Arnold Schwarzenegger
Governor

NATURAL GAS VARIABILITY IN CALIFORNIA: ENVIRONMENTAL IMPACTS AND DEVICE PERFORMANCE

EXPERIMENTAL EVALUATION OF POLLUTANT EMISSIONS FROM RESIDENTIAL APPLIANCES

APPENDIX F. SUMMARY REPORTS FOR OVENS OV08–OV13

PIER INTERIM PROJECT REPORT

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Prepared By:
Lawrence Berkeley National Laboratory

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Prepared By:
Brett C. Singer (Principal Investigator and Lead Author),
Michael G. Apte, Douglas R. Black, Toshifumi Hotchi, Donald Lucas,
Melissa M. Lunden, Douglas P. Sullivan
Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory
Berkeley, CA 94720
Commission Contract No. 500-05-026

Prepared For:
Public Interest Energy Research (PIER)
California Energy Commission

Marla Mueller
Contract Manager

Linda Spiegel
Program Area Lead
Energy-Related Environmental Research

Kenneth Koyama
Office Manager
Energy Generation Research

Thom Kelly, Ph.D.
Deputy Director
ENERGY RESEARCH & DEVELOPMENT DIVISION

Melissa Jones
Executive Director

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.

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1.0 Oven OV08

1.1. Experimental information for OV08

Four experiments were conducted on the same day, in the following order: PG&E line gas (WN = 1328), mix 1C (WN = 1390), mix 3C (WN = 1419), and mix 2C (WN = 1359). The heater for the dilution sampler inlet was set to automatic mode. The SMPS was used to collect size-resolved particle number concentrations in the ultrafine mode (<100 nm particle diameter). Appliance manifold pressure was not measured because access was not possible without dismantling the internal fuel transfer lines.

Table 1. Appliance and burner information OV08.

Burner ID	OV08
Appliance manufacturer	General Electric
Model number	JGSP30GER1B7
Serial number	MG221447Q
Age (years)	Estimated range of 11-15 years based on burner design
Burner technologies	Hot surface ignition; single tube-type oven burner beneath raised oven bottom
Burner rating (Btu/h)	18,000
Other information	Procured December 2008
Test location	Laboratory
History notes	Identified via Craig's List. Purchased from associate of owner with no knowledge of age or history of use (but did check to confirm it was in fully working order).

Figure 1. Oven compartment for OV08.

Figure 2. Oven bottom burner OV08.

Figure 3. Spreader plate for oven bottom burner OV08.

Table 2. Interchangeability experiments for oven bottom burner OV08.

<table>
<tr><th>Exp.</th><th>Fuel</th><th>Date</th><th>Burner operation</th></tr>
<tr><td>L139</td><td>PG&E</td><td rowspan="4">01/08/2009</td><td rowspan="4">Purge burn with each fuel change using cooktop burners. Operate oven through initial ramp plus 2 maintenance cycles at 350, 425 and 500F. Cool to touch between experiments.</td></tr>
<tr><td>L140</td><td>1C</td></tr>
<tr><td>L141</td><td>3C</td></tr>
<tr><td>L142</td><td>2C</td></tr>
</table>

Table 3. Fuel analysis for interchangeability experiments with OV08.

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
L139	PG&E	L139 [2]	95.5	2.35	0.22	0.08	0.89	0.90	1015	1331
L140	1C	Cylinder[3]	92.0	8.00	-	-	-	-	1071	1390
L141	3C	Cylinder[3]	86.4	12.00	1.60	-	-	-	1125	1419
L142	2C	Cylinder[3]	90.4	7.90	-	-	1.70	-	1053	1359

[1] Calculated using the American Gas Association interchangeability program.
[2] Composition of gas distributed to LBNL, as measured by PG&E online GC.
[3] Certified composition in cylinder (determined by the supplier, AirLiquide).

