Arnold Schwarzenegger
Governor

NATURAL GAS VARIABILITY IN CALIFORNIA: ENVIRONMENTAL IMPACTS AND DEVICE PERFORMANCE

EXPERIMENTAL EVALUATION OF POLLUTANT EMISSIONS FROM RESIDENTIAL APPLIANCES

APPENDIX H. SUMMARY REPORTS FOR FURNACES

PIER INTERIM PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

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Lawrence Berkeley National Laboratory

June 2010
CEC-500-2009-099-APH

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Introduction

This document is an appendix to an interim project report for California Energy Commission Contract 500-05-026, *Natural Gas Variability in California: Environmental Impacts and Device Performance*. The full interim project report caries the same base report number as this document and should be cited as the primary source of information about the work described in this appendix. As its title suggests, the main report describes objectives, methods, primary results, and analysis related to the experimental evaluation of pollutant emissions from residential appliances. The material contained in this appendix was originally compiled as a series of individual burner reports that were used to present interim results to the Project Advisory Committee. The appendices to the main report compile these individual burner reports by appliance, with cooktops and ovens each divided between two appendices to satisfy Energy Commission file size limits. A complete list of appendices is provided in the main report.

An overview of the information contained in the main report is presented below.

The effect of liquefied natural gas (LNG) on pollutant emissions was evaluated experimentally with used and new appliances in the laboratory and appliances installed in residences, targeting information gaps from previous studies. This report describes methods and provides summary results with analysis. Burner selection targeted available technologies projected to comprise the majority of installed appliances over the next decade. Experiments were conducted on 13 cooktop sets, 12 ovens, 5 broiler burners, 5 storage water heaters, 4 forced air furnaces, 1 wall furnace, and 6 tankless water heaters. Air-free concentrations and fuel-based emission factors were determined for carbon monoxide, nitrogen oxides, nitrogen dioxide, and the number of (predominantly ultrafine) particles over complete burns—including transient effects following ignition—and during more stable end-of-burn conditions. Formaldehyde was measured over multi-burn cycles. The baseline fuel was PG&E line gas with Wobbe numbers of 1320–1340; test fuels were simulated LNGs with Wobbe numbers of roughly 1390 and 1420, and in some cases 1360. No ignition or operational problems were observed during simulated LNG use. Baseline emissions varied widely across and within burner groups, and with burner operational mode. Statistically significant emissions changes were observed for some pollutants on some burners.

Table of Contents

Introduction i
List of Figures iii
List of Tables v
1.0 Central Furnace CF01 1
1.1. Experimental information for CF01 1
1.2. Results for CF01 5
2.0 Central Furnace CF02 10
2.1. Experimental information for CF02 10
2.2. Results for CF02 10
3.0 Central Furnace CF03 20
3.1. Experimental information for CF03 20
3.2. Results for CF03 25
4.0 Central Furnaces CF04 30
4.1. Experimental information for CF04 30
4.2. Results for CF04 30
5.0 Wall Furnace WF01 35
5.1. Experimental information for WF01 39
5.2. Results for WF01 39

List of Figures

Figure 1. Pollutant sampling configuration for central furnace CF01. 2

Figure 2. Experimental apparatus installed for central furnace CF01. 3

Figure 3. Measured analyte concentrations for forced air furnace CF01 with PG&E line gas (F011). 7

Figure 4. Measured analyte concentrations for forced air furnace CF01 with fuel 1C (F012). 7

Figure 5. Measured analyte concentrations for forced air furnace CF01 with fuel 3C (F013). 8

Figure 6. Experimental apparatus installed for central furnace CF02. 11

Figure 7. Pollutant sampling configuration for central furnace CF02. 12

Figure 8. Measured analyte concentrations for central forced air furnace CF02 with PG&E line gas (F019). 16

Figure 9. Size-resolved number concentrations of particles larger than 0.1 μm for experiment F019, Burn 1 (Lasair data). 16

Figure 10. Measured analyte concentrations for central forced air furnace CF02 with fuel 1C (F020). 17

Figure 11. Size-resolved number concentrations of particles larger than 0.1 μm for experiment F020 (Lasair data). 17

Figure 12. Measured analyte concentrations for central forced air furnace CF02 with fuel 3C (F021). 18

Figure 13. Size-resolved number concentrations of particles larger than 0.1 μm for experiment F021 (Lasair data). 18

Figure 14. Central furnace CF03. 21

Figure 15. Burners of central furnace CF03, PG&E line gas. 22

Figure 16. Experimental apparatus installed for central furnace CF03. 23

Figure 17. Pollutant sampling configuration for central furnace CF03. 24

Figure 18. Measured analyte concentrations for forced air furnace CF03 with PG&E line gas (F039). 27

Figure 19. Measured analyte concentrations for forced air furnace CF03 with fuel 1C (F040). 27

Figure 20. Measured analyte concentrations for central forced air furnace CF03 with fuel 3C (F041). 28

Figure 21. Measured analyte concentrations for forced air furnace CF03 with PG&E line gas (F042). 28

Figure 22. Experimental apparatus installed for central furnace CF04. 31

Figure 23. Installation of sample probes for CF04. 32

Figure 24. Pollutant sampling configuration for central furnace CF04. 33

Figure 25. Measured analyte concentrations for forced air furnace CF04 with PG&E line gas (F043). 36

Figure 26. Measured analyte concentrations for forced air furnace CF04 with fuel 1C (F044). 36

Figure 27. Measured analyte concentrations for forced air furnace CF04 with fuel 3C (F045). 37

Figure 28. Measured analyte concentrations for forced air furnace CF04 with PG&E line gas (F046). 37

Figure 29.Experimental apparatus installed for wall furnace WF01. 40

Figure 30. Experimental apparatus installed for wall furnace WF01. 41

Figure 31. Sampling probes installed in wall furnace WF01. 42

Figure 32. Gas meter and cylinder of simulated LNG installed for wall furnace WF01. 42

Figure 33. Pollutant sampling configuration for wall furnace WF01. 43

Figure 34. Measured analyte concentrations for wall furnace WF01 with PG&E line gas (F025). 46

Figure 35. Size-resolved number concentrations of particles larger than 0.1 μm for experiment F025 (Lasair data). 46

Figure 36. Measured analyte concentrations for wall furnace WF01 with fuel 3C (F026). 47

Figure 37. Size-resolved number concentrations of particles larger than 0.1 μm for experiment F026 (Lasair data). 47

Figure 38. Measured analyte concentrations for wall furnace WF01 with fuel 1C (F027). 48

Figure 39. Size-resolved number concentrations of particles larger than 0.1 μm for experiment F027 (Lasair data). 48

List of Tables

Table 1. Appliance and burner information. 1

Table 2. Interchangeability experiments for central forced air furnace CF01 1

Table 3. Fuel analysis for interchangeability experiments with central forced air furnace CF01 2

Table 4. Burner operating intervals for experiments with central forced air furnace CF01. 3

Table 5. Burner operating parameters for experiments with central forced air furnace CF01. 4

Table 6. Analyte ranges and calibration levels for experiments with central forced air furnace CF01. 4

Table 7. Aerosol instrumentation used for central forced air furnace CF01. 5

Table 8. Other measurements for experiments with central forced air furnace CF01. 5

Table 9. Environmental conditions[1] (combustion air) for experiments with central forced air furnace CF01. 6

Table 10. Sampling system conditions for experiments with central forced air furnace CF01. 6

Table 11. Preliminary results for central forced air furnace CF01: calculated air-free concentrations (using CO_2) over 2 min of operation at low firing rate, during each burn. 8

Table 12. Preliminary results for central forced air furnace CF01: calculated air-free concentrations (using CO_2) over 2 min of operation at high firing rate, during each burn. 9

Table 13. Preliminary results for central forced air furnace CF01: calculated emission rates over entirety of each burn. 9

Table 14. Appliance and burner information. 10

Table 15. Interchangeability experiments for central forced air furnace CF02 10

Table 16. Fuel analysis for interchangeability experiments with central forced air furnace CF02. 11

Table 17. Analyte ranges and calibration levels for experiments with central forced air furnace CF02. 12

Table 18. Aerosol instrumentation used for central forced air furnace CF02. 13

Table 19. Other measurements for experiments with central forced air furnace CF02. 13

Table 20. Burner operating parameters for experiments with central furnace CF02.[1] 14

Table 21. Environmental conditions[1] (combustion intake air) for experiments with central forced air furnace CF02. 15

Table 22. Sampling system conditions for experiments with central forced air furnace CF02. 15

Table 23. Preliminary results for central forced air furnace CF02: calculated air-free concentrations (using CO_2) over the last 5 min of operation, during each burn. 19

Table 24. Preliminary results for central forced air furnace CF02: calculated emission rates over entirety of each burn. 19

Table 25. Appliance and burner information. 20

Table 26. Interchangeability experiments for central forced air furnace CF03 20

Table 27. Fuel analysis for interchangeability experiments with central forced air furnace CF03. 21

Table 28. Analyte ranges and calibration levels for experiments with central forced air furnace CF03. 24

Table 29. Aerosol instrumentation used for central forced air furnace CF03. 25

Table 30. Other measurements for experiments with central forced air furnace CF03. 25

Table 31. Burner operating parameters for experiments with central furnace CF03. 26

Table 32. Combustion air conditions[1] for experiments with central furnace CF03. 26

Table 33. Sampling system conditions for experiments central furnace CF03. 26

Table 34. Formaldehyde samples for experiments with central furnace CF03. 26

Table 35. A. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, CF03. 29

Table 36. B. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, CF03. 29

Table 37. A. Calculated emission rates over entirety of each burn for central furnace CF03. 29

Table 38. B. Calculated emission rates over entirety of each burn for central furnace CF03. 29

Table 39. Appliance and burner information. 30

Table 40. Interchangeability experiments for central forced air furnace CF04 30

Table 41. Fuel analysis for interchangeability experiments with central forced air furnace CF04. 31

Table 42. Analyte ranges and calibration levels for experiments with central forced air furnace CF04. 33

Table 43. Aerosol instrumentation used for central forced air furnace CF04. 34

Table 44. Other measurements for experiments with central forced air furnace CF04. 34

Table 45. Burner operating parameters for experiments with central furnace CF04. 35

Table 46. Combustion air conditions[1] for experiments with central furnace CF04. 35

Table 47. Sampling system conditions for experiments central furnace CF04. 35

Table 48. Formaldehyde samples for experiments with central furnace CF04. 35

Table 49. A. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, central furnace CF04. 38

Table 50. B. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, central furnace CF04. 38

Table 51. A. Calculated emission rates over entirety of each burn for central furnace CF04..... 38

Table 52. B. Calculated emission rates over entirety of each burn for central furnace CF04. 38

Table 53. Appliance and burner information. 39

Table 54. Interchangeability experiments for wall furnace WF01. 39

Table 55. Fuel analysis for interchangeability experiments with wall furnace WF01. 40

Table 56. Analyte ranges and calibration levels for experiments with wall furnace WF01. 43

Table 57. Aerosol instrumentation used for wall furnace WF01. 44

Table 58. Other measurements for experiments with wall furnace WF01. 44

Table 59. Burner operating parameters for experiments with wall furnace WF01. 45

Table 60. Environmental conditions[1] (outdoor air) for experiments with wall furnace WF01; burner is direct vent and thus draws combustion air from outdoors. 45

Table 61. Sampling system conditions for experiments with wall furnace WF01. 45

Table 62. Preliminary results for wall furnace WF01: calculated air-free concentrations (using CO_2) over the last 5 min of operation, during each burn. 49

Table 63. Preliminary results for wall furnace WF01: calculated emission rates over entirety of each burn. 49

1.0 Central Furnace CF01

1.1. Experimental information for CF01

This was the first appliance tested with simulated LNG blends to evaluate interchangeability at a residence. Experiments were conducted on the same day with PG&E line gas (WN = 1348), fuel mix 1C (WN = 1390) and fuel 3C (WN = 1418). The aerosol inlet heater was manually set to match approximately the temperature at the sampling point in the flue; this was based on the temperature observed during the range finding run. The operational protocol for this furnace started with a longer (19-min) burn with a shorter (9-min) burn following. Subsequent furnace experiments started with a 10-min burn after which followed a 20-min burn. The abbreviated burns occurred because of the one-minute delay between the start of the inducer fan and burner ignition. This was observed to occur in the first experiment and it was incorporated for the other 2 experiments for consistency. PN and speciated NO_X (NO and NO_X by Thermo 42i) background concentrations were measured in the flue at times when there was no exhaust flow. Especially for PN, this may understate the true background concentrations in combustion supply air.

Table 1. Appliance and burner information.

Burner ID	CF01
Burner category	Central forced air furnace
Technology	Modern induced combustion furnace with direct vent; 2-stage burners; condensing
Appliance manufacturer	Carrier
Model	WeatherMaker Infinity - Ultra Efficiency (58-MVP060-F-15114)
Serial number	4901A11995
Manifold P (in. H_2O)	High: 3.2–3.8; Low: 1.3–1.7
Rated input (Btu/h)	High: 60,000; Low: 39,000
Rated output (Btu/h)	High: 56,000; Low: 36,000
AFUE rating	94%
Age	5 years at time of testing (installed 2002)
Test location	As installed on ground floor garage of residence
History notes	Unit installed in 2002 (manufactured in Dec, 2001 based on serial #)

Table 2. Interchangeability experiments for central forced air furnace CF01.

Exp.	Fuel	Date	Burner operation
F011	PG&E	11/20/07	Start with purge burn.[1] Each experiment included a 19 min burn and a 9 min burn following cooling periods of approximately 20 min and 10 min, respectively (see table below).[2]
F012	1C	11/20/07	
F013	3C	11/20/07	

[1] The "purge" burn is used to flush the system and ensure that the first experimental burn uses the test fuel. A purge burn is conducted in all experiments, even those not involving fuel switching from previous experiments.
[2] The protocol calls for burns of 20 min and 10 min. For this furnace, the 1-minute of inducer fan operation was included in the burn interval; the burn period was extended by this minute for subsequent furnace experiments.

Table 3. Fuel analysis for interchangeability experiments with central forced air furnace CF01.

Expt. ID	Fuel ID	Sample ID	C_1 (%)	C_2 (%)	C_3 (%)	C_{4+} (%)	N_2 (%)	CO_2 (%)	HHV[1] (Btu/scf)	Wobbe[1] number
F011	Line	Post	93.1%	3.88%	1.07%	0.32%	0.59%	1.08%	1046	1348
F012	1C	Pre	92.0%	7.96%	0.00%	0.00%	0.00%	0.00%	1070	1389
F012	1C	Post	91.9%	8.10%	0.00%	0.05%	0.00%	0.00%	1073	1391
F013	3C	15:27	86.7%	11.8%	1.56%	0.00%	0.00%	0.00%	1123	1418
F013	3C	15:35	86.8%	11.6%	1.54%	0.02%	0.00%	0.00%	1122	1417
F013	3C	16:36	86.6%	11.8%	1.56%	0.00%	0.00%	0.00%	1123	1418

[1] Calculated using the American Gas Association interchangeability program.
[2] Sample contaminated (distributed gas quality data requested from PG&E). Assumed values based on typical PG&E line gas as analyzed at LBNL; provided on interim basis for purposes of comparison.

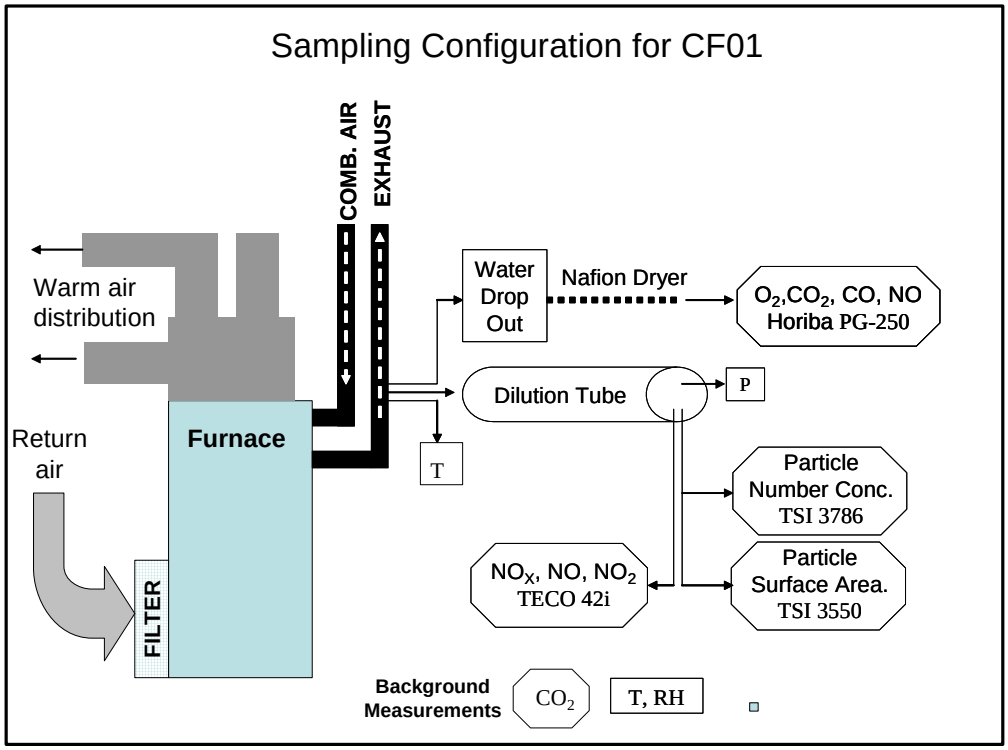

Figure 1. Pollutant sampling configuration for central furnace CF01.

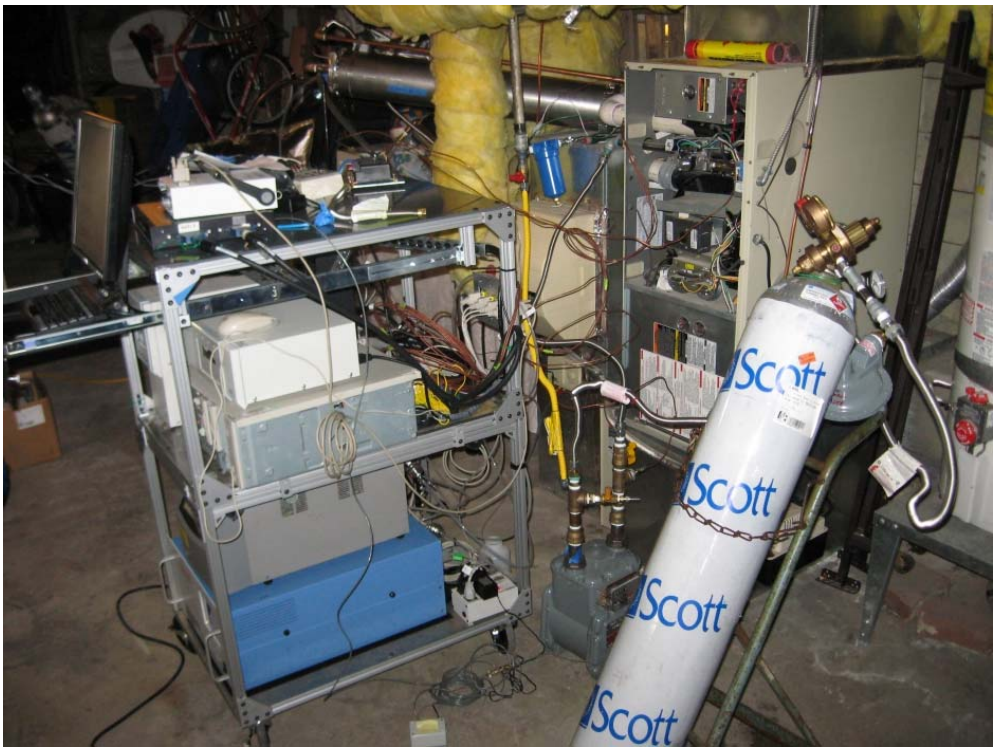

Figure 2. Experimental apparatus installed for central furnace CF01.
Shown in foreground are experimental cart with analytical instrumentation, gas meter (on floor), and cylinder containing simulated LNG. Dilution sampler is in background, behind furnace and duct.

Table 4. Burner operating intervals for experiments with central forced air furnace CF01.

