	13	5.8	2.8	11
		LNG	10	13	6.3	3.0	12
Summer	Empirical	Base	6.4	8.6	3.9	1.8	7.6
		LNG	6.8	9.2	4.2	2.0	8.3
(b) Indoor NO₂ due to GCBs and outdoor sources							
Winter	Infiltration	Base	17	15	13.3	9.2	20
		LNG	18	16	13.9	9.5	21
Winter	Empirical	Base	21	13	18.3	14	24
		LNG	22	14	18.8	14	25
Summer	Empirical	Base	17.6	10	16.0	11	22
		LNG	18.0	10	16.3	14	22

Table I-2. Summary Statistics of Modeled Maximum 8-hr Average Indoor NO₂ Concentration Attributable to GCBs and Outdoor Sources, Across 6,634 HHs in the 6-county SoCal HHs

Season	AER	Fuel	Mean	Std Dev	Median	25th %	75th %
Winter	Infiltration	Base	55	55	41	25	66
		LNG	59	59	44	27	71
Winter	Empirical	Base	55	49	43	29	64
		LNG	58	52	45	31	68
Summer	Empirical	Base	40	34	32	22	47
		LNG	43	36	33	23	49

Table I-3. Summary Statistics of Modeled 1-hr Maximum Indoor NO₂ Concentration Attributable to (a) GCBs and (b) GCBs and Outdoor Sources, Across 6,634 HHs in the 6-county SoCal HHs

Season	AER	Fuel	Mean	Std Dev	Median	25th %	75th %
(a) Indoor NO₂ due to GCBs							
Winter	Infiltration	Base	207	209	153	86	258
		LNG	223	223	166	92	281
Winter	Empirical	Base	190	194	139	79	235
		LNG	204	207	151	84	256
Summer	Empirical	Base	148	152	107	59	182
		LNG	159	163	115	64	199
(b) Indoor NO₂ due to GCBs and outdoor sources							
Winter	Infiltration	Base	215	210	161	93	266
		LNG	231	224	174	99	289
Winter	Empirical	Base	204	194	154	92	249
		LNG	219	208	165	98	271
Summer	Empirical	Base	158	152	118	70	192
		LNG	170	163	126	75	208

Table I-4. Summary Statistics of Modeled Average 1-week Indoor NO₂ Concentration Attributable to (a) GCBs and (b) GCBs and Outdoor Sources, Across 19,288 Residents of the Six-county SoCal RASS Cohort

Season	AER	Fuel	Mean	Std Dev	Median	25th %	75th %
(a) Indoor NO₂ due to GCBs							
Winter	Infiltration	Base	12.1	16	7.7	3.7	15
		LNG	13.0	17	8.3	4.0	16
Winter	Empirical	Base	10.5	14	6.5	3.1	13
		LNG	11.3	15	7.0	3.3	14
Summer	Empirical	Base	7.5	10	4.5	2.1	9.0
		LNG	8.1	11	4.9	2.3	9.7
(b) Indoor NO₂ due to GCBs and outdoor sources							
Winter	Infiltration	Base	17.4	16	13.0	8.8	20
		LNG	18.3	17	13.6	9.1	22
Winter	Empirical	Base	20.5	15	17.3	13	24
		LNG	21.3	15	17.8	13	25
Summer	Empirical	Base	16.7	11	14.6	10	20
		LNG	17.3	11	15.0	11	21

Table I-5. Summary Statistics of Modeled Maximum 1-hr Indoor NO₂ Concentration Attributable to (a) GCBs and (b) GCBs and Outdoor Sources, Across 19,288 Residents of the 6-county SoCal HHs

Season	AER	Fuel	Mean	Std Dev	Median	25 th %	75 th %
(a) Indoor NO₂ due to GCBs							
Winter	Infiltration	Base	251	283	172	94	313
		LNG	270	302	186	101	335
Winter	Empirical	Base	231	264	158	86	285
		LNG	249	282	170	92	307
Summer	Empirical	Base	183	208	123	66	226
		LNG	197	223	133	71	244
(b) Indoor NO₂ due to GCBs and outdoor sources							
Winter	Infiltration	Base	259	284	180	101	321
		LNG	278	303	193	108	344
Winter	Empirical	Base	246	264	172	100	300
		LNG	263	282	184	106	322
Summer	Empirical	Base	194	208	133	77	236
		LNG	208	223	143	82	255

Table I-6. Summary Statistics of Modeled Average 1-week Indoor CO Concentrations Attributable to (a) GCBs and (b) GCBs and Outdoor Sources, Across 6,634 SoCal RASS HHs