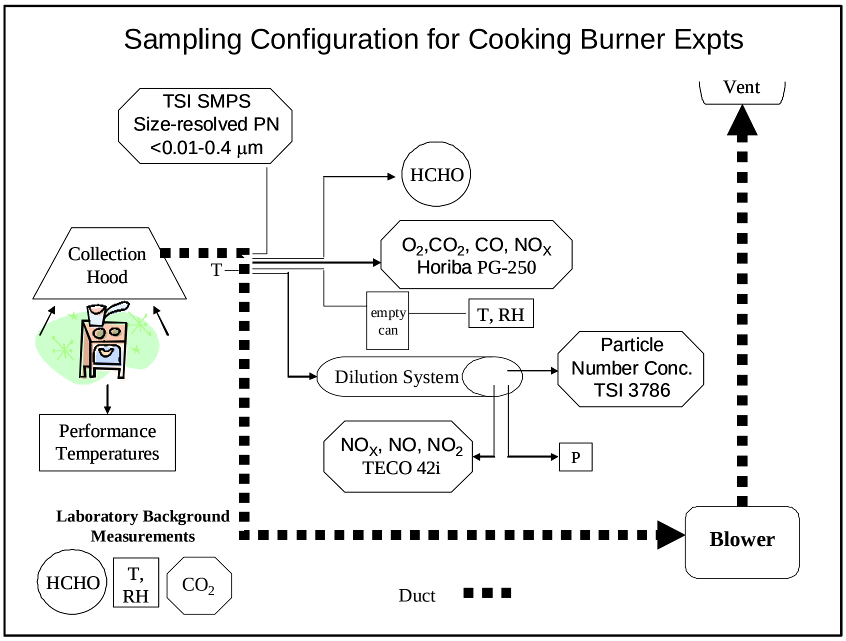

Figure 4. Analytical sampling configuration for OV08.

The empty can is used to measure RH of the airstream from the collection hood at room temperature. This indicates the potential for condensation in sampling system. PG-250 also has water removal system. HCHO sampled through 30-cm Teflon tubing (nominal ¼" diameter) for primary sample, duplicate sampled through 90-cm Teflon tubing.

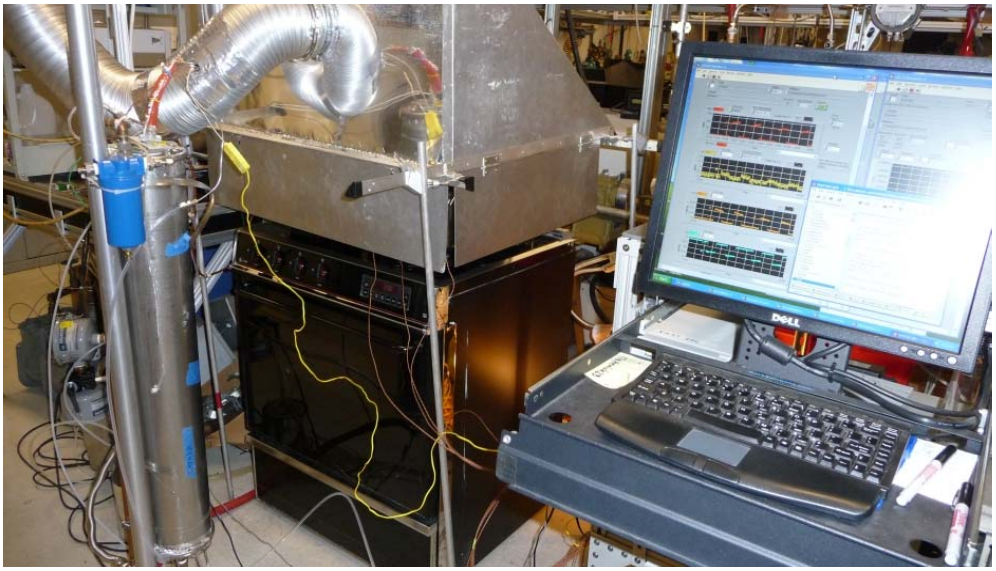

Figure 5. Installation of OV08.

Table 4. Analyte ranges and calibration levels for experiments with CT07.