Exp.	Complete burn times		
	Purge[1]	Burn 1	Burn 2
F011	11:06:00–11:09:40	11:31:50–11:50:50	12:01:40–12:10:40
F012	12:44:00–12:50:20	13:11:50–13:30:50	13:41:50–13:50:50
F013[2]	15:01:50–15:05:50	(a) 15:26:50–15:45:50 (b) 16:06:50–16:25:50	16:36:50–16:45:50

[1] The "purge" burn is used to flush fuel from the previous experiment. The purge burn for F012 included a burn from 12:36:50 to 12:41:20. The initial purge burn for F013 was from 15:01:50 to 15:05:05.
[2] In experiment F013, the first sample burn was repeated because particle number concentration data (CPC) were not recorded. The replicate Burn 1 included a 20+ min waiting period following the first Burn 1.

Table 5. Burner operating parameters for experiments with central forced air furnace CF01.

Exp.	Time at each firing rate (min:sec)[1]		Fuel flow rate[2] ($ft^3\ h^{-1}$)		Firing rate[2] (kBtu/h)		Manifold pressure (in. H_2O)	
	Low	High	Low	High	Low	High	Low	High
F011, B1	16:30	2:50	36.4	57.2	38.0	59.8	1.46	3.49
F011, B2	7:30	1:40	36.0	57.6	37.7	60.2	1.43	3.47
F012, B1	16:30	2:40	36.4	56.3	39.0	60.3	1.40	3.49
F012, B2	7:30	1:40	35.2	54.0	37.7	57.9	1.39	3.41
F013, B1a[3]	16:30	2:50	34.5	55.1	38.8	61.8	1.42	3.41
F013, B1b[3]	7:30	11:40	35.2	54.5	39.5	61.2	1.42	3.41
F013, B2	-	9:00	-	54.7	-	61.4	-	3.39

[1] For most burns, burner first fired at low rate then switched and remained at high firing rate. In some cases, manifold pressure was at higher rate for 20 sec for ignition. Times shown for initial low firing rate include this period. Burner fired at high rate for entirety of F013, Burn 2

[2] Fuel flow rate ($ft^3\ h^{-1}$) calculated from fuel volume counts over period of burner operation at low or high firing; firing rate calculated from measured fuel flow rate and higher heating value from fuel composition.

[3] In experiment F013, the first sample burn was repeated because particle number concentration data (CPC) were not recorded. The replicate Burn 1 included a 20+ min waiting period following the first Burn 1.

Table 6. Analyte ranges and calibration levels for experiments with central forced air furnace CF01.

Analyte	**Sample location[1]**	**Equipment[2]**	**Range**	**Calibration levels**
Carbon dioxide (CO_2)	PVC exhaust duct	Horiba PG-250	0-20%	0, 10%
Oxygen (O_2)	PVC exhaust duct	Horiba PG-250	0-25%	0, 20.95%
Carbon monoxide (CO)	PVC exhaust duct	Horiba PG-250	0-1000 ppm	0, 500 ppm
Nitrogen oxide (NO)	PVC exhaust duct	Horiba PG-250	0-50 ppm	0, 50 ppm [3]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-10 ppm	0, 5.0 ppm (3)
Carbon dioxide (CO_2)	ambient air in laboratory[4]	PPSystems EGM-4	5000 ppm	factory calibrated; check at 507 ppm

[1] Sample air drawn from duct connected to outlet of hood through 3/8" Teflon tubing to gas manifold; analyzers sampled most directly from gas manifold.

[2] Horiba Environmental and Process Instruments, Irvine CA (environ.hii.horiba.com); Thermo Fisher Scientific, Waltham, MA (thermo.com); TSI Instruments, Shoreview, MN (tsi.com); PP Systems, Amesbury, MA (ppsystems.com).

[3] Intended calibration mixture of 4 ppm NO (4:1 dilution by gas divider of cylinder containing 20 ppm NO) gave reading of 2.5 ppm. Since instrument calibration does not drift this much, a problem with the mixture was assumed. Instrument response settings left in place from last calibration at 5.0 ppm on 11/1/07.

Table 7. Aerosol instrumentation used for central forced air furnace CF01.

Analyte	Instrument[1]	Configuration	Min. size (D_{50})[2]	Max. Conc.	Accuracy
Total particle number conc. (PN), # cm^{-3}	TSI 3786 ultrafine CPC	sample from dilution tube via 2.2 m × 0.48 cm ID conductive tubing[3]	2.5 nm	10^5 cm^{-3} single particle mode	±12%
Surface area of particles (SA) depositing in lung alveolar region[4]	TSI 3550 nanoparticle surface area monitor	sample from dilution tube via 2.2 m × 0.48 cm ID conductive tubing[3]	10 nm	10^5 um^2 cm^{-3}	±20% at 20-200 um^2 cm^{-3}

[1] TSI Instruments, Shoreview, MN (tsi.com). CPC = condensation particle counter. Detailed information provided in product literature.
[2] 50% detection. Ultrafine particles (UFP) are generally defined as having aerodynamic diameters <100 nm.
[3] Product 3001788, purchased from TSI.
[4] Monitor has settings available for tracheobronchial (TB) or alveolar (A) regions; specifications are provided for the alveolar option which is being used in this study.
[5] Product literature reports <10% coincidence loss at maximum recommended ambient concentration.

Table 8. Other measurements for experiments with central forced air furnace CF01.

Measured Quantity	Location(s)	Device(s)[1]
Fuel pressure	Attached to gas meter Pressure tap of furnace regulator	Model 264 transducer (Setra)
Fuel volume and flow rate to appliance during burner operation	Meter installed upstream of appliance; connected to local shut-off valve (PG&E line gas) or low pressure regulator and cylinder of simulated LNG.	AC-250-TC T-compensating dry gas meter with 1- and ¼-ft dials (American Meter) with pulse counter resolved to 0.1 ft^3; flow rate also checked by stopwatch.
Dilution sampler vacuum	Dilution tube	Setra Model 264 transducer
Temperature, combustion air	Inside garage with garage door open	Precision NTC thermistor (APT)
Relative humidity, combustion air	Inside garage with garage door open	Thermostet polymer based capacitance RH sensor (APT)
Temperature, exhaust	Alongside pollutant sampling location in exhaust duct	Thermocouple (K), probe, Omega KQSS-18E-12

[1] APT: Automated Performance Testing System, Energy Conservatory, Minneapolis, MN (energyconservatory.com); Setra: Boxborough, MA (setra.com); Riotronics: Engelwood, CO (riotronics.com); American Meter (americanmeter.com); obtained via Miners & Pisani, San Leandro, CA; Omega Engineering, Stamford, CT (omega.com).

1.2. Results for CF01

CO emissions were limited to a brief spike on ignition; steady concentrations at the end of each burn were at low ppm levels. PN concentrations during burner operation were generally lower than measured during periods without burner operation. A spike in PN concentrations occurred

before ignition and appears to be associated with the start of the inducer fan. The interpretation of this spike is unclear. NO_X and NO air-free concentrations (during steady burner firing) and full-burn emission rates each increased with fuel Wobbe number: NO_X and NO increased by approximately 10% between PG&E line gas and fuel 3C experiments. NO_X was overwhelmingly (~95%) in the form of NO. Full burn emission rates were <10 ng/J for CO, 34-37 ng/J for NO_X, and <1 $x10^4$ J^{-1} for PN.

Table 9. Environmental conditions[1] (combustion air) for experiments with central forced air furnace CF01.

Exp.	T, Burn 1 (°C)	T, Burn 2 (°C)	RH, Burn 1 (%)	RH, Burn 2 (%)
F011	17.4 ± 0.3	17.6 ± 0.1	57 ± <1	55 ± <1
F012	18.3 ± 0.2	18.4 ± 0.1	52 ± <1	49 ± <1
F013	18.4 ± 0.3	18.7 ± 0.2	46 ± <1	48 ± <1

[1] Mean ± standard deviation measured each burn.

Table 10. Sampling system conditions for experiments with central forced air furnace CF01.

Exp.	Exhaust sample location T (°C) [1]		Dilution Ratio (2 burns)[2]	
	Burn 1	Burn 2	Burn 1	Burn 2
F011	19.9 ± 0.8	20.9 ± 0.2	16.2	15.3
F012	21.1 ± 0.5	21.7 ± 0.1	16.0	15.6
F013	20.9 ± 0.7	34.3 ± 9.3	16.5	16.2

[1] Mean ± standard deviation over each burn

[2] Calculated by comparing NO measured in gas manifold (PG-250) and dilution sampler (Thermo 42i) over entirety of each burn.

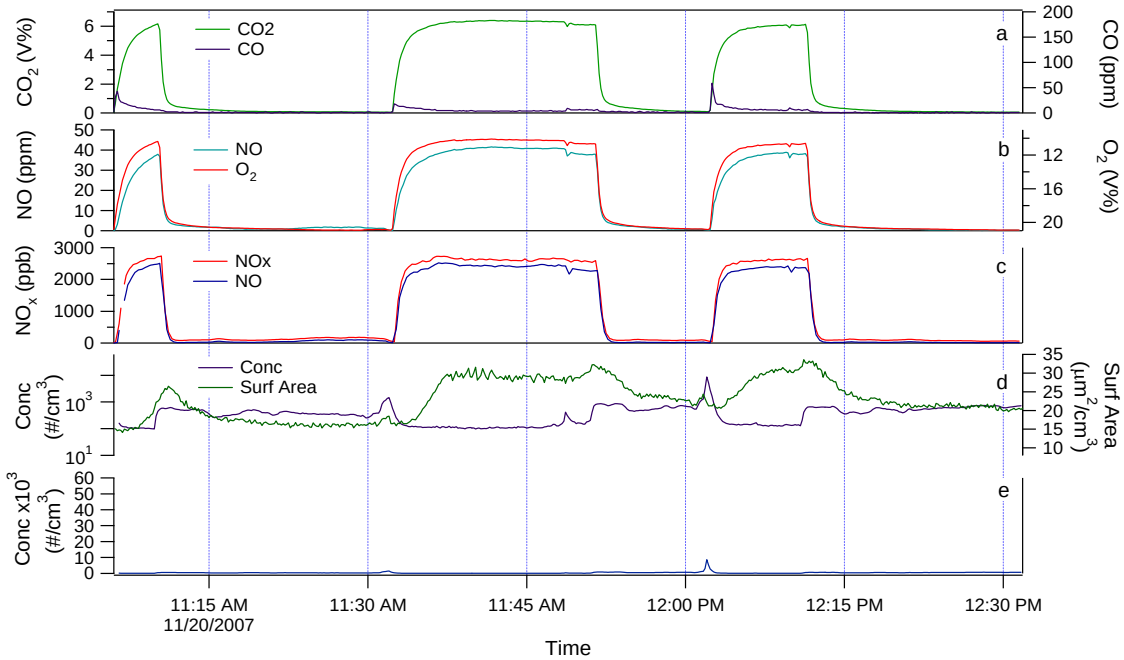

Figure 3. **Measured analyte concentrations for forced air furnace CF01 with PG&E line gas (F011).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(d) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

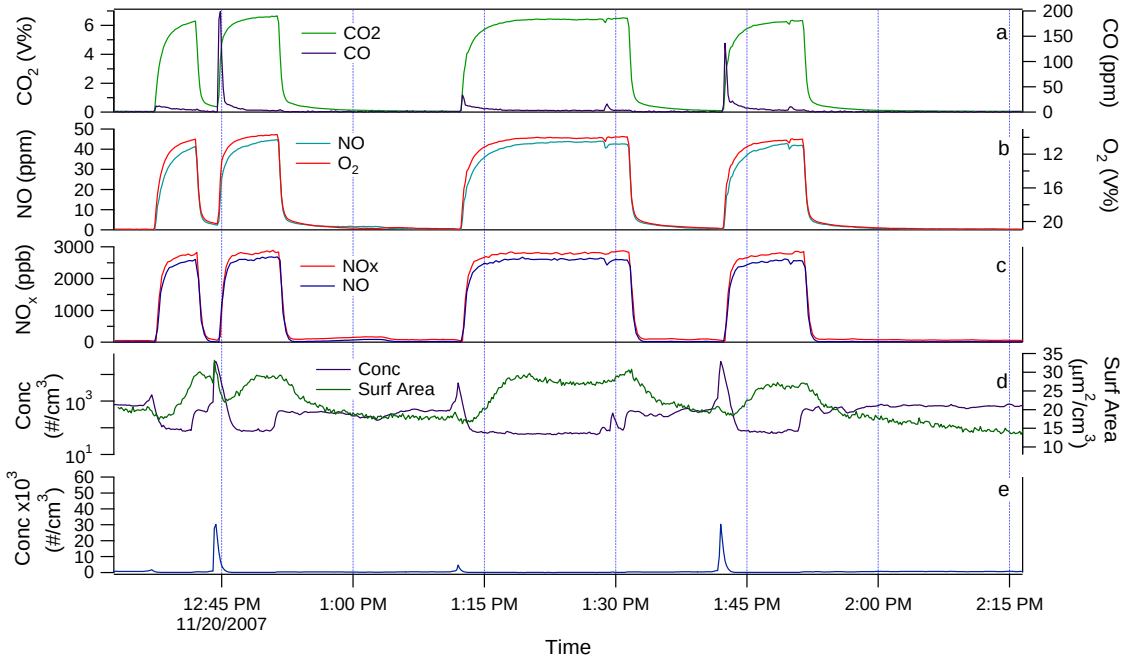

Figure 4. **Measured analyte concentrations for forced air furnace CF01 with fuel 1C (F012).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(d) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

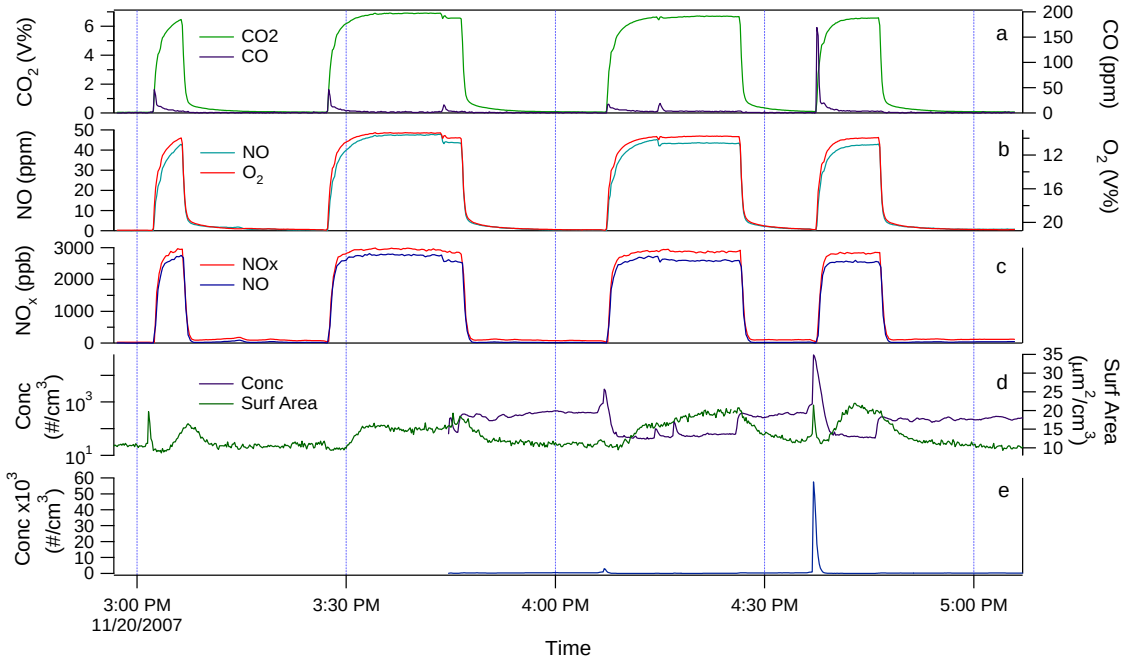

Figure 5. **Measured analyte concentrations for forced air furnace CF01 with fuel 3C (F013).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(d) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

Table 11. Preliminary results for central forced air furnace CF01: calculated air-free concentrations (using CO_2) over 2 min of operation at <u>low firing rate</u>, during each burn.

Exp.:	F011		F012		F013	
Fuel:	PG&E		1C		3C	
Wobbe:	1348		1390		1418	
CO, ppm	6	13	4	11	2	7
PG-250 NO, ppm	76	73	81	78	83	80
NO_X, ppm	80	79	85	84	87	84
NO, ppm	76	73	81	79	83	80
NO_2, ppm	4.2	5.5	4.3	5.5	4.1	4.6
PN, 10^5 cm^{-3}	-0.1	-0.1	-0.2	-0.2	-0.0	-0.0

Table 12. Preliminary results for central forced air furnace CF01: calculated air-free concentrations (using CO_2) over 2 min of operation at high firing rate, during each burn.

Exp.:	F011		F012		F013	
Fuel:	PG&E		1C		3C	
Wobbe:	1348		1390		1418	
CO, ppm	8	11	7	9	5	4
PG-250 NO, ppm	75	74	80	79	81	78
NO_X, ppm	81	80	85	85	87	85
NO, ppm	75	74	80	80	82	78
NO_2, ppm	5.9	5.8	5.5	5.7	5.4	7.0
PN, 10^5 cm^{-3}	-0.1	-0.1	-0.2	-0.2	-0.0	-0.0

Table 13. Preliminary results for central forced air furnace CF01: calculated emission rates over entirety of each burn.

Exp.:	F011		F012		F013	
Fuel:	PG&E		1C		3C	
Wobbe:	1348		1390		1418	
CO, μg KJ^{-1}	3	5	2	6	2	2
PG-250 NO, μg KJ^{-1}	31.7	30.9	34.5	34.0	35.3	34.2
NO_X, μg KJ^{-1}	34.0	33.5	36.8	36.8	37.4	37.0
NO, μg KJ^{-1}	31.8	31.0	34.5	34.1	35.4	34.3
NO_2, μg KJ^{-1}	2.2	2.5	2.2	2.7	2.0	2.8
PN, 10^7 KJ^{-1}	-0.2	0.0	-0.3	0.8	-0.1	0.0

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2.0 Central Furnace CF02

2.1. Experimental information for CF02

This was the second central furnace tested at a residence with simulated LNG blends to evaluate interchangeability. Experiments were conducted on the same day with PG&E line gas (WN = 1337), fuel mix 1C (WN = 1390) and fuel 3C (WN = 1418). The furnace is located in a crawl space with height (floor to bottom of joists) <6 feet. The ground surface underneath the furnace is unpaved, i.e. open dirt. The furnace burners are open, in-shot with local air intake. Sampling occurred in an enclosed flue duct, several feet away from the furnace. The operational protocol for this furnace started with a 10-min burn after which followed a 20-min burn. The burner was controlled by manually connecting wires to close the thermostat control circuit. The burner fired at a lower rate throughout the first burn then at a higher rate throughout most of the second burn. The lower rate was about 60% of the rated capacity and the higher rate was about 90% of capacity. PN and speciated NO_X (NO and NO_X by Thermo 42i) background concentrations were measured in the flue at times when there was no exhaust flow. Especially for PN, this may understate the true background concentrations in combustion supply air. The aerosol inlet heater was manually set to match approximately the temperature at the sampling point in the flue; this was based on the temperature observed during the range finding run.

Table 14. Appliance and burner information.

Burner ID	CF02
Burner category	Central forced air furnace
Technology	Modern induced combustion furnace with 4 inshot burners and local air intake; two-stage; non-condensing
Appliance manufacturer	Carrier
Model	WeatherMaker 8000VS (model 58UXV080-16)
Serial number	3799A13719
Manifold P (in. H_2O)	3.2–3.8
Rated input (Btu/h)	80,000
Rated output (Btu/h)	65,000
AFUE rating	80%
Age	4 years at time of testing; (installed in 2003)
Test location	As installed on ground floor garage of residence
History notes	Homeowner reports installation in 2003 (home purchased in 2002); unit manufactured in 1999 based on serial #.

Table 15. Interchangeability experiments for central forced air furnace CF02.

Exp.	Fuel	Date	Burner operation
F019	PG&E	11/28/07	Start with purge burn.[1] Two experimental burns. Burn 1 started 10 min after purge and lasted for 10 min duration. Burn 2 started 20 min after Burn 1 and lasted for 20 min duration.
F020	1C	11/28/07	
F021	3C	11/28/07	

[1] The "purge" burn is used to flush the system and ensure that the first experimental burn uses the test fuel. A purge burn is conducted in all experiments, even those not involving fuel switching from previous experiments.