Season	AER	Fuel	Mean	Std Dev	Median	25 th %	75 th %
(a) Indoor CO due to GCBs							
Winter	Infiltration	Base	0.86	2.0	0.35	0.11	0.92
		LNG	1.0	2.2	0.44	0.14	1.1
Winter	Empirical	Base	0.48	1.1	0.17	0.051	0.45
		LNG	0.56	1.2	0.21	0.067	0.56
Summer	Empirical	Base	0.20	0.59	0.06	0.020	0.19
		LNG	0.24	0.64	0.08	0.026	0.23
(b) Indoor CO due to GCBs and outdoor sources							
Winter	Infiltration	Base	1.7	2.1	1.1	0.80	1.9
		LNG	1.9	2.2	1.2	0.83	2.2
Winter	Empirical	Base	1.3	1.3	0.90	0.74	1.4
		LNG	1.4	1.4	0.95	0.76	1.5
Summer	Empirical	Base	0.43	0.66	0.24	0.15	0.42
		LNG	0.47	0.71	0.25	0.16	0.47

Table I-7. Summary Statistics of Maximum 8-hr Average Indoor CO Concentrations Across 6,634 SoCal HHs in Winter (W) and Summer (S) Assuming Infiltration or Empirical AER Arising from the Use of GCBs and Outdoor Sources

Season	AER	Fuel	Mean	Std Dev	Median	25th %	75th %
Winter	Infiltration	Base	3.9	6.0	2.5	1.3	4.4
		LNG	4.5	6.4	2.9	1.4	5.2
Winter	Empirical	Base	2.9	3.9	1.8	1.1	3.6
		LNG	3.2	4.3	2.0	1.2	4.1
Summer	Empirical	Base	1.1	2.0	0.53	0.28	1.4
		LNG	1.3	2.2	0.64	0.30	1.6

Table I-8. Summary Statistics of Modeled Maximum 1-hour Indoor CO Concentrations Attributable to (a) GCBs and (b) GCBs and Outdoor Sources, Across 6,634 HHs in the 6-county SoCal HHs

Season	AER	Fuel	Mean	Std Dev	Median	25th %	75th %
(a) Indoor CO due to GCBs							
Winter	Infiltration	Base	5.1	10.0	2.5	0.86	5.8
		LNG	6.0	10.8	3.2	1.1	7.0
Winter	Empirical	Base	4.3	8.1	2.0	0.71	4.8
		LNG	5.0	8.8	2.6	0.90	5.8
Summer	Empirical	Base	2.9	5.1	1.4	0.47	3.3
		LNG	3.4	5.6	1.7	0.60	4.0
(a) Indoor CO due to GCBs and outdoor sources							
Winter	Infiltration	Base	5.9	10.0	3.5	1.6	6.6
		LNG	6.8	10.8	4.1	1.8	7.8
Winter	Empirical	Base	5.1	8.1	3.0	1.4	5.6
		LNG	5.9	8.8	3.6	1.6	6.6
Summer	Empirical	Base	3.2	5.1	1.7	0.67	3.5
		LNG	3.7	5.6	2.1	0.81	4.2

Table I-9. Summary Results for 1-week Indoor CO Concentration Attributable to (a) GCBs and (b) GCBs and Outdoor Sources, Across 19,288 Residents of the 6-county SoCal HHs

Season	AER	Fuel	Mean	Std Dev	Median	25th %	75th %
(a) Indoor CO due to GCBs							
Winter	Infiltration	Base	0.86	1.9	0.36	0.11	0.94
		LNG	1.0	2.0	0.45	0.15	1.1
Winter	Empirical	Base	0.48	1.1	0.17	0.05	0.47
		LNG	0.56	1.2	0.22	0.07	0.58
Summer	Empirical	Base	0.23	0.63	0.071	0.021	0.20
		LNG	0.27	0.71	0.088	0.028	0.25
(b) Indoor CO due to GCBs and outdoor sources							
Winter	Infiltration	Base	1.6	1.9	1.0	0.70	1.9
		LNG	1.7	2.1	1.1	0.73	2.1
Winter	Empirical	Base	1.2	1.2	0.82	0.64	1.3
		LNG	1.3	1.3	0.87	0.67	1.5
Summer	Empirical	Base	0.42	0.69	0.22	0.13	0.43
		LNG	0.46	0.77	0.24	0.14	0.49

Table I-10. Summary Statistics of Modeled Maximum 8-hr Indoor CO Concentration Attributable to GCBs and Outdoor Sources, Across 19,288 Residents of the 6-county SoCal HHs