Analyte	Sample location	Equipment[1]	Range	Calibration levels
Carbon dioxide (CO_2)	outlet of collection hood	Horiba PG-250	0-5%	0, 1%
Oxygen (O_2)			0-25%	0, 20.95%
Carbon monoxide (CO)			0-200 ppm	0, 40 ppm
Nitrogen oxides (NO_X)			0-25 ppm	0, 2.0 ppm[3]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-5 ppm	0, 2.0 ppm[3]
Carbon dioxide (CO_2)	laboratory air	PP Systems EGM-4	5000 ppm	Periodic[2]

[1] Horiba Environmental and Process Instruments (environ.hii.horiba.com); Thermo Fisher Scientific (thermo.com); PP Systems (ppsystems.com). [2] Not checked daily; observed to remain within 10s of ppm at ambient conditions.

Table 5. Aerosol instrumentation used for CT07.

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 part. mode	±12%
PN resolved by aerodynamic diameter	TSI 3071A classifier, TSI 3025A CPC	Sort using electrostatic classifier, count with CPC	3 nm	10^5 cm^{-3}	±10%

[1]TSI Instruments, Shoreview, MN (tsi.com). CPC = condensation particle counter. Detailed information provided in product literature. [2]50% detection. [3] Product 3001788, purchased from TSI.

Table 6. Other measurements for experiments with CT07.

Measured Quantity	Location(s)	Device(s)[1]
Fuel pressure	Gas supply line	Model 264 transducer (Setra)
Fuel volume & flow	Fuel flow to appliance during burner operation	AC-250-TC dry gas meter, 1- & ¼-ft dials (American Meter); stopwatch
Fuel flow rate	Fuel flow to appliance during burner operation	Pulse counter for AC-250-TC, 10 counts per rev (Riotronics)
Dilution sampler vacuum	Dilution tube	Setra Model 264 transducer
Temperature, combustion air	In vicinity of range	Precision NTC thermistor (APT)
Relative humidity, combustion air	In vicinity of range	Thermostet polymer based capacitance RH sensor (APT)
Temperature, air sample location in hood	At point of air sampling in duct connected to hood	Thermocouple (K), probe, Omega KQSS-18E-12
Temperature, water	Inside pots, cooktop	Thermocouple (K), probe, Omega KQSS-18E-12

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

1.2. Results for OV08

Full-burn CO emission rates were much higher during the first burn of the cycle (temperature set to 350 F) than during the initial burns at each of the other temperature settings (425 and 500 F). On this first burn, CO emission rates increased monotonically with fuel Wobbe number: from 237 ng/J (PG&E) to 347 ng/J (fuel 3C), representing an increase of roughly 50%. On the initial burns at 425 and 500 F, full burn CO emission rates were similar for PG&E and 2C, then increased for 1C and 3C; CO emissions with fuel 3C were roughly 55-70% higher than with PG&E fuel. End of burn CO concentrations for all three burns (initial burn at each temperature setting) also increased monotonically with fuel Wobbe Number; CO concentrations increased by factors of 2-3 between PG&E and fuel 3C. Air-free CO concentrations at the end of the 350 F burn ranged from roughly 110 to 320 ppm. Full burn emission rates of NO_X were 24-29 ng/J at 350 F, 32-35 ng/J at 425 F and 35-37 ng/J at 500 F. NO emissions followed a similar trend with temperature while full-burn NO_2 emission rates were highest at 350 F (at 7-8 ng/J) and decreased with oven temperature (to 4-6 ng/J at 500 F). NO_X emissions trended down with fuel WN at 350 F but no trend was observed at the other temperature settings. PN emission rates varied across experiments without a clear trend by fuel; however PN emissions were consistently higher on the 350 and 500 F burns relative to the 425 F burn. Formaldehyde emission rates were among the highest observed to date for ovens, ranging from 1.6 (fuel 3C) to roughly 3 ng/J for PG&E. Formaldehyde emission rates were intermediate for fuels 2C (WN=1359) and 1C (WN=1390).

Table 7. Burner operating parameters for experiments with oven OV08.