Table 16. Fuel analysis for interchangeability experiments with central forced air furnace CF02.

Expt. ID	Fuel ID	Sample ID	C_1 (%)	C_2 (%)	C_3 (%)	C_{4+} (%)	N_2 (%)	CO_2 (%)	HHV[1] (Btu/scf)	Wobbe[1] number
F019	PG&E	Post	95.5	2.35	0.26	0.07	1.01	0.80	1020	1337
F020[2]	1C	Cont.[2]	92.0	8.0	-	-	-	-	1071	1390
F021[2]	3C	Cont.[2]	86.5	12.0	1.57	-	-	-	1125	1419

[1] Calculated using the American Gas Association interchangeability program.
[2] Sample was contaminated by air entry in sample bag. Use mean composition of this fuel from other experiments.

Figure 6. Experimental apparatus installed for central furnace CF02.
Shown are the following: cart with analytical instrumentation and computer data acquisition system (center); blowers for dilution sampling system (bottom left); dilution sampling tube (back end visible just above and to left of computer display); gas meter (to right and behind cart). Exhaust samples were drawn from section of flue behind the instrumentation cart.

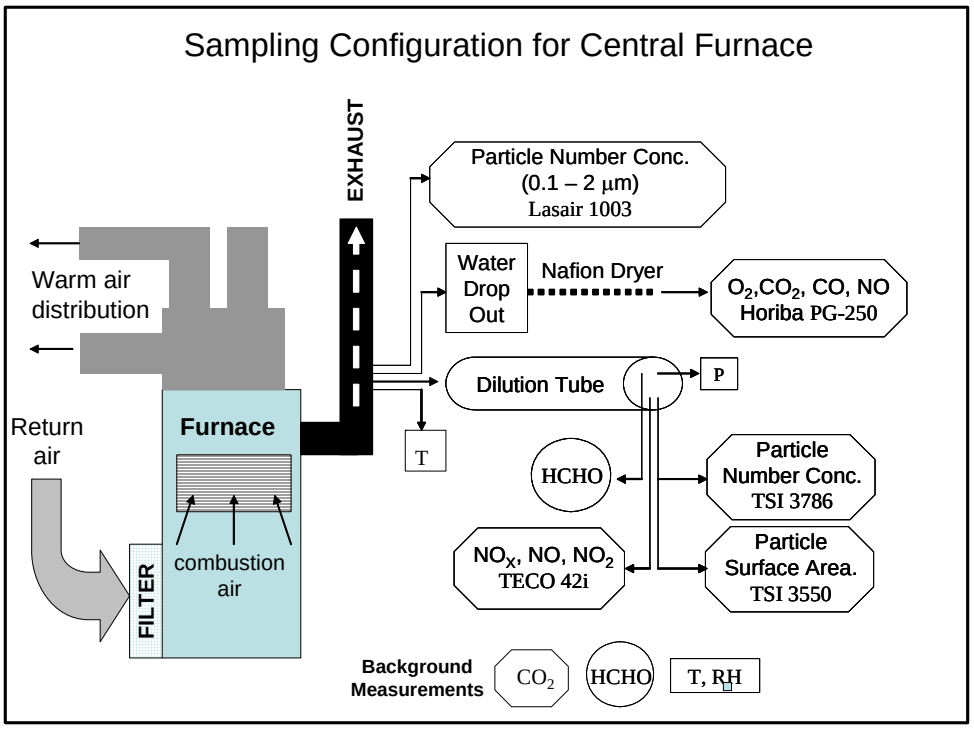

Figure 7. Pollutant sampling configuration for central furnace CF02.

Table 17. Analyte ranges and calibration levels for experiments with central forced air furnace CF02.

Analyte	Sample location[1]	Equipment[2]	Range	Calibration levels
Carbon dioxide (CO_2)	flue >4 ft from bend, Fig 1	Horiba PG-250	0-10%	0, 10%
Oxygen (O_2)	flue >4 ft from bend	Horiba PG-250	0-25%	0, 20.95%
Carbon monoxide (CO)	flue >4 ft from bend	Horiba PG-250	0-500 ppm	0, 500 ppm check 40 ppm[3]
Nitrogen oxide (NO)	flue >4 ft from bend	Horiba PG-250	0-50 ppm	0, 50 ppm check 2.5 ppm[4]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-5 ppm	0, 2.5 ppm
Carbon dioxide (CO_2)	basement air near furnace[4]	PPSystems EGM-4	5000 ppm	factory calibrated; check at 507 ppm

[1] Sample air drawn from duct connected to outlet of hood through 3/8" Teflon tubing to gas manifold; analyzers sampled most directly from gas manifold. [2] Horiba Environmental and Process Instruments, Irvine CA (environ.hii.horiba.com); Thermo Fisher Scientific, Waltham, MA (thermo.com); TSI Instruments, Shoreview, MN (tsi.com); PP Systems, Amesbury, MA (ppsystems.com). [3] Following calibration at 500 ppm, 40 ppm calibration bag gave reading of 43 ppm. [4] Calibrated from mixture of NO in N_2. Questionable reading using calibration bag prepared with gas divider; use instrument response setting from calibration at 50 ppm conducted on 11/20/07. 2.5 ppm calibration bag gave reading of 2.7 ppm.

Table 18. Aerosol instrumentation used for central forced air furnace CF02.

Analyte	Instrument[1]	Configuration	Min. size (D_{50})[2]	Max. Conc.	Accuracy
Total particle number conc. (PN), # cm^{-3}	TSI 3786 ultrafine CPC	sample from dilution tube via 2.2 m × 0.48 cm ID conductive tubing[3]	2.5 nm	10^5 cm^{-3} single particle mode	±12%
Surface area of particles (SA) depositing in lung alveolar region[4]	TSI 3550 nanoparticle surface area monitor	sample from dilution tube via 2.2 m × 0.48 cm ID conductive tubing[3]	10 nm	10^5 um^2 cm^{-3}	±20% at 20-200 um^2 cm^{-3}
Number conc. of particles 0.1-2.0 μm diameter	Lasair 1003 optical particle counter (OPC)	Sample direct from exhaust via ~2.5 m × 1.7 mm ID flexible copper tubing.	0.1 μm	1.4×10^4 cm^{-3}	<10%[5]

[1] TSI Instruments, Shoreview, MN (tsi.com). CPC = condensation particle counter. Detailed information provided in product literature. [2] 50% detection. Ultrafine particles (UFP) are generally defined as having aerodynamic diameters <100 nm. [3] Product 3001788, purchased from TSI. [4] Monitor has settings available for tracheobronchial (TB) or alveolar (A) regions; specifications are provided for the alveolar option which is being used in this study. [5] Product literature reports <10% coincidence loss at maximum recommended ambient concentration.

Table 19. Other measurements for experiments with central forced air furnace CF02.

Measured Quantity	Location(s)	Device(s) [1]
Fuel pressure	Attached to gas meter Pressure tap of furnace regulator	Magnehelic gauge; Model 264 transducer (Setra)
Fuel volume and flow rate to appliance during burner operation	Meter installed upstream of appliance; connected to local shut-off valve (PG&E line gas) or low pressure regulator and cylinder of simulated LNG	AC-250-TC T-compensating dry gas meter with 1- and ¼-ft dials (American Meter) with pulse counter resolved to 0.1 ft^3; flow rate also checked by stopwatch.
Dilution sampler vacuum	Dilution tube	Magnehelic gauge (early expts); Setra Model 264 transducer
Temperature, combustion air	Near air intake for furnace	Precision NTC thermistor (APT)
Relative humidity, combustion air	Near air intake for furnace	Thermostet polymer based capacitance RH sensor (APT)
Temperature, exhaust	Alongside pollutant sampling location in exhaust duct	Thermocouple (K), probe, Omega KQSS-18E-12

[1] APT: Automated Performance Testing System, Energy Conservatory, Minneapolis, MN (energyconservatory.com); Setra: Boxborough, MA (setra.com); Riotronics: Engelwood, CO (riotronics.com); American Meter (americanmeter.com); obtained via Miners & Pisani, San Leandro, CA; Omega Engineering, Stamford, CT (omega.com).

2.2. Results for CF02

CO emissions spiked on ignition then settled at a relatively stable level during each burn. For each fuel, CO emissions were higher during the high firing burn. Steady burn CO air-free concentrations were in the range of 80-90 ppm for the higher rate burns and in the range of 30-60

ppm during the lower firing rate burns. There was no clear CO trend with fuel Wobbe number. PN concentrations varied substantially during the course of most burns without any obvious trend associated with burner operation. There appeared to be PN concentration increases associated with researcher movement nearby to the furnace, potentially associated with large particle suspension from the unpaved ground / floor. The number concentrations of particles larger than 0.1 decreased during each burner firing (see Lasair data). We offer the possibility that larger particles suspended by movement were being converted in the flame to smaller particles. NO_X air-free concentrations and full-burn emission rates did not vary substantially among experiments. The non-NO fraction of NO_X (mostly NO_2) was substantially higher during the low firing rate burns compared with the high firing rate burns for each fuel. There was not a large change in the NO_2 emissions between fuels. Full burn emission rates were 16-31 ng/J for CO, 34-37 ng/J for NO_X, and 1-5 x10^4 J^{-1} for PN.

Table 20. Burner operating parameters for experiments with central furnace CF02.[1]

Exp.	Burn times			Fuel flow rate (ft^3 h^{-1}) [1,3]		Firing rate (kBtu/h) [1,3]		Manifold P (in. H_2O) [1,3]	
	Purge[2]	Burn 1[3]	Burn 2[4]	B1	B2	B1	B2	B1	B2
F019	13:29:30–13:30:40[3]	13:40:30–13:50:30	14:10:10–14:30:20	46.5	69.7	47.4	71.1	1.5	3.4
F020	14:44:30–14:46:40; 14:58:10–14:59:50[2]	15:12:30–15:22:40	15:42:50–16:03:00	48.8	66.2	49.8	67.5	1.5	3.5
F021	16:14:20–16:15:30	16:25:30–16:35:40	16:54:50–17:15:10	45.3	69.7	47.4	73.0	1.5	3.5

[1] Fuel flow rate (ft^3 h^{-1}) calculated from fuel use measured for each burn (by pulse counter) divided by time; firing rate calculated from calculated fuel flow rate and higher heating value from fuel composition. Fuel flow rate, firing rate and manifold pressure calculated over the final 5 min of each burn.

[2] The "purge" burn is used to flush fuel from the previous experiment. Two purge burns occurred during F020. Burners fired at the lower rate during F019 and F020 purges, but fired at the higher rate during the F021 purge.

[3] The burner operated at the low firing rate throughout the first burn of each experiment.

[4] During the second burn of each experiment, the burner initially fired at the low rate, then switched within 2-3 min to the higher firing rate and continued to fire at the higher rate through the second burn. The switch to higher firing rate occurred at the following times: F019, 14:12:30; F020, 15:44:20; F021, 14:50:20.

Table 21. Environmental conditions[1] (combustion intake air) for experiments with central forced air furnace CF02.

Exp.	T, Burn 1 (°C)	T, Burn 2 (°C)	RH, Burn 1 (%)	RH, Burn 2 (%)
F019	17.6 ± 0.2	18.4 ± 0.5	42 ± 1	43 ± 1
F020	18.1 ± 0.3	18.9 ± 0.5	43 ± 1	40 ± 1
F021	17.8 ± 0.1	17.7 ± 0.2	38 ± 2	37 ± 1

[1] Mean ± standard deviation measured from start of first burn through end of second burn.

Table 22. Sampling system conditions for experiments with central forced air furnace CF02.

Exp.	Exhaust sample location T (°C) [1]		Dilution Ratio (2 burns)[2]	
F019	103 ± 23	130 ± 28	12.2	14.5
F020	107 ± 23	136 ± 28	12.6	14.7
F021	108 ± 21	136 ± 28	12.8	14.7

[1] Mean ± standard deviation over last 5 min of each burn

[2] Calculated by comparing NO measured in gas manifold (PG-250) and dilution sampler (Thermo 42i) over entirety of each burn.

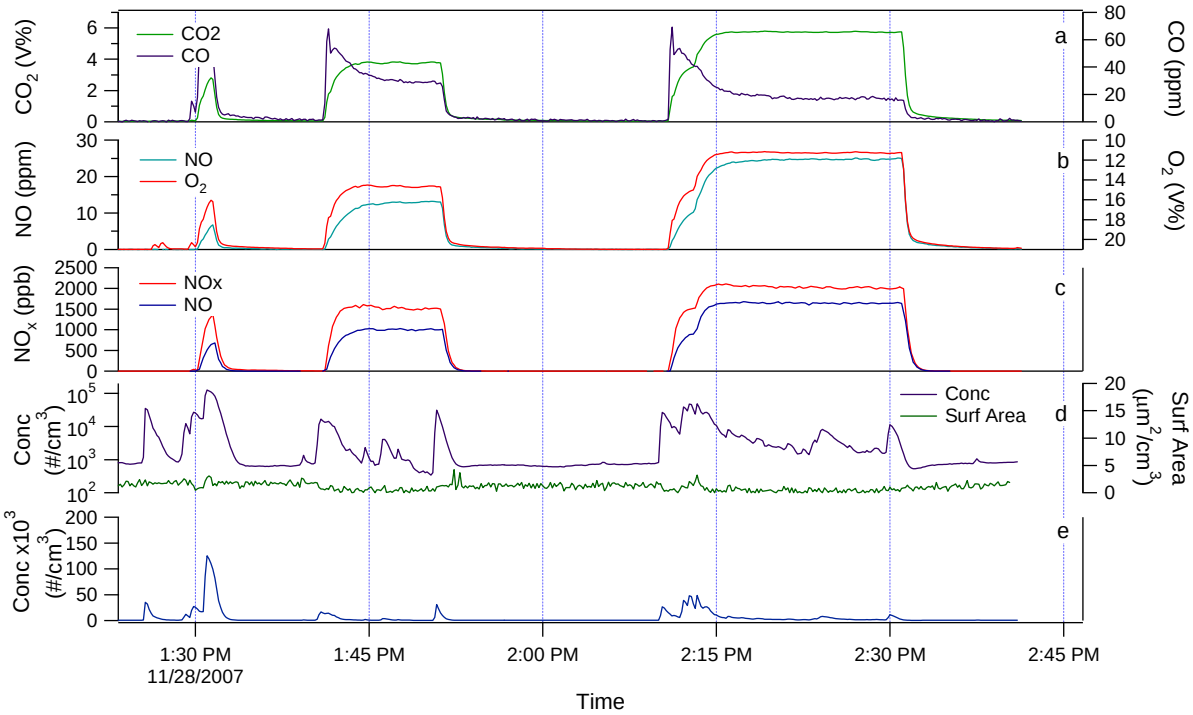

Figure 8. Measured analyte concentrations for central forced air furnace CF02 with PG&E line gas (F019). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(d) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

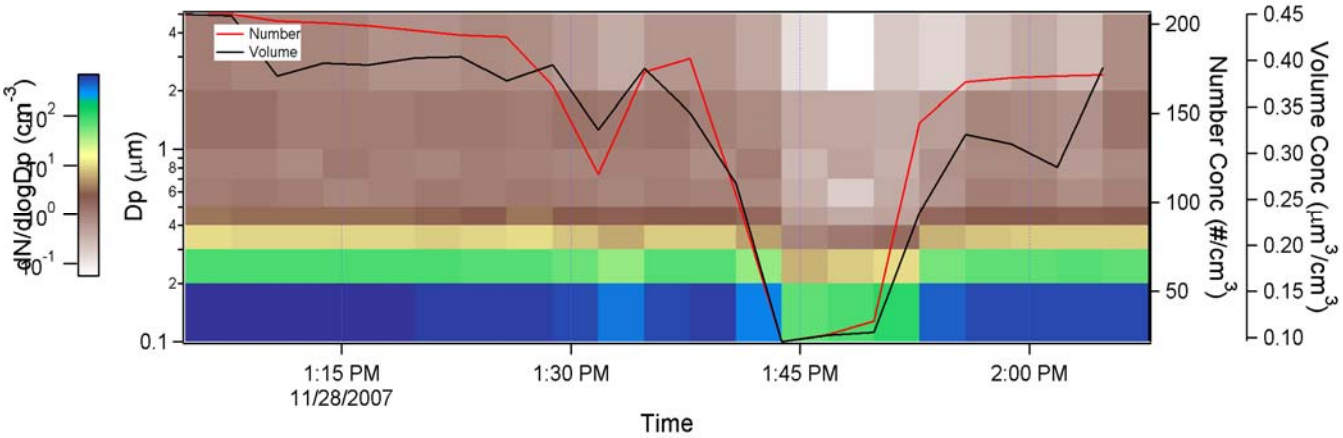

Figure 9. Size-resolved number concentrations of particles larger than 0.1 µm for experiment F019, Burn 1 (Lasair data).

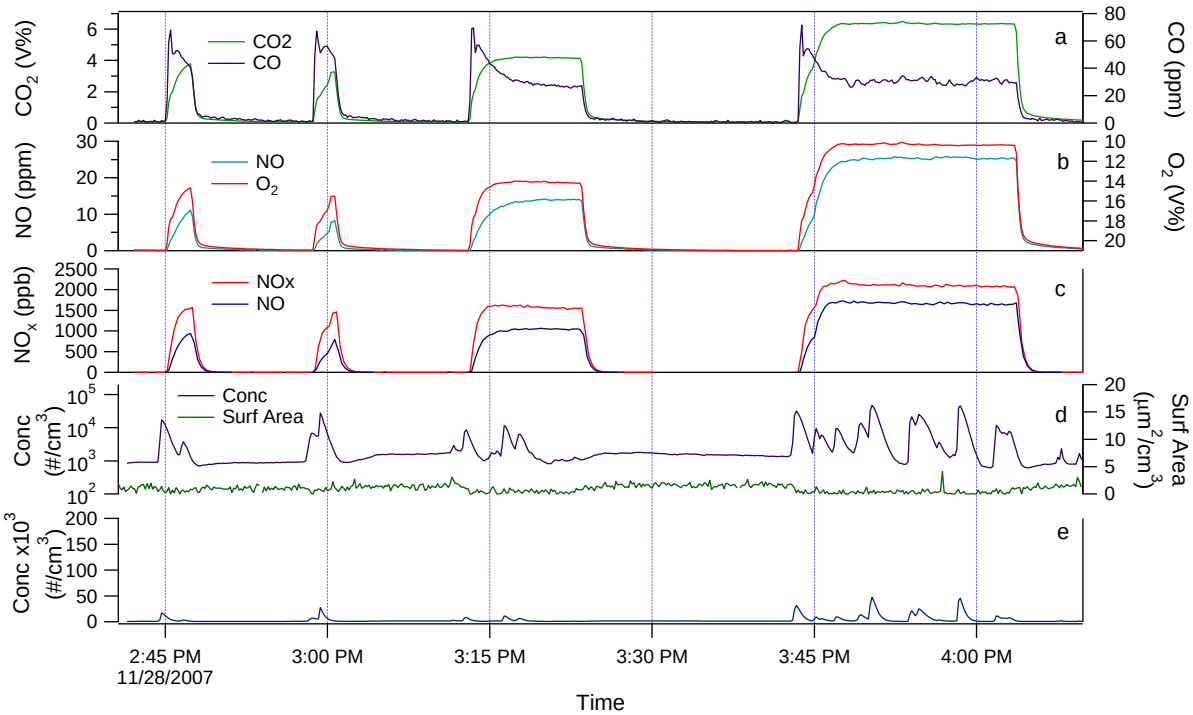

Figure 10. **Measured analyte concentrations for central forced air furnace CF02 with fuel 1C (F020).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(d) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

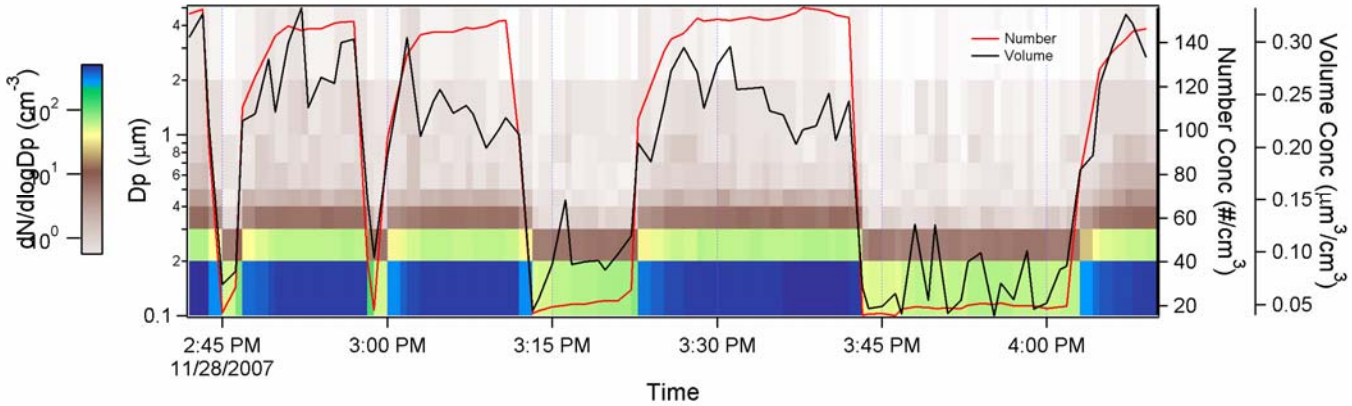

Figure 11. Size-resolved number concentrations of particles larger than 0.1 μm for experiment F020 (Lasair data).