Season	AER	Fuel	Mean	Std Dev	Median	25th %	75th %
Winter	Infiltration	Base	4.0	6.1	2.5	1.3	4.5
		LNG	4.6	6.6	3.0	1.4	5.3
Winter	Empirical	Base	3.0	4.0	1.8	1.2	3.8
		LNG	3.3	4.4	2.0	1.2	4.2
Summer	Empirical	Base	1.2	2.2	0.56	0.28	1.5
		LNG	1.4	2.4	0.68	0.29	1.7

Table I-11. Summary Statistics of Modeled Maximum 1-hr Indoor CO Concentration Attributable to (a) GCBs and (b) GCBs and Outdoor Sources, Across 19,288 Residents of the 6-county SoCal HHs

Season	AER	Fuel	Mean	Std Dev	Median	25th %	75th %
(a) Indoor CO due to GCBs							
Winter	Infiltration	Base	5.8	12	2.7	0.92	6.4
		LNG	6.9	13	3.4	1.2	7.8
Winter	Empirical	Base	4.9	10	2.2	0.74	5.4
		LNG	5.7	11	2.8	0.94	6.5
Summer	Empirical	Base	3.5	6.5	1.5	0.51	3.8
		LNG	4.1	7.1	1.9	0.65	4.7
(b) Indoor CO due to GCBs and outdoor sources							
Winter	Infiltration	Base	6.6	12	3.8	1.6	7.2
		LNG	7.6	13	4.3	1.9	8.6
Winter	Empirical	Base	5.8	10	3.3	1.5	6.2
		LNG	6.6	11	4.0	1.7	7.4
Summer	Empirical	Base	3.8	6.5	2.0	0.72	4.1
		LNG	4.4	7.1	2.3	0.88	5.0

Table I-12. Summary Statistics of Modeled Indoor HCHO Time-Averaged Concentrations [$\mu\text{g}/\text{m}^3$], Including (A) Maximum 1-hour, (B) Maximum 8-hour, and (C) Average 1-Week Concentrations Arising from GCB Use Across 6,634 SoCal HHs in Winter and Summer Assuming Infiltration and Empirical AER

Season	AER	Fuel	Mean	Std Dev	Median	25th %	75th %
(a) Average 1-week HCHO [$\mu\text{g}/\text{m}^3$]							
Winter	Infiltration	Base	6.8	15	2.9	1.0	7.0
		LNG	7.0	15	3.1	1.1	7.5
Winter	Empirical	Base	3.7	8.3	1.4	0.47	3.6
		LNG	3.9	8.4	1.5	0.50	3.8
Summer	Empirical	Base	1.6	4.7	0.53	0.19	1.5
		LNG	1.7	4.8	0.57	0.20	1.5
(b) Maximum 8-hr HCHO [$\mu\text{g}/\text{m}^3$]							
Winter	Infiltration	Base	24.0	46	11.7	4.8	26
		LNG	24.6	44	12.5	5.1	28
Winter	Empirical	Base	14.9	29	6.4	2.5	15
		LNG	15.4	29	6.9	2.6	17
Summer	Empirical	Base	6.9	16	2.7	1.0	7.0
		LNG	7.1	16	2.8	1.1	7.4
(c) Maximum 1-hr HCHO [$\mu\text{g}/\text{m}^3$]							
Winter	Infiltration	Base	41	78	20	8.0	44
		LNG	42	76	21	8.5	47
Winter	Empirical	Base	34	63	16	6.4	36
		LNG	35	62	17	6.8	39
Summer	Empirical	Base	23	43	11	4.3	25
		LNG	24	42	12	4.7	27

Table I-13. Summary Statistics of Modeled Indoor HCHO Time-averaged Concentrations [$\mu\text{g}/\text{m}^3$] Across 19,288 Residents of SoCal GCB RASS Cohort, Including (a) Maximum 1-hour, (b) Maximum 8-hour, (c) Average 1-week Concentrations Arising from the use of GCB in the Winter and Summer, Assuming Infiltration and Empirical AER