Experiment	Burn	Start Time	End Time	Firing Rate, counter[1] (kBTU h^{-1})	Firing Rate, stopwatch[2] (kBTU h^{-1})	Supply P (in. H_2O)[3]
L139	350F	09:06	09:12	15		7.7
L139	425F	09:26	09:29	19	18	7.7
L139	500F	09:42	09:45	18		7.7
L140	350F	10:44	10:49	19		7.7
L140	425F	11:04	11:06	19	20	7.8
L140	500F	11:19	11:21	19		7.8
L141	350F	13:10	13:15	22		7.7
L141	425F	13:29	13:32	22	20	7.8
L141	500F	13:44	13:47	19		7.8
L142	350F	14:41	14:46	20		7.8
L142	425F	15:00	15:03	18	20	7.8
L142	500F	15:16	15:19	19		7.8

[1] Fuel flow (ft^3 h^{-1}) calculated over duration of first burn at each temperature setting using counter on gas meter; firing rate calculated from measured fuel flow rate and higher heating value from fuel composition. Individual values are imprecise owing to small total volume of gas used during a burn.
[2] Fuel flow calculated from stopwatch timing of 1/4-foot dial of gas meter, one timing event for the first burn at each temperature setting (n=3 per experiment). Firing rate calculated from measured fuel flow rate and higher heating value from fuel composition.
[3] Pressure in fuel supply line during burn. Pressure at outlet of appliance regulator was not readily accessible without dismantling the fuel transfer lines within the appliance, and was therefore not measured.

Table 8. Environmental conditions[1] for experiments with OV08.

Exp.	Fuel	T (°C)	RH (%)
L139	PG&E	21.7 ± 0.2	43 ± 1
L140	1C	21.6 ± 0.2	44 ± 0
L141	3C	21.5 ± 0.1	47 ± 0
L142	2C	21.9 ± 0.1	47 ± 0

[1] Measured over period of formaldehyde sample.

Table 9. Sample location temperatures and dilution ratios for each burn.

	Sample location T (°C)[1]			Dilution ratio[2]		
Exp.	350 F	425 F	500 F	350 F	425 F	500 F
L139	32 ± 0	38 ± 0	42 ± 0	33	32	33
L140	32 ± 0	38 ± 0	42 ± 0	32	33	33
L141	32 ± 1	38 ± 0	42 ± 0	31	32	33
L142	33 ± 0	38 ± 0	42 ± 0	32	33	34

[1] Measured in exhaust duct from collection hood alongside pollutant sampling inlets. Mean ± standard deviation measured over last min of each burn to achieve new temperature setting.
[2] Calculated by comparing NO_X measured in gas manifold (PG-250) and dilution sampler (Thermo 42i) over last min of each burn.

Table 10. Measured RH of sample stream at room temperature. [1]

Exp.	Gas manifold T (°C)			Gas manifold RH (%)		
	350 F	425 F	500 F	350 F	425 F	500 F
L139	19.2 ± 0	19.1 ± 0	19.1 ± 0	57 ± 0	55 ± 0	56 ± 1
L140	19.3 ± 0	19.2 ± 0	19.2 ± 0	57 ± 1	56 ± 1	57 ± 1
L141	19.5 ± 0	19.3 ± 0	19.3 ± 0	59 ± 1	59 ± 1	60 ± 0
L142	19.7 ± 0	19.5 ± 0	19.5 ± 0	60 ± 1	58 ± 1	59 ± 1

[1] Measured in 1-gal vessel in parallel sample stream from hood outlet; measured to confirm that hood dilution is sufficient to avoid condensation in sampling stream for PG-250.

Table 11. Aldehyde samples for experiments with oven OV08.

Exp(s)	Location	Date	Sample start/end time		Flow (L/min)	Air vol. (L)	HCHO extract conc. (ng/μL)	Acet extract conc. (ng/μL)	HCHO air conc.[1] (μg/m³)	Acet. air conc.[1] (μg/m³)
Bkg	Lab air	01/08/09	9:00	15:31	0.96	377	0.750	0.236	4	1
L139a	Collection hood outlet	01/08/09	9:03	9:57	1.07	58	4.563	0.161	158	6
L139b			9:03	9:57	1.17	63	5.288	0.182	168	6
L140			10:42	11:34	1.07	55	3.713	0.202	134	7
L141			13:08	14:00	1.08	56	2.996	0.235	107	8
L142			14:39	15:31	1.07	56	3.429	0.172	123	6

[1] Concentration in the air stream being sampled for other gaseous analytes.