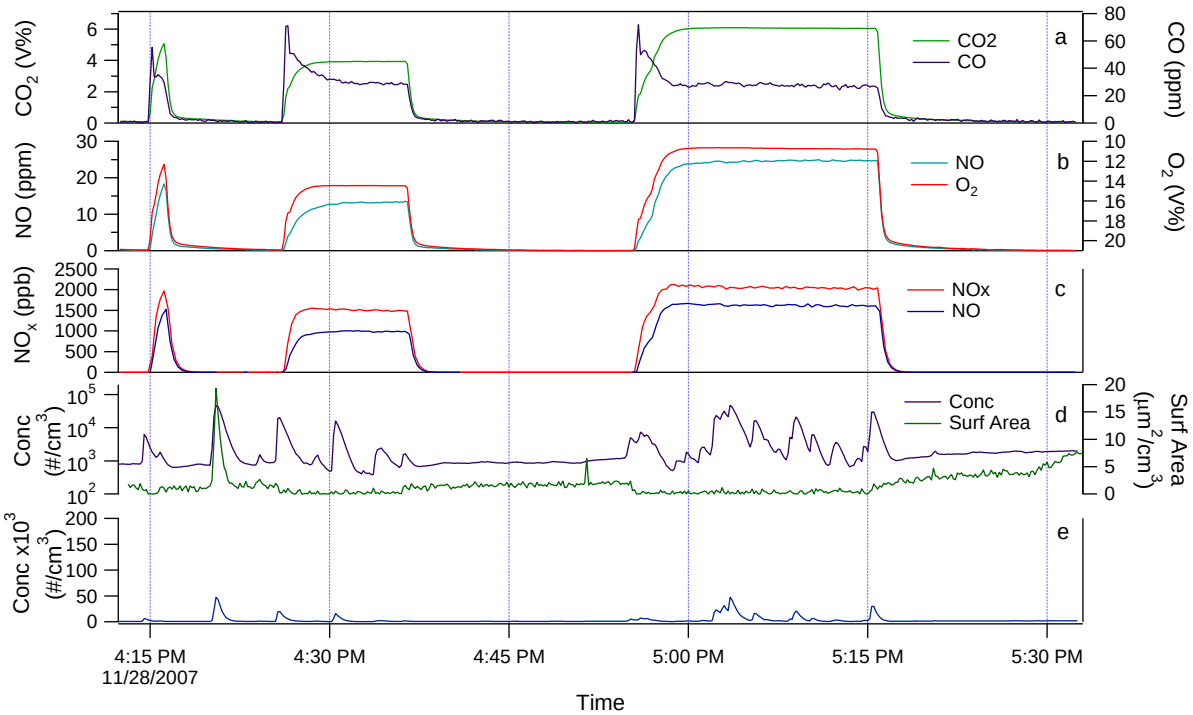

Figure 12. **Measured analyte concentrations for central forced air furnace CF02 with fuel 3C (F021).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(d) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

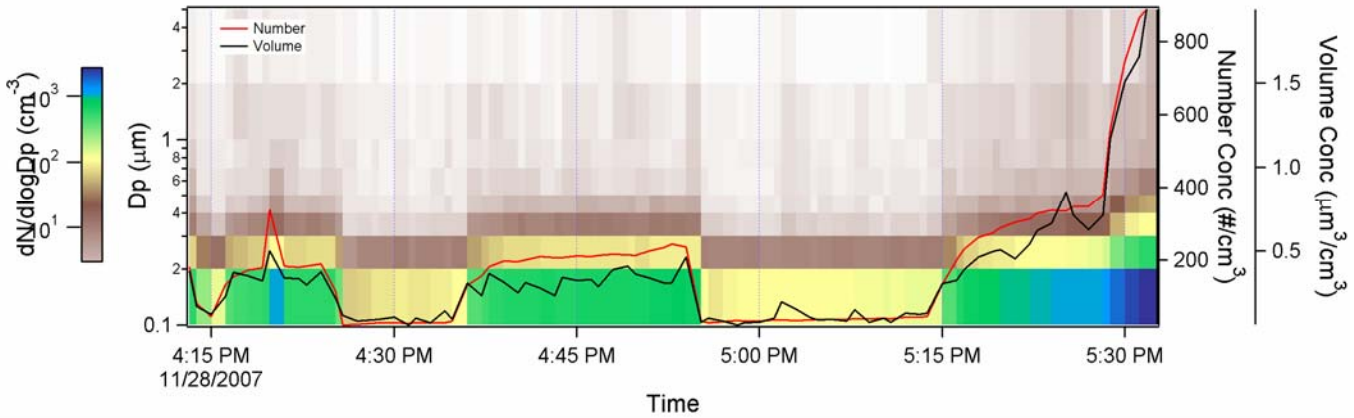

Figure 13. Size-resolved number concentrations of particles larger than 0.1 µm for experiment F021 (Lasair data). Increase at end of run may correspond to disconnection of Lasair from furnace flue.

Table 23. Preliminary results for central forced air furnace CF02: calculated air-free concentrations (using CO_2) over the last 5 min of operation, during each burn.

Exp.:	F019		F020		F021	
Fuel:	PG&E		1C		3C	
Wobbe:	1337		1390		1419	
	B1	B2	B1	B2	B1	B2
	Low	High	Low	High	Low	High
CO, ppm	92	34	79	57	86	51
PG-250 NO, ppm	41	51	40	48	40	49
NO_X, ppm	62	63	60	61	61	62
NO, ppm	41	52	40	48	40	49
NO_2, ppm	21	11.5	20	12.5	21	13.0
PN, 10^5 cm^{-3}	0.2	0.7	0.2	2.1	0.5	0.2

Table 24. Preliminary results for central forced air furnace CF02: calculated emission rates over entirety of each burn.

Exp.:	F019		F020		F021	
Fuel:	PG&E		1C		3C	
Wobbe:	1337		1390		1419	
CO, μg KJ^{-1}	31	13	28	17	28	16
PG-250 NO, μg KJ^{-1}	16.5	21.2	16.4	20.5	16.3	20.2
NO_X, μg KJ^{-1}	26.3	27.1	26.2	26.5	25.9	26.2
NO, μg KJ^{-1}	16.5	21.2	16.5	20.6	16.4	20.3
NO_2, μg KJ^{-1}	9.7	5.9	9.7	6.0	9.5	5.9
PN, 10^7 KJ^{-1}	3.5	5.5	1.0	4.9	1.5	3.8

3.0 Central Furnace CF03

3.1. Experimental information for CF03

This was the third central furnace tested at a residence with simulated LNG blends to evaluate interchangeability. Experiments were conducted on the same day with PG&E line gas (WN = 1329), fuel mix 1C (WN = 1390) and fuel 3C (WN = 1418); following the 3C experiment, a replicate experiment was conducted with PG&E line gas. The furnace is located in a crawl space with very limited access. The furnace burners are open, in-shot with local air intake. Sampling occurred in the vertical flue riser on the side of the house, approximately 4 m from the furnace. The operational protocol for this furnace started with a 10-min burn after which followed a 20-min burn. The burner was controlled by manually connecting wires to close the thermostat control circuit. The aerosol inlet heater was set to track the temperature at the sampling point in the flue. The sample transfer line from the dilution system to the aerosol analyzers (condensation particle counter and lung-depositing surface area monitor) was disconnected between the 3rd and 4th experiments to directly measure background concentrations of PN. In error, this connection remained open for the last experiment (F046); as a result, there are no PN results for F046. Speciated NO_X data for this experiment appear to be valid with the caveat that they are calculated based on the larger dilution ratio that resulted from an open port at the back end of the dilution tube.

Table 25. Appliance and burner information.

Burner ID	CF03
Burner category	Central forced air furnace
Technology	Modern induced combustion furnace with 3 inshot burners and local air intake; single-stage burner; non-condensing
Appliance manufacturer	Bryant
Model	373LAV036070
Serial number	3999A07194
Manifold P (in. H_2O)	3.2–3.8
Rated input (Btu/h)	69,000
Rated output (Btu/h)	56,000
AFUE rating	80%
Age	Installed in 1999
Test location	Vertical riser of flue, 4-5 m from furnace
History notes	Furnace was installed when current homeowner purchased residence.

Table 26. Interchangeability experiments for central forced air furnace CF03.

Exp.	Fuel	Date	Burner operation
F039	PG&E	3/12/08	Start with purge burn.[1] Two experimental burns. Burn 1 started 10 min after purge and lasted for 10 min duration. Burn 2 started 20 min after Burn 1 and lasted for 20 min duration.
F040	1C		
F041	3C		
F042	PG&E		

[1] The "purge" burn is used to flush the system and ensure that the first experimental burn uses the test fuel. A purge burn is conducted in all experiments, even those not involving fuel switching from previous experiments.

Table 27. Fuel analysis for interchangeability experiments with central forced air furnace CF03.

Expt. ID	Fuel ID	Sample ID	C_1 (%)	C_2 (%)	C_3 (%)	C_{4+} (%)	N_2 (%)	CO_2 (%)	HHV[1] (Btu/scf)	Wobbe[1] number
F039	PG&E	F039	95.8	2.12	0.20	0.07	1.10	0.75	1012	1329
F040	1C	F040	91.9	8.05	0.00	0.00	0.00	0.00	1071	1390
F041[2]	3C	cylinder	86.4	12.0	1.60				1125	1419

[1] Calculated using the American Gas Association interchangeability program.
[2] Sample collected during F041 was contaminated with air; values show are for composition in cylinder.

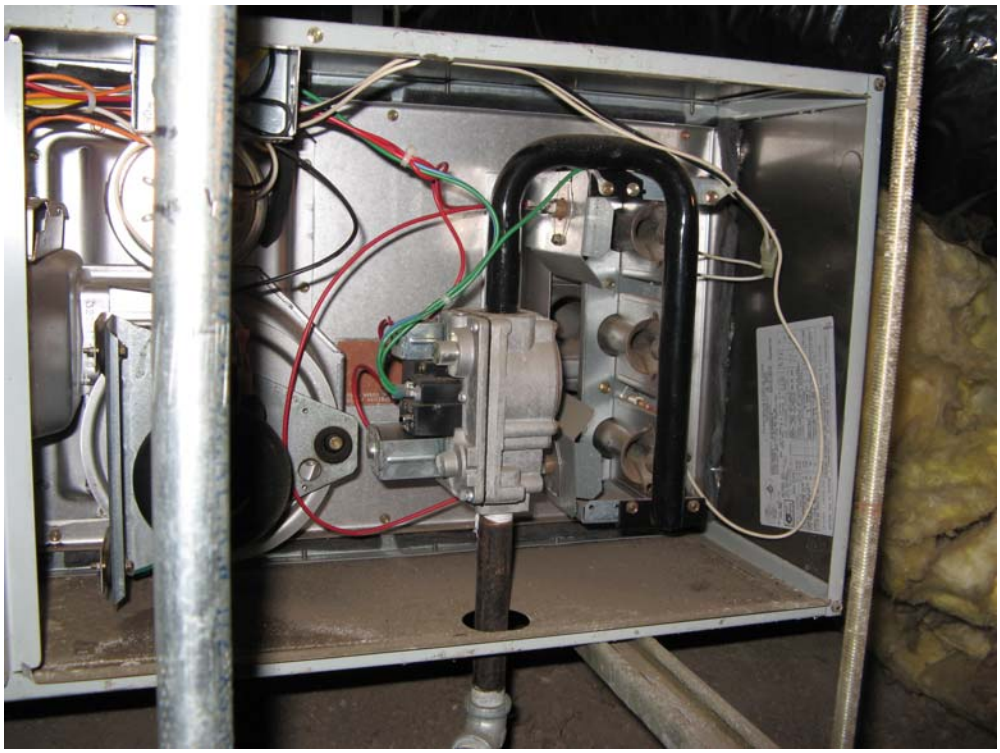

Figure 14. Central furnace CF03.

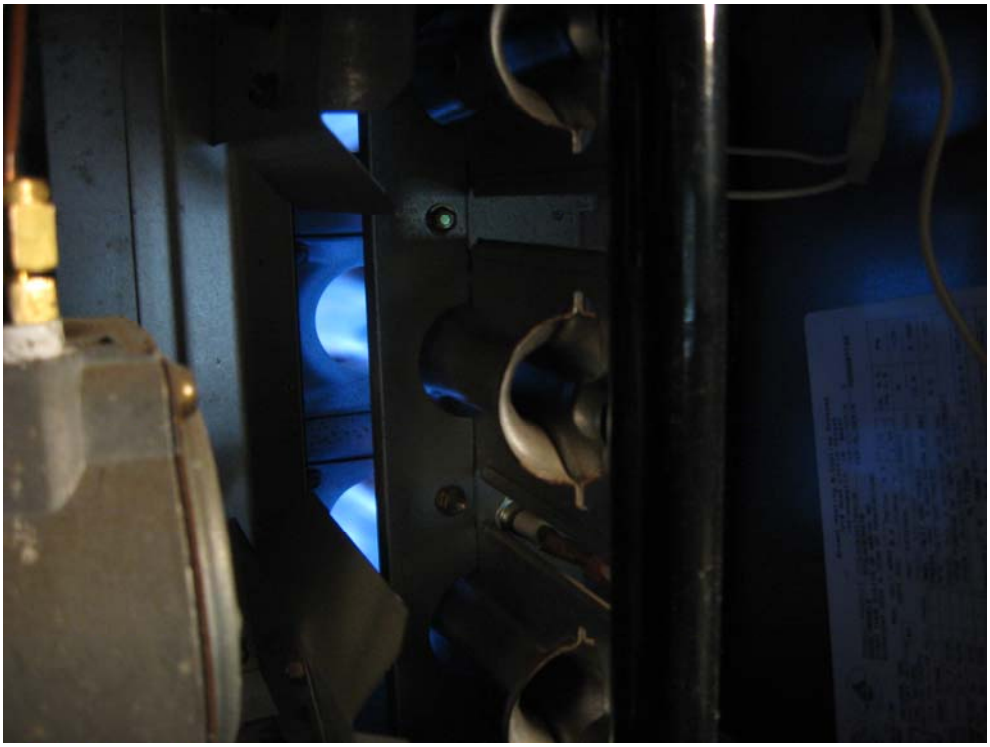

Figure 15. Burners of central furnace CF03, PG&E line gas.

Figure 16. Experimental apparatus installed for central furnace CF03.
Shown are cart with analytical instrumentation and computer data acquisition system (left); blowers for dilution sampling system (on ground, next to cart); dilution sampling tube (mounted on opposite side of ladder); and supply air conditioning filters for dilution system (mounted on ladder). Furnace is installed in crawl space of house.

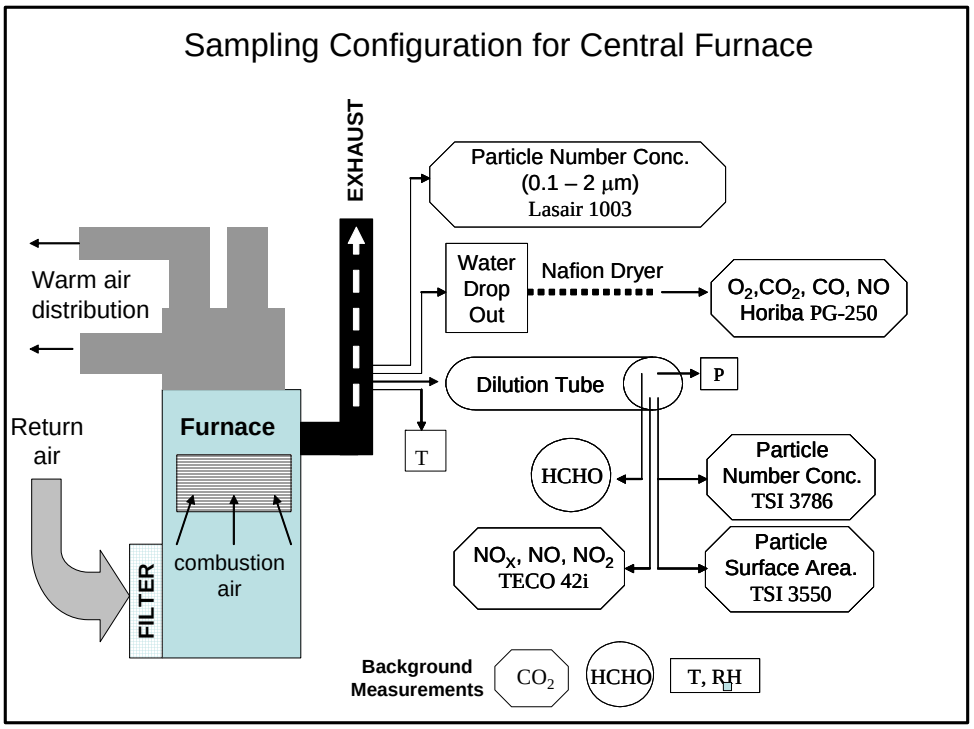

Figure 17. Pollutant sampling configuration for central furnace CF03.
Lasair was not used in these experiments.

Table 28. Analyte ranges and calibration levels for experiments with central forced air furnace CF03.

Analyte	Sample location[1]	Equipment[2]	Range	Calibration levels
Carbon dioxide (CO_2)	flue riser, >4 ft from bend	Horiba PG-250	0-10%	0, 10%
Oxygen (O_2)	flue riser, >4 ft from bend	Horiba PG-250	0-25%	0, 20.95% check 8%[3]
Carbon monoxide (CO)	flue riser, >4 ft from bend	Horiba PG-250	0-500 ppm	0, 350 ppm
Nitrogen oxides (NO_X)	flue riser, >4 ft from bend	Horiba PG-250	0-50 ppm	0, 20 ppm[4]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-5 ppm	0, 2.4 ppm[4]
Carbon dioxide (CO_2)	ambient air in laboratory[4]	PPSystems EGM-4	5000 ppm	factory calibrated; check at 507 ppm

[1] Sample air drawn from duct connected to outlet of hood through 3/8" Teflon tubing to gas manifold; analyzers sampled most directly from gas manifold. [2] Horiba Environmental and Process Instruments, Irvine CA (environ.hii.horiba.com); Thermo Fisher Scientific, Waltham, MA (thermo.com); TSI Instruments, Shoreview, MN (tsi.com); PP Systems, Amesbury, MA (ppsystems.com). [3] Instrument read 7.8% for mixture with 8% O_2 following calibration at 20.95%. [4] Calibrated from mixture of NO in N_2.

Table 29. Aerosol instrumentation used for central forced air furnace CF03.