Season	AER	Fuel	Mean	Std Dev	Median	25th %	75th %
(a) Average 1-week HCHO [$\mu\text{g}/\text{m}^3$]							
Winter	Infiltration	Base	6.8	14	3.0	1.1	7.1
		LNG	7.0	14	3.2	1.2	7.6
Winter	Empirical	Base	3.8	7.9	1.4	0.48	3.7
		LNG	3.9	8.0	1.5	0.52	4.0
Summer	Empirical	Base	1.8	4.8	0.58	0.20	1.6
		LNG	1.9	5.1	0.63	0.21	1.7
(b) Maximum 8-hr HCHO [$\mu\text{g}/\text{m}^3$]							
Winter	Infiltration	Base	24.7	47	11.9	4.8	26
		LNG	25.3	45	12.7	5.2	28
Winter	Empirical	Base	15.3	30	6.5	2.5	16
		LNG	15.7	30	7.0	2.6	17
Summer	Empirical	Base	7.6	17	2.9	1.0	7.4
		LNG	7.8	17	3.1	1.1	8.0
(c) maximum 1-hr HCHO [$\mu\text{g}/\text{m}^3$]							
Winter	Infiltration	Base	47	95	21	8.4	49
		LNG	48	92	23	9.1	53
Winter	Empirical	Base	38	77	17	6.8	41
		LNG	40	75	19	7.2	44
Summer	Empirical	Base	28	53	12	4.7	29
		LNG	29	51	13	5.0	32

Table I-14. Summary Statistics of (a) Maximum 1-hr and (b) Average 1-week Indoor NO₂ Concentrations Attributable to GCB Across 19,288 Individual Residents of SoCal HHs with Varying Assumptions of F_{prox}. Winter empirical AER is assumed for all scenarios.

Scenario	Mean	Std Dev	Median	25th %	75th %
(a) Max 1-hr indoor NO₂ [µg/m³] from GCB use					
F _{prox} = 1					
	184	187	135	78	230
F _{prox} = baseline					
Baseline NG	231	264	158	86	285
LNG	249	282	170	92	307
F _{prox} = 2 x baseline					
Baseline NG	336	479	186	96	388
LNG	362	512	201	103	418
(b) 1-week Average indoor NO₂ [µg/m³] from GCB use					
F _{prox} = 1					
Baseline NG	9.0	11	5.7	2.8	11
F _{prox} = baseline					
Baseline NG	10.5	14	6.5	3.1	13
LNG	11.3	15	7.0	3.3	14
F _{prox} = 2 x baseline					
Baseline NG	13.8	22	7.6	3.5	16
LNG	14.8	23	8.2	3.7	17

Table I-15. Summary Statistics of (a) Maximum 1-hr and (b) Average 1-week Indoor CO Concentrations [ppm] Across 19,288 Individual Residents of SoCal HHs with Varying Assumptions of F_{prox}. Winter empirical AER is assumed for all scenarios.

Scenario	Mean	Std Dev	Median	25th %	75th %
(a) Maximum 1-hr indoor CO [ppm] from GCB use					
F _{prox} = 1					
Baseline NG	4.2	7.8	2.0	0.68	4.6
F _{prox} = baseline					
Baseline NG	4.9	10	2.2	0.74	5.4
LNG	5.7	11	2.8	0.94	6.5
F _{prox} = 2 x baseline					
Baseline NG	6.8	17	2.6	0.83	6.9
LNG	8.0	18	3.3	1.1	8.5
(b) 1-week average indoor CO [ppm] from GCB use					
F _{prox} = 1					
Baseline NG	0.45	0.95	0.16	0.052	0.44
F _{prox} = baseline					
Baseline NG	0.48	1.1	0.17	0.050	0.47
LNG	0.56	1.2	0.22	0.072	0.58
F _{prox} = 2 x baseline					
Baseline NG	0.54	1.4	0.19	0.057	0.53
LNG	0.63	1.5	0.24	0.067	0.65

Table I-16. Summary Statistics of (a) Maximum 1-hr and (b) Average 1-week Indoor HCHO Concentrations Attributable to GCB Use Across 19,288 Individual Residents of SoCal HHs Across Varying Fprox Assumptions. Winter empirical AER is assumed for all scenarios.

Scenario	Mean	Std Dev	Median	25th %	75th %
(a) Maximum 1-hr indoor HCHO [$\mu\text{g}/\text{m}^3$] from GCB use					
F _{prox} = 1					
Baseline NG	33	59	15	6.3	35
F _{prox} = baseline					
Baseline NG	39	77	17	6.8	41
LNG	40	75	19	7.2	44
F _{prox} = 2 x baseline					
Baseline NG	54	129	20	7.7	55
LNG	56	126	22	8.3	58
(b) 1-week average indoor HCHO [$\mu\text{g}/\text{m}^3$] from GCB use					
F _{prox} = 1					
Baseline NG	3.6	7.1	1.3	0.46	3.5
F _{prox} = baseline					
Baseline NG	3.8	7.9	1.4	0.48	3.7
LNG	4.4	10	1.7	0.52	4.4
F _{prox} = 2 x baseline					
Baseline NG	4.3	10	1.5	0.52	4.1
LNG	4.4	10	1.7	0.56	4.4