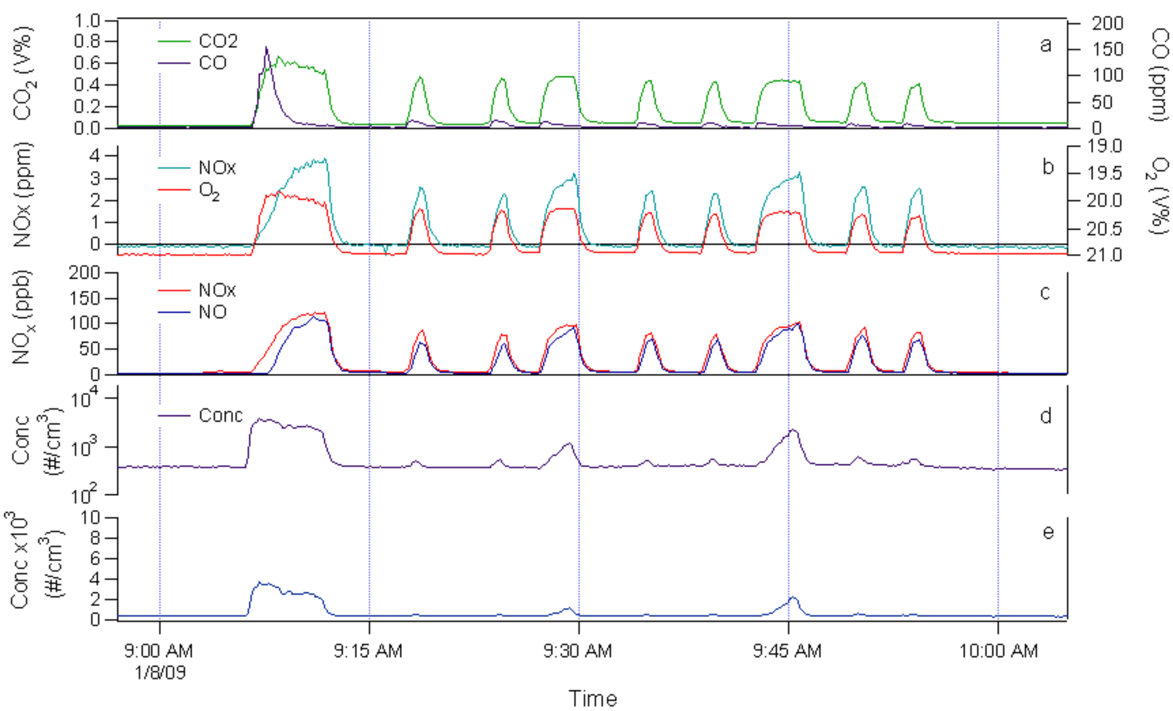

Figure 6. Measured analyte concentrations for oven OV08 with PG&E line gas (L139).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