Analyte	Instrument[1]	Configuration	Min. size (D_{50})[2]	Max. Conc.	Accuracy
Total particle number conc. (PN), # cm^{-3}	TSI 3786 ultrafine CPC	sample from dilution tube via 2.2 m × 0.48 cm ID conductive tubing[3]	2.5 nm	10^5 cm^{-3} single particle mode	±12%
Surface area of particles (SA) depositing in lung alveolar region[4]	TSI 3550 nanoparticle surface area monitor	sample from dilution tube via 2.2 m × 0.48 cm ID conductive tubing[3]	10 nm	10^5 um^2 cm^{-3}	±20% at 20-200 um^2 cm^{-3}

[1] TSI Instruments, Shoreview, MN (tsi.com). CPC = condensation particle counter. Detailed information provided in product literature. [2] 50% detection. Ultrafine particles (UFP) are generally defined as having aerodynamic diameters <100 nm. [3] Product 3001788, purchased from TSI. [4] Monitor has settings available for tracheobronchial (TB) or alveolar (A) regions; specifications are provided for the alveolar option which is being used in this study.

Table 30. Other measurements for experiments with central forced air furnace CF03.

Measured Quantity	Location(s)	Device(s) [1]
Fuel pressure	Attached to gas meter Pressure tap of furnace regulator	Model 264 transducer (Setra)
Fuel volume and flow rate to appliance during burner operation	Meter installed upstream of appliance; connected to local shut-off valve (PG&E line gas) or low pressure regulator and cylinder of simulated LNG	AC-250-TC T-compensating dry gas meter with 1- and ¼-ft dials (American Meter) with pulse counter resolved to 0.1 ft^3; flow rate also checked by stopwatch.
Dilution sampler vacuum	Dilution tube	Setra Model 264 transducer
Temperature, combustion air	Near air intake for furnace	Precision NTC thermistor (APT)
Relative humidity, combustion air	Near air intake for furnace	Thermostet polymer based capacitance RH sensor (APT)
Temperature, exhaust	Alongside pollutant sampling location in exhaust duct	Thermocouple (K), probe, Omega KQSS-18E-12

[1] APT: Automated Performance Testing System, Energy Conservatory, Minneapolis, MN (energyconservatory.com); Setra: Boxborough, MA (setra.com); Riotronics: Engelwood, CO (riotronics.com); American Meter (americanmeter.com); obtained via Miners & Pisani, San Leandro, CA; Omega Engineering, Stamford, CT (omega.com).

3.2. Results for CF03

Full burn emission rates were 9-21 ng/J for CO, 22-24 ng/J for NO_X, 0.2-0.4 ng/J for HCHO and 13-46 x10^4 J^{-1} for PN. NO was about 75-80% of total NO_X. There were no substantive changes in CO or NO_X as a function of fuel. End-of-burn and full-burn PN emissions were relatively consistent on the two burns for each fuel and there appears a clear trend of decreasing PN with increasing fuel WN. Full-burn PN emissions were 45 and 46 x10^4 J^{-1} with PG&E, 20 and 34 x10^4 J^{-1} with 1C (WN=1390) and 13 and 14 x10^4 J^{-1} with fuel 3C (WN = 1420). HCHO emission decreased with increasing fuel WN in rough proportions to the PN decrease. HCHO emissions (ng/J) were 0.58 with PG&E, 0.37 with 1C and 0.23 with fuel 3C.

Table 31. Burner operating parameters for experiments with central furnace CF03.

Exp.	Burn	Start time	End time	Fuel flow[1] ($ft^3\ h^{-1}$)	Firing rate[1] (kbtu/h)	Supply pressure (in. H_2O)	Appliance manifold P (in. H_2O)
F039	B1	11:24	11:33	64	65	5.9	3.2
	B2	11:53	12:13	64	65	5.9	3.3
F040	B1	12:57	13:07	64	69	7.3	3.2
	B2	13:27	13:47	63	68	7.1	3.4
F041	B1	14:08	14:17	61	69	7.2	3.2
	B2	14:38	14:57	62	70	7.3	3.4
F042	B1	15:16	15:25	63	63	6.8	2.2
	B2	15:46	16:06	64	64	6.2	1.6

[1] Fuel flow rate ($ft^3\ h^{-1}$) calculated from fuel use measured for each burn (by pulse counter) divided by time of burn; firing rate calculated from calculated fuel flow rate and higher heating value from fuel composition.

Table 32. Combustion air conditions[1] for experiments with central furnace CF03.

Exp.	Fuel	T (°C)	RH (%)
F039	PG&E	16.0 ± 0.5	75 ± 1
F040	1C	16.7 ± 0.6	74 ± 1
F041	3C	17.3 ± 0.7	73 ± 2
F042	PG&E	18.6 ± 0.3	68 ± 2

[1] Mean ± standard deviation of laboratory air conditions measured over period of two sampling burns.

Table 33. Sampling system conditions for experiments central furnace CF03.

Exp.	Sample Location T (°C)[1]		Dilution Ratio[2]	
	Burn 1	Burn 2	Burn 1	Burn 2
F039	103 ± 4	109 ± 0	14	13
F040	105 ± 4	110 ± 0	14	13
F041	107 ± 3	113 ± 0	14	14
F042	107 ± 3	111 ± 0	31[3]	30[3]

[1] Mean ± standard deviation measured during last 5 min of each burn.
[2] Calculated by comparing NO_X measured in gas manifold (PG-250) and dilution sampler (Thermo 42i) for each burn.
[3] Aerosol sampling line from dilution system not connected during this experiment; dilution tube was therefore open to atmosphere at back end.

Table 34. Formaldehyde samples for experiments with central furnace CF03.

Exp(s)	Location	Date	Sample start/end time		Air vol. (L)	Extract conc. (ng/μL)	Air conc.[1] (μg/m^3)
ALL	Bkg air	3/12/08	10:59	16:06	291	0.141	0.969
F039	Dilution Tube	3/12/08	11:22	12:14	48	0.683	28.256
F040			12:56	13:48	48	0.429	17.711
F041			14:06	14:58	49	0.279	11.441
F042			No sample taken				

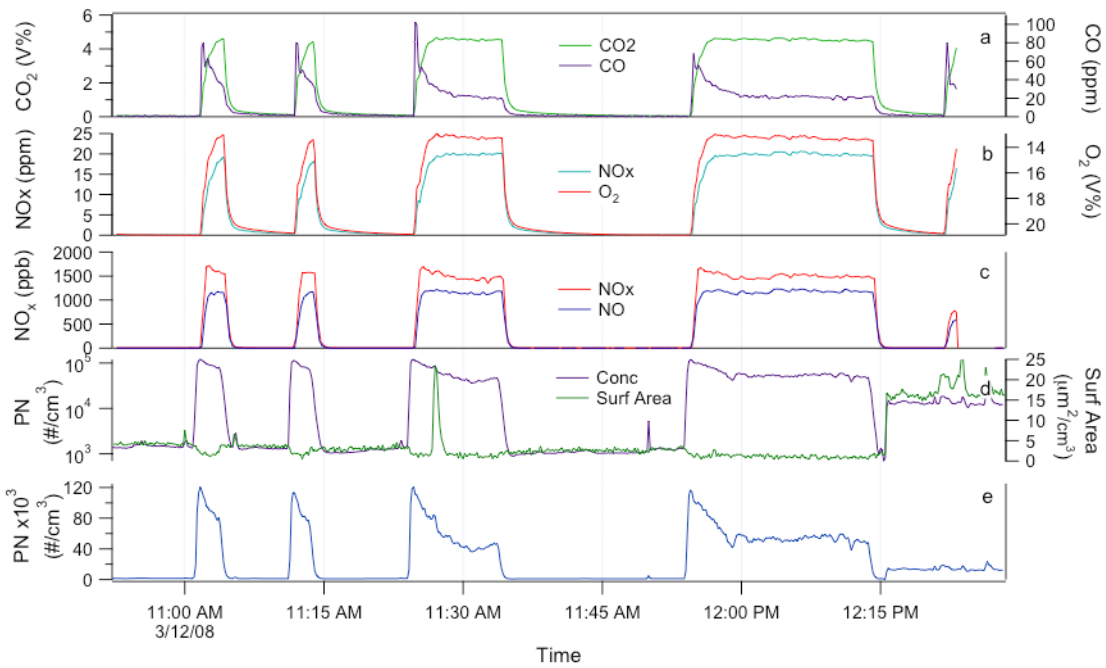

Figure 18. Measured analyte concentrations for forced air furnace CF03 with PG&E line gas (F039). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area. The peaks prior to Burn 1 are purge burns. Following Burn 2 the aerosol instruments sampled undiluted ambient air.

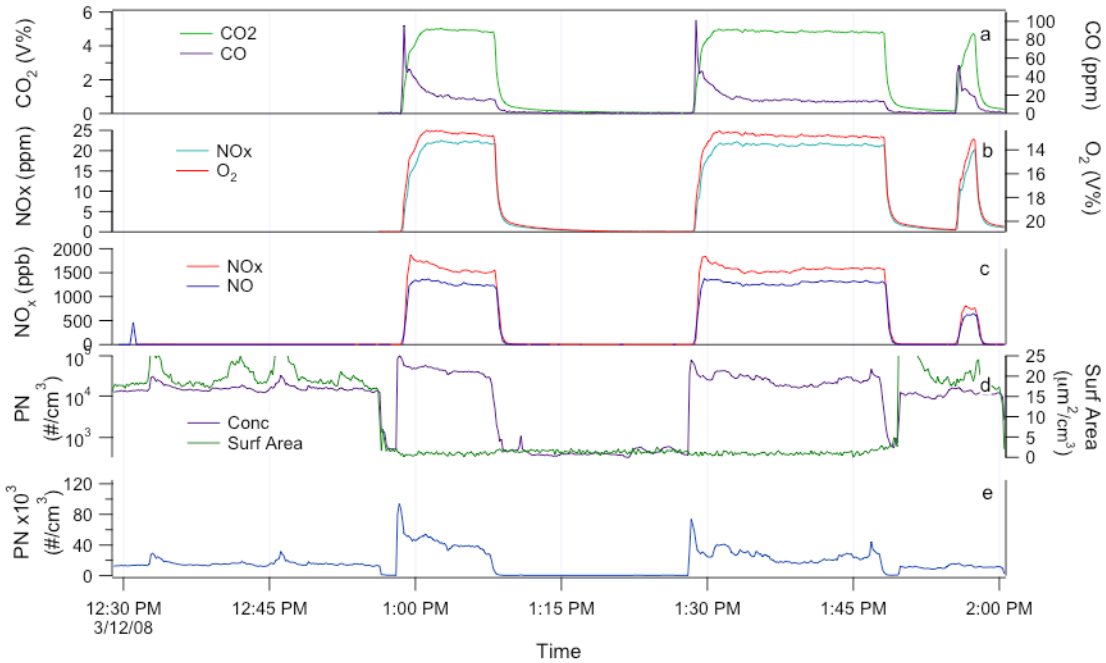

Figure 19. Measured analyte concentrations for forced air furnace CF03 with fuel 1C (F040). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area. Prior to Burn 1, the aerosol instruments sampled from undiluted ambient air.

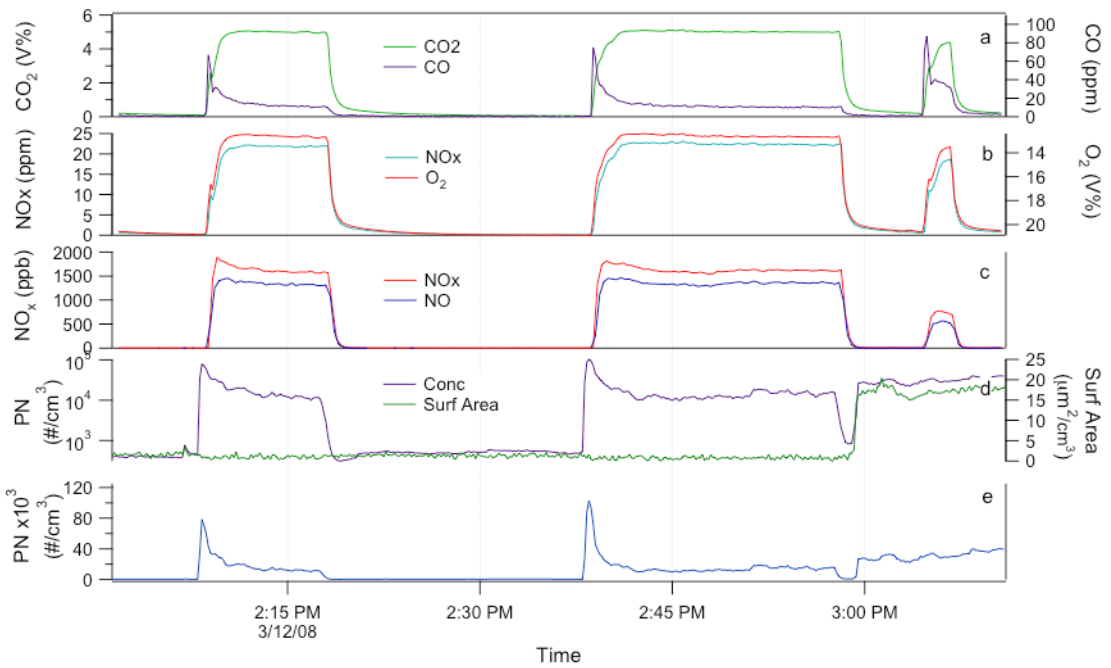

Figure 20. **Measured analyte concentrations for central forced air furnace CF03 with fuel 3C (F041).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area. Following Burn 2 the aerosol instruments sampled undiluted ambient air.

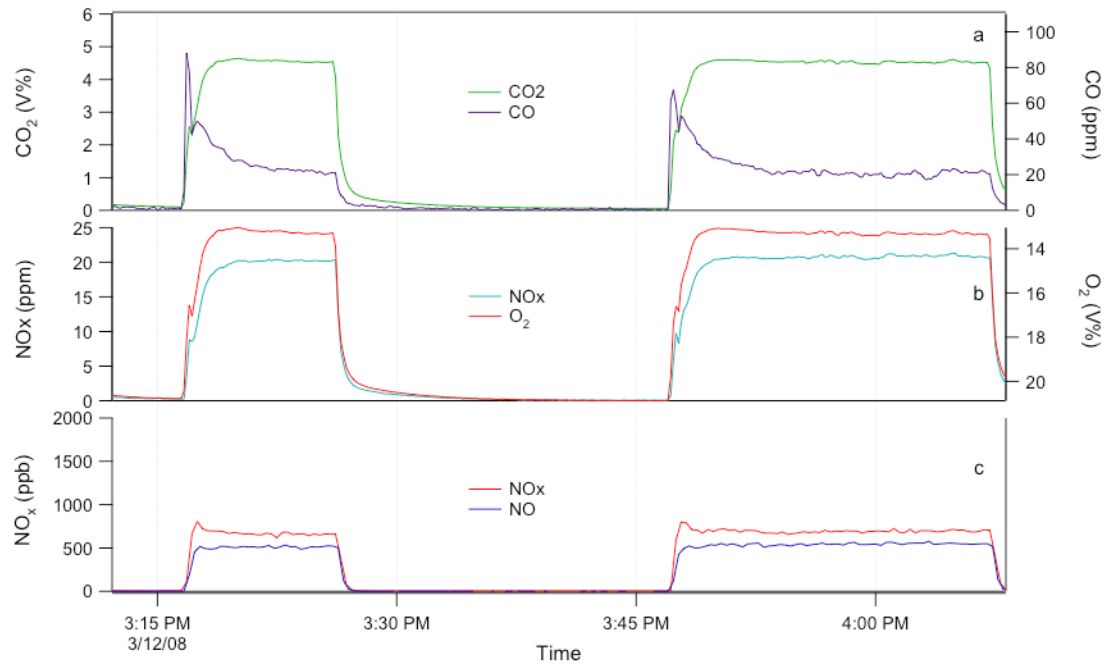

Figure 21. Measured analyte concentrations for forced air furnace CF03 with PG&E line gas (F042). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panel (c) presents measurements from the dilution system. The aerosol sample inlet was disconnected during this experiment.

Table 35. A. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, CF03.

Exp	Fuel	Wobbe	CO (ppm)		PG250 NO_X (ppm)		PN (10^5 cm^{-3})	
			B1	B2	B1	B2	B1	B2
F039	PG&E	1329	56	54	52	52	15	18
F040	1C	1390	39	32	54	53	13	8.3
F041	3C	1420	28	24	53	54	4.8	5.8
F042	PG&E	1329	59	54	53	55	NA[1]	NA[1]

[1] Aerosol sampling line from dilution system not connected during this experiment; dilution tube was therefore open to atmosphere at back end.

Table 36. B. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, CF03.

Exp	Fuel	Wobbe	NO_X (ppm)		NO (ppm)		NO_2 (10^5 cm^{-3})	
			B1	B2	B1	B2	B1	B2
F039	PG&E	1329	52	52	41	42	10.6	10.6
F040	1C	1390	54	53	44	44	9.6	9.1
F041	3C	1420	53	54	63	64	10.4	9.9
F042	*PG&E*	*1329*	*41* [1]	*44* [1]	*52* [1]	*55* [1]	*11.4* [1]	*11* [1]

[1] Aerosol sampling line from dilution system not connected during this experiment; dilution tube was therefore open to atmosphere at back end. Thermo 42i NO, NO_X, NO_2 results have been adjusted using the observed dilution ratio; these results may nevertheless be impacted by poor mixing of extra dilution air being pulled in from the back of the tube.

Table 37. A. Calculated emission rates over entirety of each burn for central furnace CF03.

Exp	Fuel	Wobbe	CO ($\mu g\ KJ^{-1}$)		PG250 NO_X ($\mu g\ KJ^{-1}$)		PN (10^7 KJ^{-1})		HCHO ($\mu g\ KJ^{-1}$)
			B1	B2	B1	B2	B1	B2	
F039	PG&E	1329	21	18	22	22	46	45	0.38
F040	1C	1390	16	12	23	23	34	20	0.24
F041	3C	1420	11	9	23	24	17	16	0.18
F042	PG&E	1329	21	17	22	23	NA[1]	NA[1]	

[1] Aerosol sampling line from dilution system not connected during this experiment; dilution tube was therefore open to atmosphere at back end.

Table 38. B. Calculated emission rates over entirety of each burn for central furnace CF03.

Exp	Fuel	Wobbe	NO_X ($\mu g\ KJ^{-1}$)		NO ($\mu g\ KJ^{-1}$)		NO_2 ($\mu g\ KJ^{-1}$)	
			B1	B2	B1	B2	B1	B2
F039	PG&E	1329	22	22	16.7	17.3	5.1	4.8
F040	1C	1390	23	23	18.4	18.9	4.6	4.2
F041	3C	1420	23	24	28	28	5.0	4.8
F042	*PG&E*	*1329*	*22* [1]	*23* [1]	*16.7* [1]	*18.0* [1]	*5.4* [1]	*5.1* [1]

[1] Aerosol sampling line from dilution system not connected during this experiment; dilution tube was therefore open to atmosphere at back end. Thermo 42i NO, NO_X, NO_2 results have been adjusted using the observed dilution ratio; these results may nevertheless be impacted by poor mixing of extra dilution air being pulled in from the back of the tube.

4.0 Central Furnaces CF04

4.1. Experimental information for CF04

This was the fourth central furnace tested at a residence with simulated LNG blends to evaluate interchangeability. Experiments were conducted on the same day with (in order) PG&E line gas (WN = 1327), fuel mix 1C (WN = 1390), fuel 3C (WN = 1418) and a replicate with PG&E line gas. The furnace is located in a crawl space with concrete slab and >6 ft vertical rise to the floor joists. This furnace is located alongside storage water heater WH05. The furnace used in-shot burners within a sealed direct vent combustion chamber. However, the inlet to the direct vent is open to the crawl space (i.e. not ducted directly to outdoors). Sampling occurred in an enclosed PVC flue duct >2 feet downstream of the furnace outlet. The operational protocol for this furnace started with a 10-min burn following a 10-min cooling period and a 20-min burn following a 20-min burner cooling period. The burner was controlled by manually connecting wires to close the thermostat control circuit. The aerosol inlet heater was set to track the temperature at the sampling point in the flue. The condensation particle counter did not function properly during these experiments; particle number (PN) concentrations and emission factors are thus unavailable for this burner.

Table 39. Appliance and burner information.

Burner ID	CF04
Burner category	Central forced air furnace
Technology	Modern induced combustion furnace; closed combustion chamber with direct vent intake drawing from utility room; condensing;
Appliance manufacturer	Bryant
Model	350MAV048100F (Plus-90)
Serial number	0201A01301
Manifold P (in. H_2O)	Not recorded
Rated input (Btu/h)	100,000
Rated output (Btu/h)	93,000
AFUE rating	95.5
Age	Installed new in 2002
Sampling location	Sample in PVC exhaust duct, ~1 m from furnace; furnace installed in utility room under home
History notes	Furnace installed by current homeowner

Table 40. Interchangeability experiments for central forced air furnace CF04.

Exp.	Fuel	Date	Burner operation
F043	PG&E	3/19/08	Start with purge burn.[1] Two experimental burns. Burn 1 started 10 min after purge and lasted for 10 min duration. Burn 2 started 20 min after Burn 1 and lasted for 20 min duration.
F044	1C		
F045	3C		
F046	PG&E		

[1] The "purge" burn is used to flush the system and ensure that the first experimental burn uses the test fuel. A purge burn is conducted in all experiments, even those not involving fuel switching from previous experiments.

Table 41. Fuel analysis for interchangeability experiments with central forced air furnace CF04.

Expt. ID	Fuel ID	Sample ID	C_1 (%)	C_2 (%)	C_3 (%)	C_{4+} (%)	N_2 (%)	CO_2 (%)	HHV[1] (Btu/scf)	Wobbe[1] number
F043	PG&E	F043	95.8%	2.09%	0.14%	0.03%	1.04%	0.85%	1010	1327
F044	1C	1C	92.0%	8.00%	-	-	-	-	1071	1390
F045	3C	3C	86.4%	12.0%	1.60%	-	-	-	1125	1419
F046	PG&E	F046	95.7%	2.06%	0.13%	0.03%	1.23%	0.85%	1007	1323

[1] Calculated using the American Gas Association interchangeability program.

Figure 22. Experimental apparatus installed for central furnace CF04.
Shown are cart with analytical instrumentation and computer data acquisition system (right); blowers for dilution sampling system (on top of cart); dilution sampling tube (mounted diagonally on photographic pole at left of picture); and inline gas meter (below dilution tube). Installation of sample probes is shown in next figure. Storage water heater in background was evaluated as WH05.

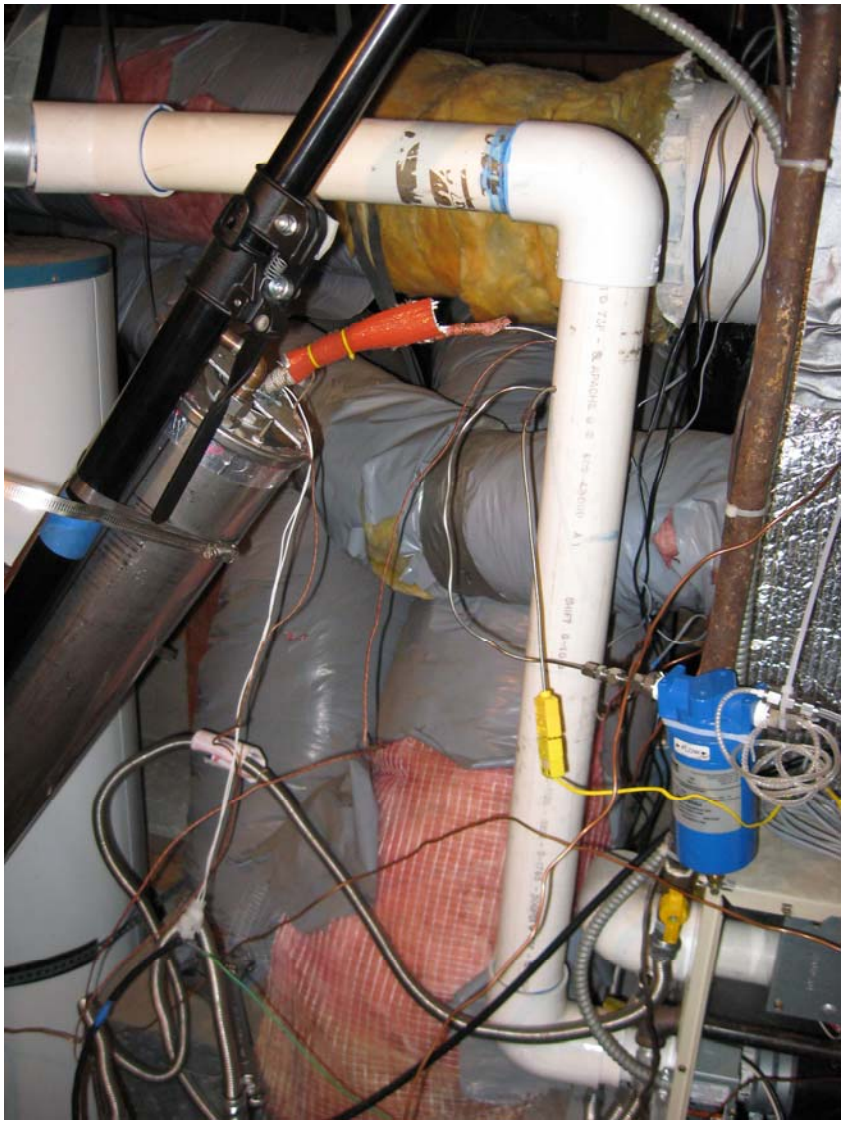

Figure 23. Installation of sample probes for CF04.

Probes include (1) dilution system inlet (wrapped with heater; top of picture); thermocouple for lead temperature for inlet heater (same location); inlet to combustion gas analyzer (going to blue water trap) and thermocouple to record sampling location temperature. Nafion permeation tube wound at outlet to water trap.

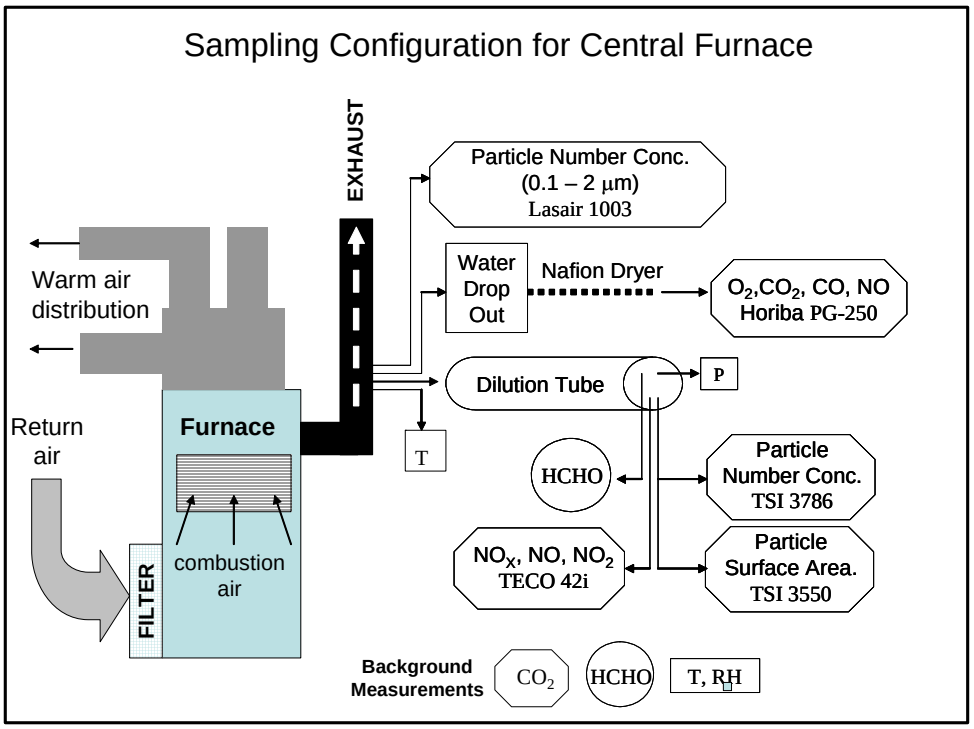

Figure 24. Pollutant sampling configuration for central furnace CF04.
Lasair was not used in these experiments.

Table 42. Analyte ranges and calibration levels for experiments with central forced air furnace CF04.

Analyte	Sample location[1]	Equipment[2]	Range	Calibration levels
Carbon dioxide (CO_2)	See Fig. 2	Horiba PG-250	0-10%	0, 10%
Oxygen (O_2)	See Fig. 2	Horiba PG-250	0-25%	0, 20.95% check 8%[3]
Carbon monoxide (CO)	See Fig. 2	Horiba PG-250	0-500 ppm	0, 350 ppm check 40 ppm[4]
Nitrogen oxides (NO_X)	See Fig. 2	Horiba PG-250	0-50 ppm	0, 20 ppm[5]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-5 ppm	0, 2.4 ppm[5]
Carbon dioxide (CO_2)	ambient air in laboratory[4]	PPSystems EGM-4	5000 ppm	factory calibrated; check at 507 ppm

[1] Sample air drawn from duct connected to outlet of hood through 3/8" Teflon tubing to gas manifold; analyzers sampled most directly from gas manifold. [2] Horiba Environmental and Process Instruments, Irvine CA (environ.hii.horiba.com); Thermo Fisher Scientific, Waltham, MA (thermo.com); TSI Instruments, Shoreview, MN (tsi.com); PP Systems, Amesbury, MA (ppsystems.com). [3] Instrument read 7.9% for mixture with 8% O_2 following calibration at 20.95%. [4] Instrument read 39 ppm for mixture with 40 ppm CO following calibration at 350 ppm. [5]Calibrated from mixture of NO in N_2.

Table 43. Aerosol instrumentation used for central forced air furnace CF04.

Analyte	Instrument[1]	Configuration	Min. size (D_{50})[2]	Max. Conc.	Accuracy
Total particle number conc. (PN), # cm^{-3}	TSI 3786 ultrafine CPC	sample from dilution tube via 2.2 m × 0.48 cm ID conductive tubing[3]	2.5 nm	10^5 cm^{-3} single particle mode	±12%
Surface area of particles (SA) depositing in lung alveolar region[4]	TSI 3550 nanoparticle surface area monitor	sample from dilution tube via 2.2 m × 0.48 cm ID conductive tubing[3]	10 nm	10^5 um^2 cm^{-3}	±20% at 20-200 um^2 cm^{-3}

[1] TSI Instruments, Shoreview, MN (tsi.com). CPC = condensation particle counter. Detailed information provided in product literature. [2] 50% detection. Ultrafine particles (UFP) are generally defined as having aerodynamic diameters <100 nm. [3] Product 3001788, purchased from TSI. [4] Monitor has settings available for tracheobronchial (TB) or alveolar (A) regions; specifications are provided for the alveolar option which is being used in this study.

Table 44. Other measurements for experiments with central forced air furnace CF04.

Measured Quantity	Location(s)	Device(s) [1]
Fuel pressure	Attached to gas meter Pressure tap of furnace regulator	Model 264 transducer (Setra)
Fuel volume and flow rate to appliance during burner operation	Meter installed upstream of appliance; connected to local shut-off valve (PG&E line gas) or low pressure regulator and cylinder of simulated LNG	AC-250-TC T-compensating dry gas meter with 1- and ¼-ft dials (American Meter) with pulse counter resolved to 0.1 ft^3; flow rate also checked by stopwatch.
Dilution sampler vacuum	Dilution tube	Setra Model 264 transducer
Temperature, combustion air	Near air intake for furnace	Precision NTC thermistor (APT)
Relative humidity, combustion air	Near air intake for furnace	Thermostet polymer based capacitance RH sensor (APT)
Temperature, exhaust	Alongside pollutant sampling location in exhaust duct	Thermocouple (K), probe, Omega KQSS-18E-12

[1] APT: Automated Performance Testing System, Energy Conservatory, Minneapolis, MN (energyconservatory.com); Setra: Boxborough, MA (setra.com); Riotronics: Engelwood, CO (riotronics.com); American Meter (americanmeter.com); obtained via Miners & Pisani, San Leandro, CA; Omega Engineering, Stamford, CT (omega.com).

4.2. Results for CF04

CO emission rates were low overall and end of burn concentrations with simulated LNG fuels were relative half of the values observed during replicate experiments with PG&E line gas. NOX emissions appeared to increase slightly with Wobbe number, on the order of 10% when comparing fuel 3C to line gas. NO accounted for over 80% of total NO_X. Formaldehyde emission factors were also low and decreased with increasing fuel WN. Replicate experiments with PG&E produced very similar results for CO, NO_X, and formaldehyde (HCHO). Full burn emission rates were 8-20 ng/J for CO, 22-26 ng/J for NO_X, and approximately 0.1 ng/J for HCHO.

Table 45. Burner operating parameters for experiments with central furnace CF04.

Exp.	Burn	Start time	End time	Fuel flow[1] ($ft^3\ h^{-1}$)	Firing rate[1] (kbtu/h)	Supply pressure (in. H_2O)	Appliance manifold P (in. H_2O)
F043	B1	11:05	11:15	93	94	5.6	3
	B2	11:36	11:56	92	93	5.4	3.1
F044	B1	12:21	12:31	91	97	7.2	3.1
	B2	12:52	13:12	91	97	7.1	3.2
F045	B1	13:33	13:43	88	99	7.2	3
	B2	14:04	14:24	91	102	7.1	3.2
F046	B1	14:44	14:54	91	92	5.5	2.9
	B2	15:15	15:34	90	91	5.3	3.1

[1] Fuel flow rate ($ft^3\ h^{-1}$) calculated from fuel use measured for each burn (by pulse counter) divided by time of burn; firing rate calculated from calculated fuel flow rate and higher heating value from fuel composition.

Table 46. Combustion air conditions[1] for experiments with central furnace CF04.

Exp.	Fuel	T (°C)	RH (%)
F043	PG&E	16.8 ± 2.2	62 ± 6
F044	1C	16.7 ± 1.6	60 ± 5
F045	3C	18.5 ± 1.3	55 ± 4
F046	PG&E	19.5 ± 1.2	55 ± 4

[1] Mean ± standard deviation of laboratory air conditions measured over period of two sampling burns.

Table 47. Sampling system conditions for experiments central furnace CF04.

Exp.	Sample Location T (°C)[1]		Dilution Ratio[2]	
	Burn 1	Burn 2	Burn 1	Burn 2
F043	39 ± 0	40 ± 0	14	16
F044	40 ± 0	42 ± 0	16	16
F045	42 ± 0	44 ± 0	15	15
F046	41 ± 0	42 ± 0	14	14

[1] Mean ± standard deviation measured during last 5 min of each burn.
[2] Calculated by comparing NO_X measured in gas manifold (PG-250) and dilution sampler (Thermo 42i) for each burn.

Table 48. Formaldehyde samples for experiments with central furnace CF04.

Exp(s)	Location	Sample start/end time		Air vol. (L)	Extract conc. (ng/μL)	Air conc.[1] ($\mu g/m^3$)
ALL	Bkg air	11:03	15:35	270	0.268	1.98
F043	Dilution Tube	11:03	11:57	49	0.269	11.0
F044		12:19	13:14	46	0.178	7.68
F045		13:31	14:25	49	0.176	7.23
F046		14:43	15:35	47	0.285	12.0

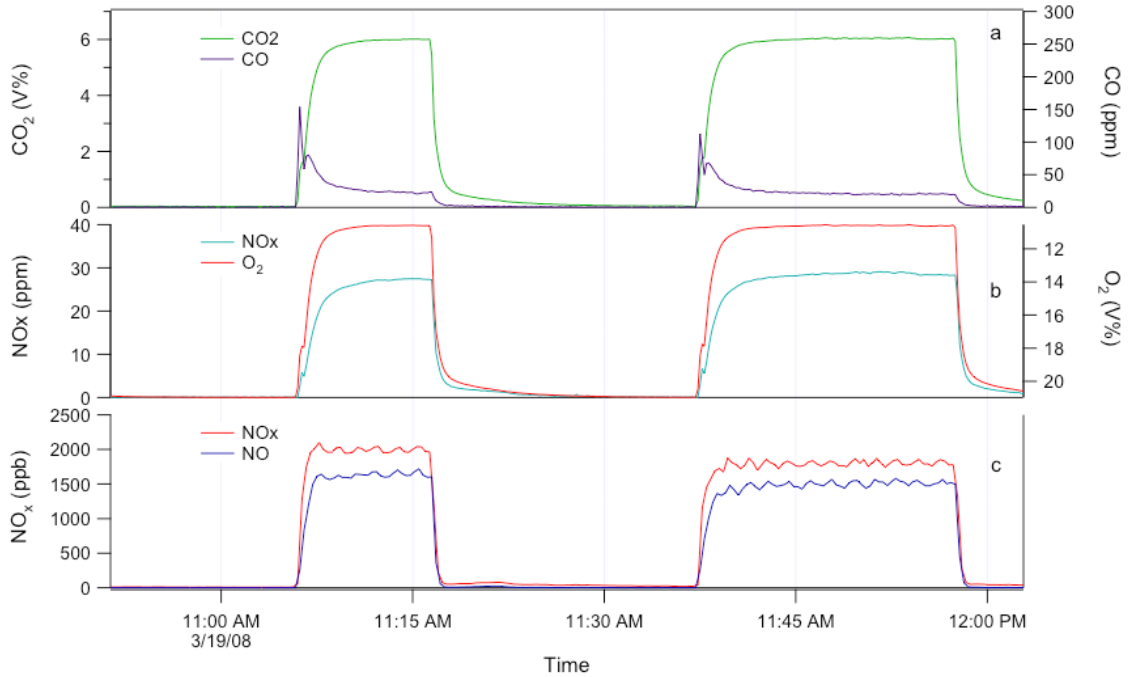

Figure 25. Measured analyte concentrations for forced air furnace CF04 with PG&E line gas (F043). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panel (c) presents measurements from the dilution system. Particles were not sampled due to instrument failure.

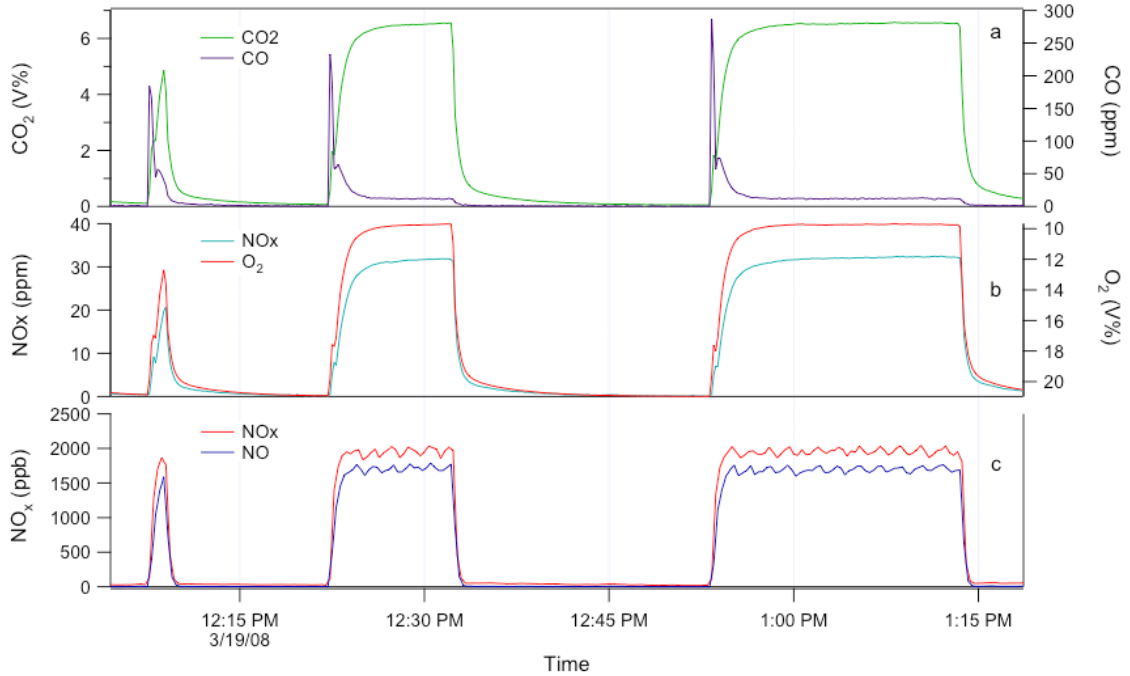

Figure 26. Measured analyte concentrations for forced air furnace CF04 with fuel 1C (F044). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panel (c) presents measurements from the dilution system. Particles were not sampled due to instrument failure. The peak prior to Burn 1 is a purge burn.