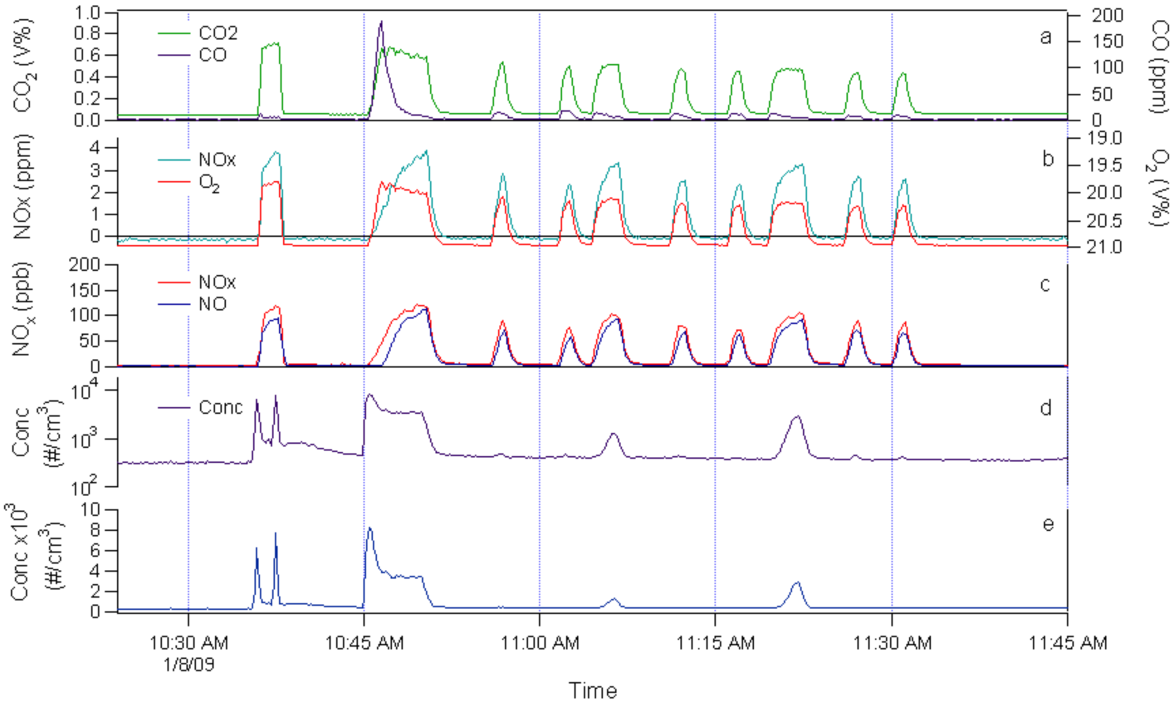

Figure 7. Measured analyte concentrations for oven OV08 with fuel 1C (L140).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