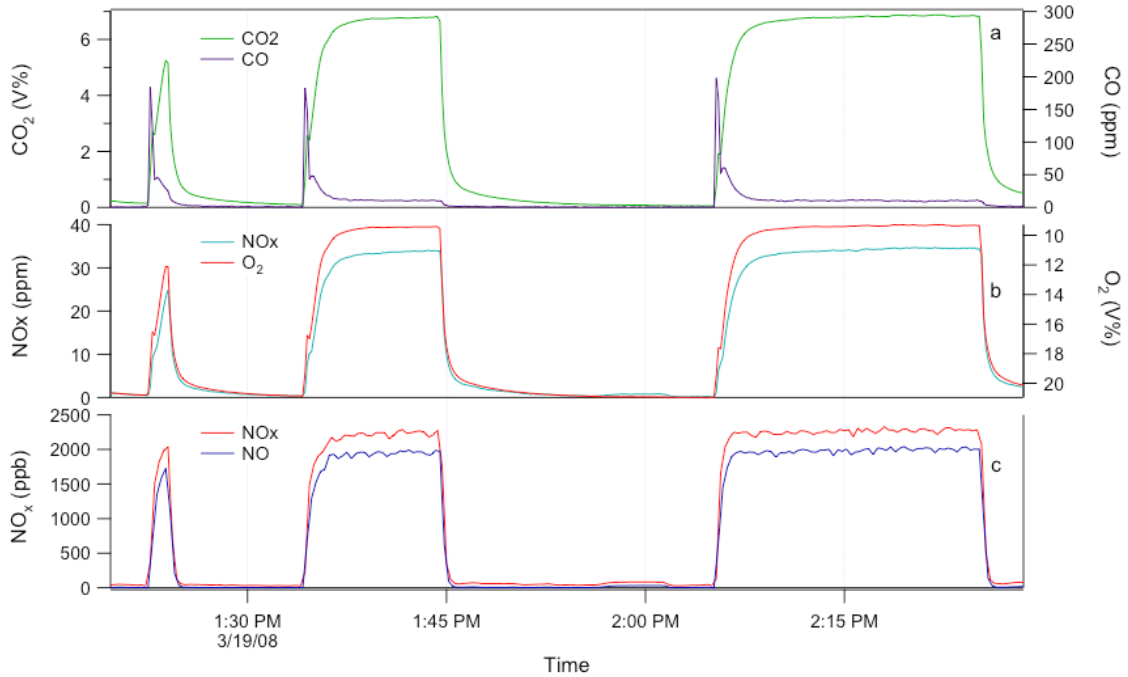

Figure 27. Measured analyte concentrations for forced air furnace CF04 with fuel 3C (F045). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panel (c) presents measurements from the dilution system. Particles were not sampled due to instrument failure. The peak prior to Burn 1 is a purge burn.

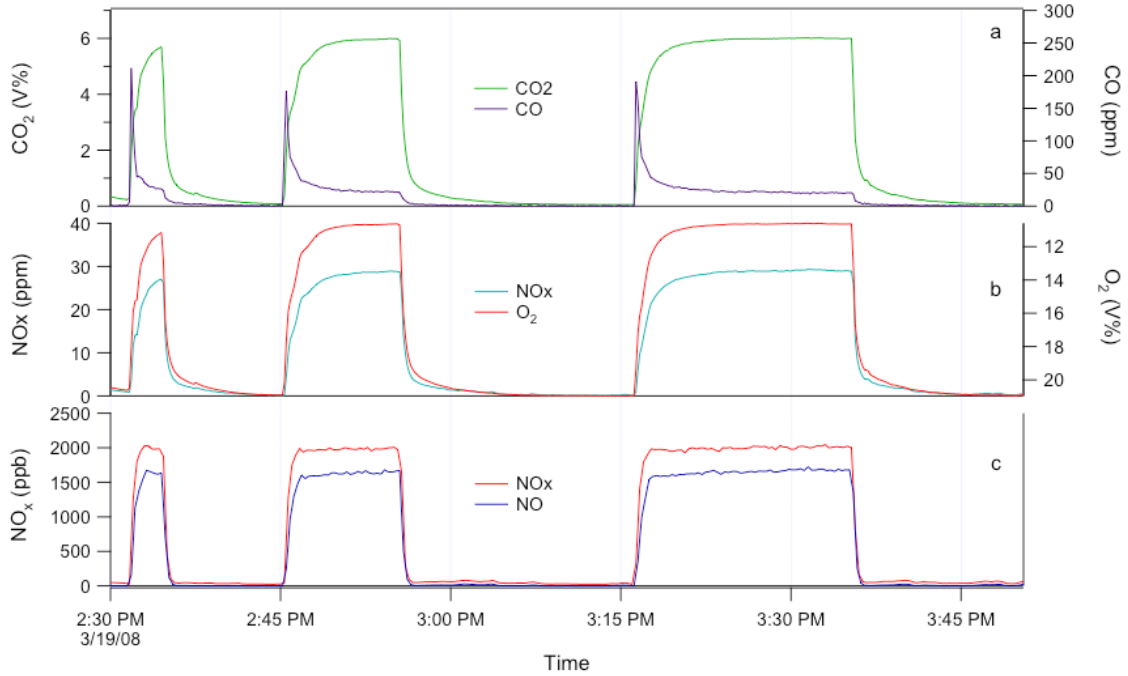

Figure 28. Measured analyte concentrations for forced air furnace CF04 with PG&E line gas (F046). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panel (c) presents measurements from the dilution system. Particles were not sampled due to instrument failure. The peak prior to Burn 1 is a purge burn.

Table 49. A. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, central furnace CF04.

Exp	Fuel	Wobbe	CO (ppm)		PG250 NO_X (ppm)		PN (10^5 cm^{-3})	
			B1	B2	B1	B2	B1	B2
F043	PG&E	1327	47	40	54	56	NA[1]	NA[1]
F044	1C	1390	21	22	58	59	NA[1]	NA[1]
F045	3C	1420	18	17	60	61	NA[1]	NA[1]
F046	PG&E	1323	45	40	57	58	NA[1]	NA[1]

[1] PN data unavailable based on equipment operational problem.

Table 50. B. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, central furnace CF04.

Exp	Fuel	Wobbe	NO_X (ppm)		NO (ppm)		NO_2 (10^5 cm^{-3})	
			B1	B2	B1	B2	B1	B2
F043	PG&E	1327	54	56	45	48	9.3	8.8
F044	1C	1390	58	59	51	51	7.2	7.5
F045	3C	1420	60	61	53	54	7.5	7.2
F046	PG&E	1323	57	58	47	48	9.8	9.2

Table 51. A. Calculated emission rates over entirety of each burn for central furnace CF04.

Exp	Fuel	Wobbe	CO ($\mu g\ KJ^{-1}$)		PG250 NO_X ($\mu g\ KJ^{-1}$)		PN (10^7 KJ^{-1})		HCHO ($\mu g\ KJ^{-1}$)
			B1	B2	B1	B2	B1	B2	
F043	PG&E	1327	20	14	22	24	NA[1]	NA[1]	0.12
F044	1C	1390	13	10	25	25	NA[1]	NA[1]	0.09
F045	3C	1420	10	8	26	26	NA[1]	NA[1]	0.08
F046	PG&E	1323	19	16	24	24	NA[1]	NA[1]	0.13

[1] PN data unavailable based on equipment operational problem.

Table 52. B. Calculated emission rates over entirety of each burn for central furnace CF04.

Exp	Fuel	Wobbe	NO_X ($\mu g\ KJ^{-1}$)		NO ($\mu g\ KJ^{-1}$)		NO_2 ($\mu g\ KJ^{-1}$)	
			B1	B2	B1	B2	B1	B2
F043	PG&E	1327	22	24	18	20	4.4	4.2
F044	1C	1390	25	25	22	22	3.4	3.6
F045	3C	1420	26	26	23	23	3.4	3.3
F046	PG&E	1323	24	24	19	20	4.6	4.4

5.0 Wall Furnace WF01

5.1. Experimental information for WF01

This wall furnace was tested following experiments on CF03 and WH03. Experiments were conducted on the same day with PG&E line gas (WN = 1333), fuel mix 1C (WN = 1390) and fuel 3C (WN = 1420). The furnace heats a freestanding one-room guest house. Sample lines were tied together and inserted into the central exhaust flue. Combustion air is drawn through the outer annulus of the direct vent assembly (see photos). The operational protocol for this furnace included burns of 10- and 20-min following burner cooling periods of 10- and 20-min. The burner was controlled by a thermostat inside the guest house. The aerosol inlet heater was manually set to match approximately the temperature at the sampling point in the flue; this was based on the temperature observed during the range finding run. Formaldehyde was not sampled during these experiments because previous measurements showed this burner to have very low formaldehyde emissions.

Table 53. Appliance and burner information.

Burner ID	WF01
Burner category	Wall furnace
Burner technology	Conventional technology, pilot, direct vent
Appliance manufacturer	Williams
Model	1403622
Serial number	27037234
Manifold P (in. H_2O)	4.0
Rated input (Btu/h)	14,000
Rated output (Btu/h)	10,038
Efficiency	72% (calculated from rated input and output)
Age	4 years at time of testing; (installed in 2003)
Test location	Equipment placed just outside of cottage to sample from flue outlet.
History notes	Installed in detached cottage that is used as guest accommodations and leisure space for homeowner. Installed by current homeowner.

Table 54. Interchangeability experiments for wall furnace WF01.

Exp.	Fuel	Date	Burner operation
F025	PG&E	11/30/07	Start with purge burn.[1] Two experimental burns. Burn 1 started 10 min after purge and lasted for 10 min duration. Burn 2 started 20 min after Burn 1 and lasted for 20 min duration.
F026	3C	11/30/07	
F027	1C	11/30/07	

[1] The "purge" burn is used to flush the system and ensure that the first experimental burn uses the test fuel. A purge burn is conducted in all experiments, even those not involving fuel switching from previous experiments.

Table 55. Fuel analysis for interchangeability experiments with wall furnace WF01.

Expt. ID	Fuel ID	Sample ID	C_1 (%)	C_2 (%)	C_3 (%)	C_{4+} (%)	N_2 (%)	CO_2 (%)	HHV[1] (Btu/scf)	Wobbe[1] number
F025	*PG&E*	*Cont.*[2]	*95.6*	*2.28*	*0.30*	*0.09*	*1.00*	*0.74*	*1016*	*1333*
F026	3C	B1[3]	86.3	11.68	1.58	0.00	0.40	0.01	1124	1417
F026	3C	B2[3]	86.5	11.71	1.60	0.00	0.13	0.02	1128	1422
F027	1C	Cont.[3]	92.0	8.0	-	-	-	-	1071	1390

[1] Calculated using the American Gas Association interchangeability program.
[2] Large nitrogen peaks indicate substantial contamination in sample. Use gas quality data for sample collected one day earlier at another residence in same BTU district; sample is from WH03.
[3] Samples not analyzed until several weeks following collection. Presence of N_2 in samples of fuel from cylinders typically indicates contamination by air. Small level of contamination in these samples does not have significant impact on Wobbe number (WN); calculated WN for these samples is similar to samples of fuel 1C from other experiments.

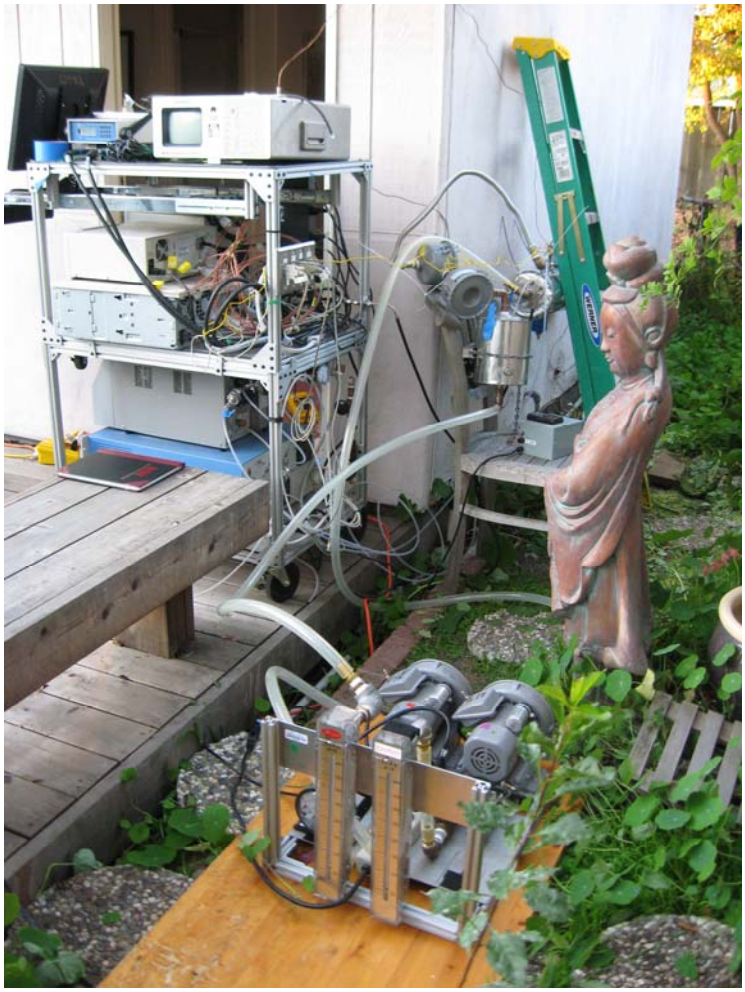

Figure 29.Experimental apparatus installed for wall furnace WF01.
The following components are visible: instrument cart (top left quadrant), aerosol dilution sampler supply system (filters and sorbent canister, to left of ladder), dilution mixing tube (strapped to underside of ladder), supply and exhaust blowers for dilution sampler (bottom). The exhaust port is not visible from this angle but it is shown below.

Figure 30. **Experimental apparatus installed for wall furnace WF01.**
The aerosol dilution sampler mixing tube is mounted on the underside of the ladder. The inlet is wrapped with insulation. Also shown are the inlet for the Lasair optical particle counter (copper line snaking to top of exhaust) and a thermocouple (connector is yellow rectangle above tube).

Figure 31. **Sampling probes installed in wall furnace WF01.**
Probes include a thermocouple, inlet for Lasair optical particle counter, inlet for aerosol dilution sampler, and inlet for combustion analyzer sample stream (includes water drop out and dryer).

Figure 32. **Gas meter and cylinder of simulated LNG installed for wall furnace WF01.**
Note hair dryer used to heat cylinder regulator.

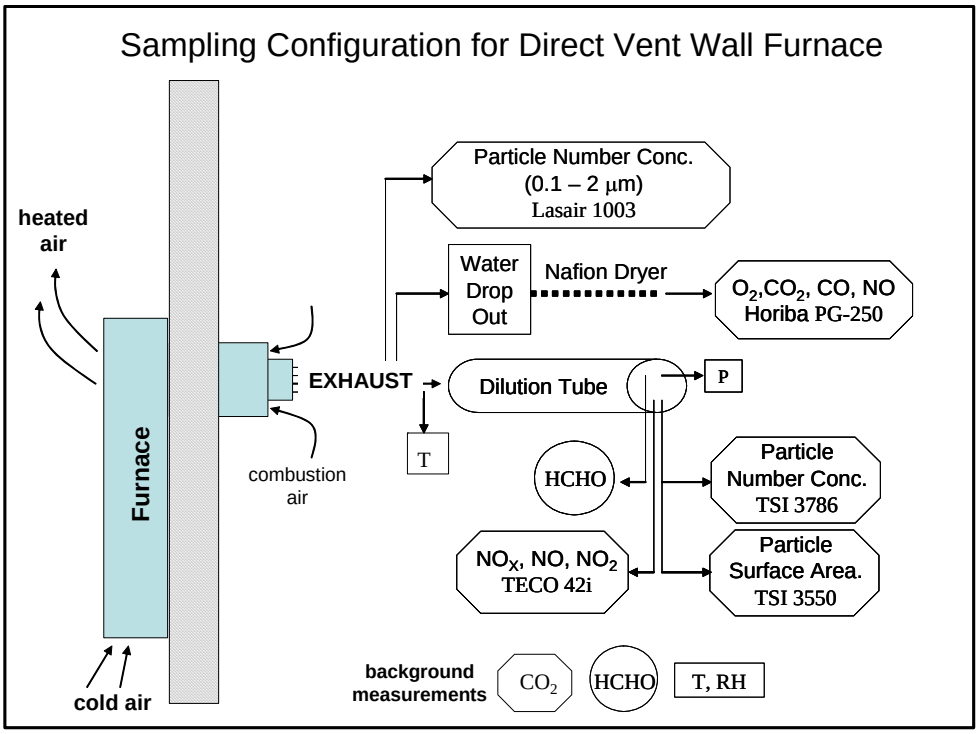

Figure 33. Pollutant sampling configuration for wall furnace WF01.

Formaldehyde was not sampled during these experiments because previous measurements showed this burner to have very low formaldehyde emissions.

Table 56. Analyte ranges and calibration levels for experiments with wall furnace WF01.

Analyte	Sample location[1]	Equipment[2]	Range	Calibration levels
Carbon dioxide (CO_2)	~3" inside flue, see Figs 2-3	Horiba PG-250	0-10%	0, 10%
Oxygen (O_2)	~3" inside flue, see Figs 2-3	Horiba PG-250	0-25%	0, 20.95%
Carbon monoxide (CO)	~3" inside flue, see Figs 2-3	Horiba PG-250	0-1000 ppm	0, 500 ppm
Nitrogen oxide (NO)	~3" inside flue, see Figs 2-3	Horiba PG-250	0-50 ppm	0, 20 ppm[3]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-5 ppm	0. 2.5 ppm[3]
Carbon dioxide (CO_2)	ambient air	PPSystems EGM-4	5000 ppm	factory calibrated; check at 507 ppm

[1] Sample air drawn from duct connected to outlet of hood through 3/8" Teflon tubing to gas manifold; analyzers sampled most directly from gas manifold.

[2] Horiba Environmental and Process Instruments, Irvine CA (environ.hii.horiba.com); Thermo Fisher Scientific, Waltham, MA (thermo.com); TSI Instruments, Shoreview, MN (tsi.com); PP Systems, Amesbury, MA (ppsystems.com).

[3] Calibrated from mixture of NO in N_2.

Table 57. Aerosol instrumentation used for wall furnace WF01.

Analyte	Instrument[1]	Configuration	Min. size (D_{50})[2]	Max. Conc.	Accuracy
Total particle number conc. (PN), # cm^{-3}	TSI 3786 ultrafine CPC	sample from dilution tube via 2.2 m × 0.48 cm ID conductive tubing[3]	2.5 nm	10^5 cm^{-3} single particle mode	±12%
Surface area of particles (SA) depositing in lung alveolar region[4]	TSI 3550 nanoparticle surface area monitor	sample from dilution tube via 2.2 m × 0.48 cm ID conductive tubing[3]	10 nm	10^5 um^2 cm^{-3}	±20% at 20-200 um^2 cm^{-3}
Number conc. of particles 0.1-2.0 μm diameter	Lasair 1003 optical particle counter (OPC)	Sample direct from exhaust via ~2.5 m × 1.7 mm ID flexible copper tubing.	0.1 μm	1.4×10^4 cm^{-3}	<10%[5]

[1] TSI Instruments, Shoreview, MN (tsi.com). CPC = condensation particle counter. Detailed information provided in product literature.
[2] 50% detection. Ultrafine particles (UFP) are generally defined as having aerodynamic diameters <100 nm.
[3] Product 3001788, purchased from TSI.
[4] Monitor has settings available for tracheobronchial (TB) or alveolar (A) regions; specifications are provided for the alveolar option which is being used in this study.
[5] Product literature reports <10% coincidence loss at maximum recommended ambient concentration.

Table 58. Other measurements for experiments with wall furnace WF01.

Measured Quantity	Location(s)	Device(s) [1]
Fuel pressure	Attached to gas meter Pressure tap of furnace regulator	Model 264 transducer (Setra)
Fuel volume and flow rate to appliance during burner operation	Meter installed upstream of appliance; connected to local shut-off valve (PG&E line gas) or low pressure regulator and cylinder of simulated LNG.	AC-250-TC T-compensating dry gas meter with 1- and ¼-ft dials (American Meter) with pulse counter resolved to 0.1 ft^3; flow rate also checked by stopwatch.
Dilution sampler vacuum	Dilution tube	Setra Model 264 transducer
Temperature, combustion air	Outside of cottage	Precision NTC thermistor (APT)
Relative humidity, combustion air	Outside of cottage	Thermostet polymer based capacitance RH sensor (APT)
Temperature, exhaust	Alongside pollutant sampling location in exhaust duct	Thermocouple (K), probe, Omega KQSS-18E-12

[1] APT: Automated Performance Testing System, Energy Conservatory, Minneapolis, MN (energyconservatory.com); Setra: Boxborough, MA (setra.com); Riotronics: Engelwood, CO (riotronics.com); American Meter (americanmeter.com); obtained via Miners & Pisani, San Leandro, CA; Omega Engineering, Stamford, CT (omega.com).

5.2. Results for WF01

Exhaust CO concentrations dropped from about 20 ppm (absolute measurement, corresponding to 0.4% CO_2) during pilot burner operation to marginally below background during steady burner operation. End of burn NO_X concentrations and full-burn emission rates were higher in the second, longer burn in each experiment; this is consistent with the expected higher temperatures and reduced quenching associated with the longer burner firing. NO_X was almost 100% in the form of NO during all burns and there was no appreciable change in NO_X as a function of fuel. PN emissions were higher during the longer burn for each fuel. Both PN and NO_X emissions were lowest with fuel 1C and highest with fuel 3C but the differences may reflect experimental variability rather than a fuel effect. Full burn emission rates were <1 ng/J for CO, 31-36 ng/J for NO_X, and 4-30 x10^4 J^{-1} for PN.

Table 59. Burner operating parameters for experiments with wall furnace WF01.

Exp.	Burn times			Fuel flow rate[1] (ft^3 h^{-1})		Firing rate[1] (kBtu/h)		Manifold pressure[1] (in. H_2O)	
	Purge[2]	Burn 1	Burn 2	B1	B2	B1	B2	B1	B2
F025	12:57 13:07	12:57:10 13:07:00	13:27:10 13:49:00	12.6	12.0	12.7	12.1	3.5	3.8
F026	14:24 14:34	14:24:10 14:36:00	14:54:10 15:16:00	12.0	11.7	13.5	13.2	3.5	3.8
F027	15:40 15:50	15:40:10 15:52:00	16:10:10 16:32:00	12.6	12.0	13.3	12.7	3.6	3.9

[1] Fuel flow rate (ft^3 h^{-1}) calculated from fuel use measured for each burn (by pulse counter) divided by time of burn; firing rate calculated from calculated fuel flow rate and higher heating value from fuel composition. Fuel flow rate, firing rate and manifold pressure calculated over the final 5 min of each burn.
[2] The "purge" burn is used to flush fuel from the previous experiment.

Table 60. Environmental conditions[1] (outdoor air) for experiments with wall furnace WF01; burner is direct vent and thus draws combustion air from outdoors.

Exp.	T, burn 1 (°C)	T, burn 2 (°C)	RH, burn 1 (%)	RH, burn 2 (%)
F025	16.6 ± 0.3	15.3 ± 0.3	39 ± <1	37 ± 2
F026	15.1 ± 0.2	15.2 ± 0.6	42 ± <1	43 ± 1
F027	13.4 ± 0.1	12.5 ± 0.3	50 ± <1	52 ± 2

[1] Mean ± standard deviation measured for each burn.

Table 61. Sampling system conditions for experiments with wall furnace WF01.

Exp.	Exhaust sample location T (°C)[1]		Dilution Ratio (2 burns)[2]	
F025	203 ± 39	227 ± 39	16	16
F026	210 ± 43	229 ± 37	16	16
F027	206 ± 40	221 ± 36	15	15

[1] Mean ± standard deviation over last 5 min of each burn.
[2] Calculated by comparing NO measured in gas manifold (PG-250) and dilution sampler (Thermo 42i) over entirety of each burn.

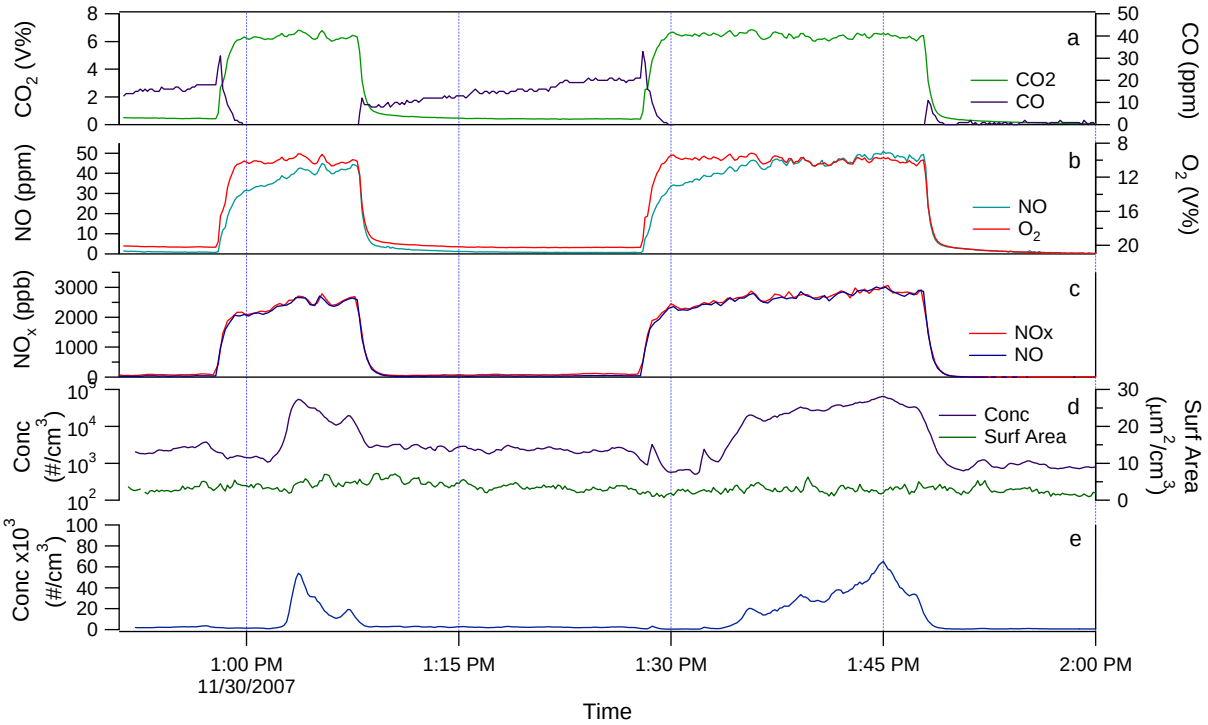

Figure 34. **Measured analyte concentrations for wall furnace WF01 with PG&E line gas (F025).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(d) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

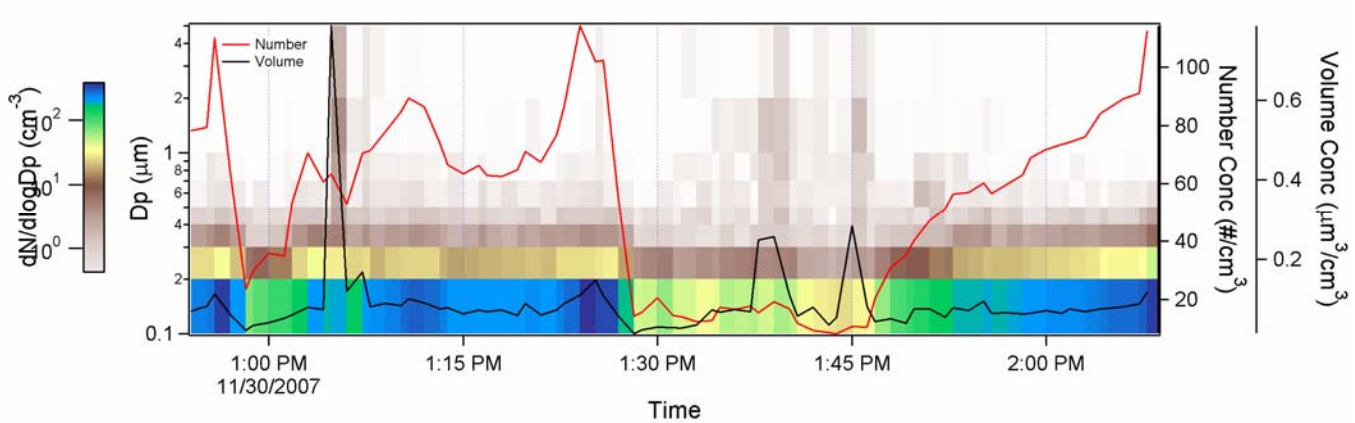

Figure 35. Size-resolved number concentrations of particles larger than 0.1 µm for experiment F025 (Lasair data).

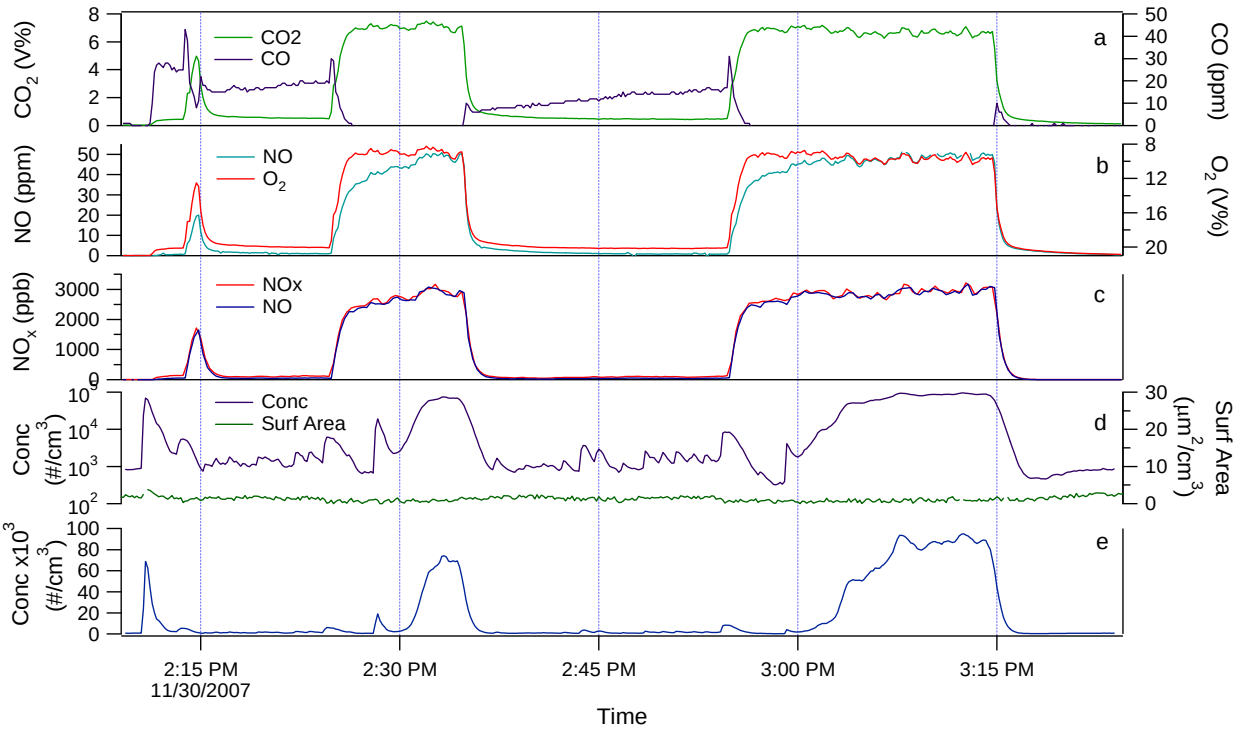

Figure 36. Measured analyte concentrations for wall furnace WF01 with fuel 3C (F026).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(d) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

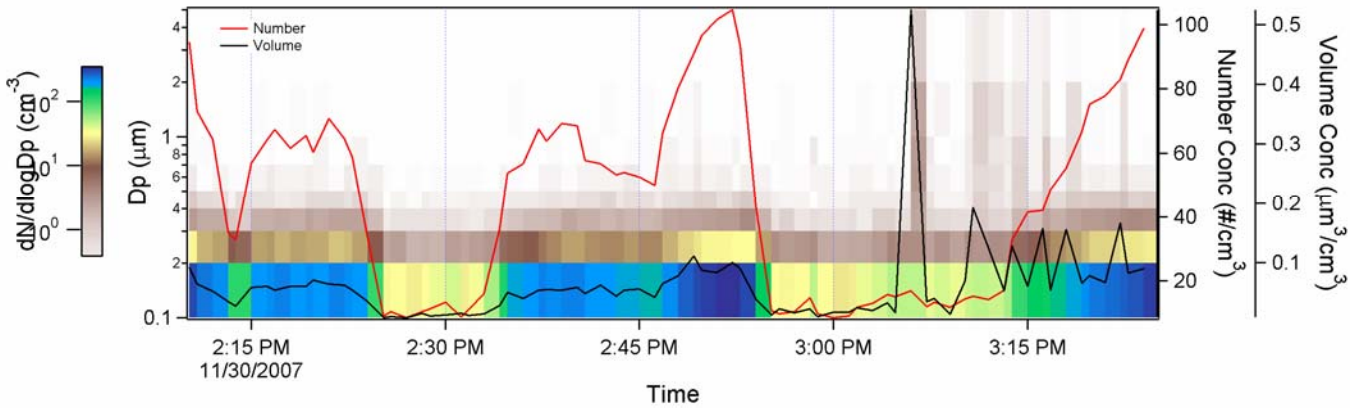

Figure 37. Size-resolved number concentrations of particles larger than 0.1 μm for experiment F026 (Lasair data).

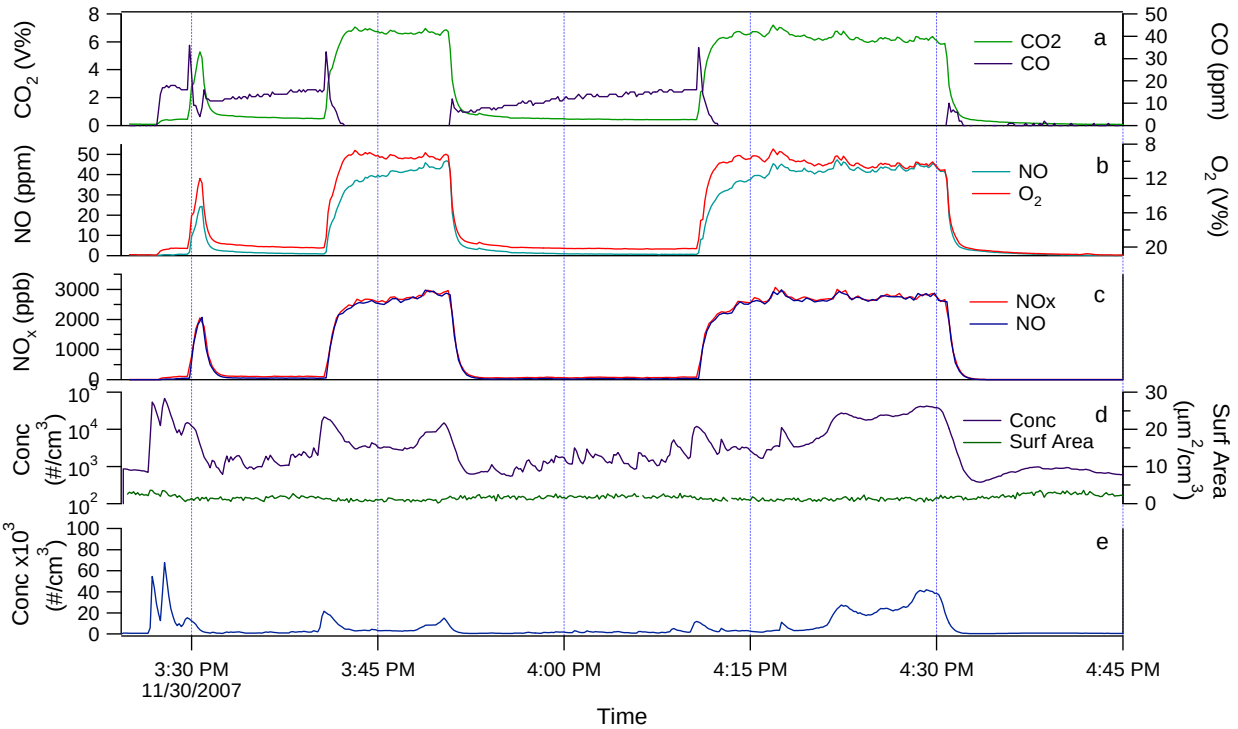

Figure 38. Measured analyte concentrations for wall furnace WF01 with fuel 1C (F027).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(d) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

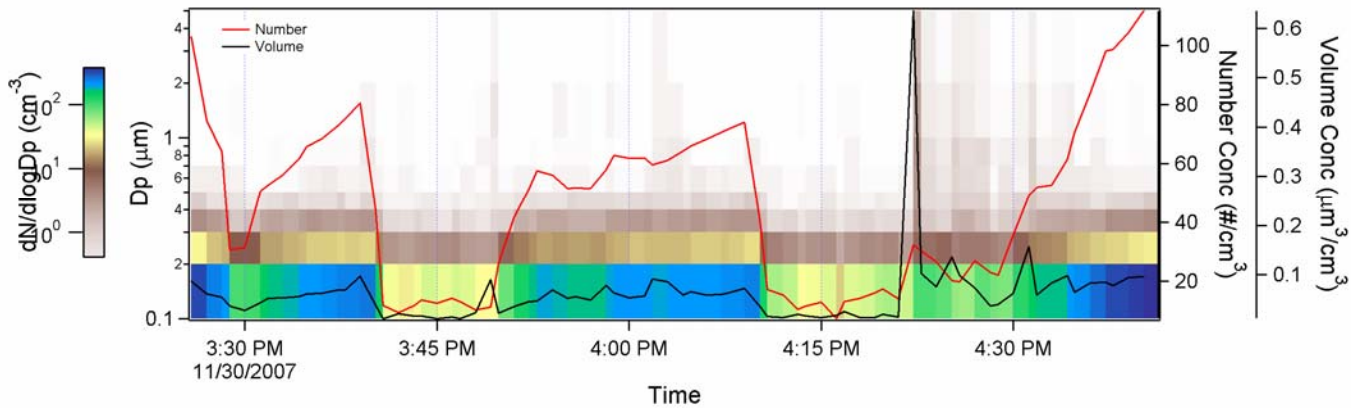

Figure 39. Size-resolved number concentrations of particles larger than 0.1 µm for experiment F027 (Lasair data).

Table 62. Preliminary results for wall furnace WF01: calculated air-free concentrations (using CO_2) over the last 5 min of operation, during each burn.

Exp.:	F025		F027		F026	
Fuel:	PG&E		1C		3C	
Wobbe:	1333		1390		1419	
	B1	B2	B1	B2	B1	B2
CO, ppm	-6	-6	-5	-6	-6	-6
PG-250 NO, ppm	75	90	75	84	79	89
NO_X, ppm	77	90	76	84	81	91
NO, ppm	76	90	76	84	80	89
NO_2, ppm	1.1	0.4	0.9	0.2	1.1	1.1
PN, 10^5 cm^{-3}	6.3	14	1.1	8.8	9.0	26

Table 63. Preliminary results for wall furnace WF01: calculated emission rates over entirety of each burn.

Exp.:	F025		F027		F026	
Fuel:	PG&E		1C		3C	
Wobbe:	1333		1390		1419	
CO, μg KJ^{-1}	0.7	-0.6	0.5	-0.4	0.4	-0.8
PG-250 NO, μg KJ^{-1}	29.9	34.2	30.2	33.0	31.7	35.2
NO_X, μg KJ^{-1}	30.7	34.9	31.1	33.6	32.6	35.8
NO, μg KJ^{-1}	30.0	34.4	30.3	33.2	31.9	35.3
NO_2, μg KJ^{-1}	0.7	0.5	0.7	0.4	0.7	0.5
PN, 10^7 KJ^{-1}	8.5	14	4.0	9.6	16	30