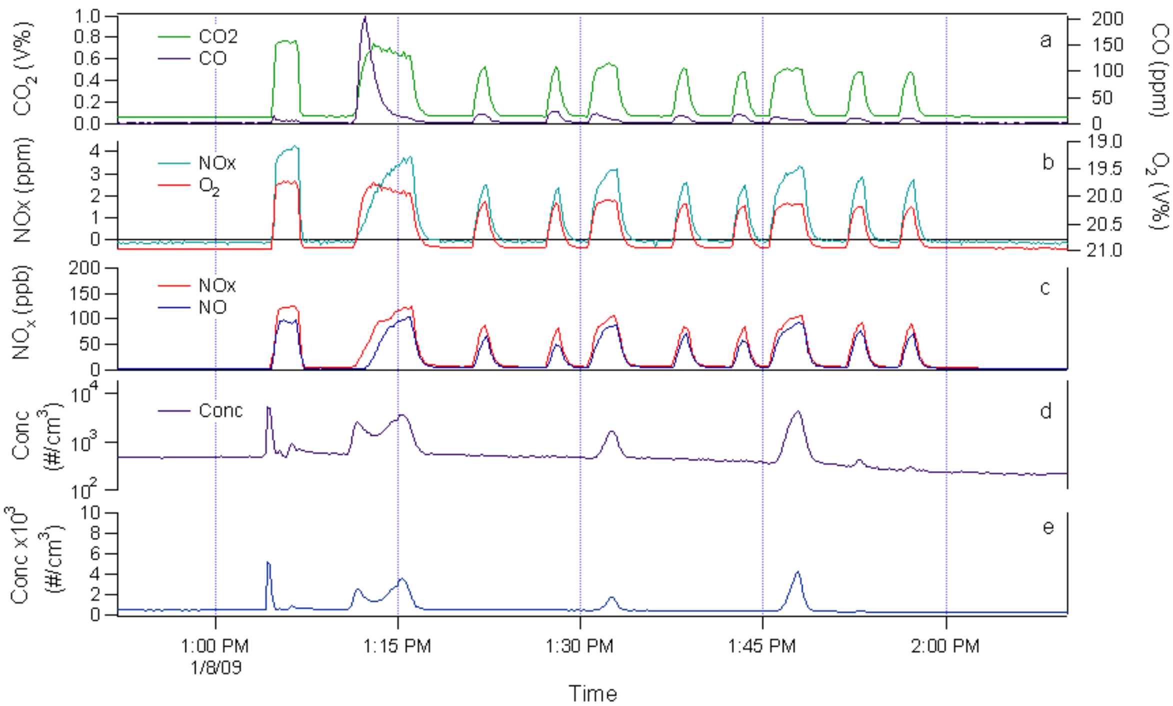

Figure 8. Measured analyte concentrations for oven OV08 with fuel 3C (L141).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

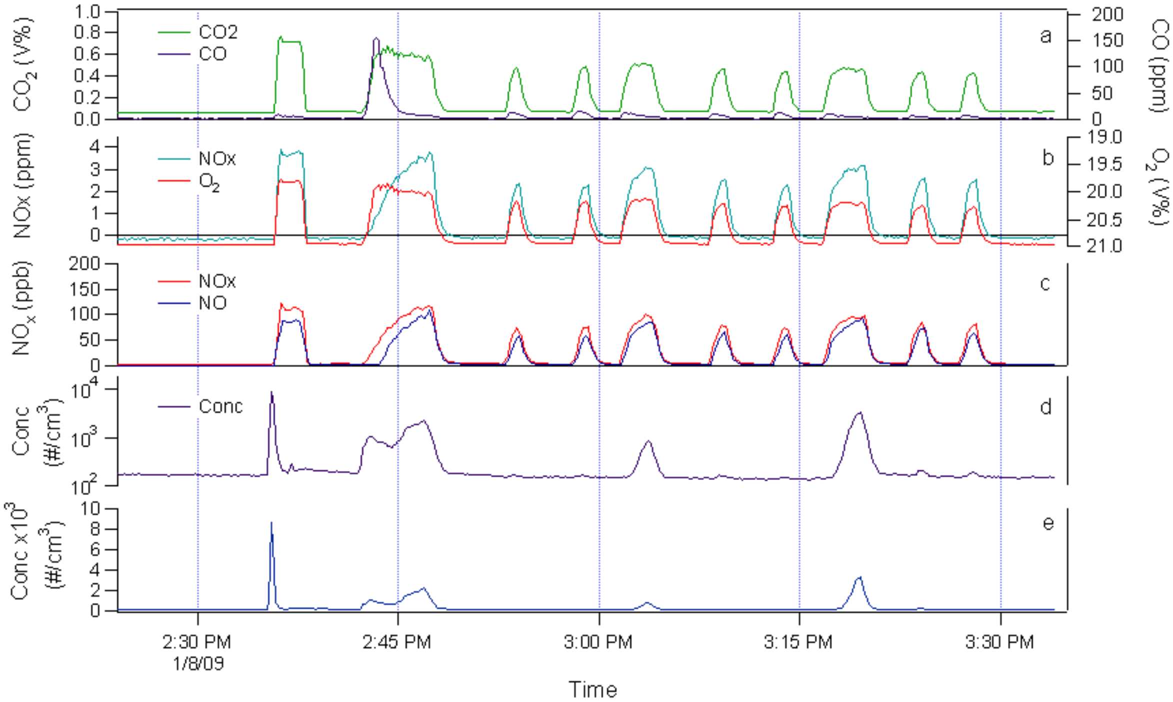

Figure 9. Measured analyte concentrations for oven OV08 with fuel 2C (L142).

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.

Table 12. Calculated air-free concentrations (using CO_2) over last 1 min of each burn; results for CO, PG250 NO_X and PN.

Exp.	Fuel	Wobbe	CO (ppm)			PG250 NO_X (ppm)			PN (10^5 cm^{-3})		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L139	PG&E	1331	113	141	88	105	76	87	15	2.9	7.9
L140	1C	1390	210	206	122	75	76	87	21	2.9	11
L141	3C	1419	323	338	180	66	69	81	13	2	9.3
L142	2C	1359	156	184	98	77	72	88	11	0.5	8.9

Table 13. Calculated air-free concentrations (using CO_2) over last 1 min of each burn; results for NO_X, NO, and NO_2 (NO_X-NO) measured with Thermo 42i.

Exp.	Fuel	Wobbe	NO_X (ppm)			NO (ppm)			NO_2 (ppm)		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L139	PG&E	1331	105	76	87	95	64	81	9.9	12.8	6.1
L140	1C	1390	75	76	87	66	65	76	9.7	11.8	11.6
L141	3C	1419	66	69	81	54	54	69	11.8	14.8	11.7
L142	2C	1359	77	72	88	63	61	78	13.6	11.1	10.1

Table 14. Calculated emission rates over entirety of first burn at each temperature setting; results for CO, PG250 NO_X and PN.

Exp.	Fuel	Wobbe	CO (μg KJ^{-1})			PG250 NO_X (μg KJ^{-1})			PN (10^7 KJ^{-1})		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L139	PG&E	1331	237	50	38	29	34	37	40	7.8	18
L140	1C	1390	291	66	52	26	35	37	61	9.6	23
L141	3C	1419	347	84	59	24	32	35	27	12	31
L142	2C	1359	237	51	36	25	32	36	17	4.7	24

Table 15. Calculated emission rates over entirety of first burn at each temperature setting; results for NO_X, NO, and NO_2 (NO_X-NO) measured with Thermo 42i.

Exp.	Fuel	Wobbe	NO_X (μg KJ^{-1})			NO (μg KJ^{-1})			NO_2 (μg KJ^{-1})		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L139	PG&E	1331	29	34	37	22	28	33	7.4	5.6	3.5
L140	1C	1390	26	35	37	18.7	28	31	7.1	6.1	6.4
L141	3C	1419	24	32	35	15.9	25	30	7.8	6.3	5.4
L142	2C	1359	25	32	36	17.5	27	31	7.9	5.2	5.2

Table 16. Calculated formaldehyde emission rates over entire period of burner operation.

Exp.	Fuel	Wobbe	HCHO (μg KJ^{-1})
L139	PG&E	1331	2.89, 3.07
L140	1C	1390	2.23
L141	3C	1419	1.64
L142	2C	1359	1.95

2.0 Oven OV09

2.1. Experimental information for OV09

Four experiments were conducted on the same day, in the following order: PG&E line gas (WN = 1328), mix 2C (WN = 1359), mix 1C (WN = 1390), and mix 3C (WN = 1419). The heater for the dilution sampler inlet was set to automatic mode. The SMPS was used to collect size-resolved particle number concentrations in the ultrafine mode (<100 nm particle diameter). Appliance manifold pressure was not measured because access was not possible without dismantling the internal fuel transfer lines.

Table 17. Appliance and burner information OV09.

Burner ID	OV09
Appliance manufacturer	Kenmore
Model number	Illegible
Serial number	Illegible
Age (years)	2 years[1]
Burner technologies	Hot surface ignition; single tube-type oven burner
Burner rating (Btu/h)	Rating label illegible
Other information	Procured December 2008
Test location	Laboratory
History notes	Identified via Craig's List. Purchased from landlord; stated reason for sale was that new tenant was bringing own stove. Frequency of use unknown. Evidence of aggressive cleaning including scratches to surface finish and rubbing away of product information label.

[1]Sellers reported this information with certainty (they had purchased unit). The date 2/17/07 was written on back of unit in permanent marker (purpose of this marking unknown).

Figure 10. Range containing OV09.

Figure 11. Oven compartment for OV09.

Figure 12. Oven bottom burner for OV09.

Figure 13. Spreader plate for oven bottom burner OV09.

Table 18. Interchangeability experiments for oven bottom burner OV09.

Exp.	Fuel	Date	Burner operation
L147	PG&E	01/08/2009	Purge burn with each fuel change using cooktop burners. Operate oven through initial ramp plus 2 maintenance cycles at 350, 425 and 500F. Cool to touch between experiments.
L148	2C		
L149	1C		
L150	3C		

Table 19. Fuel analysis for interchangeability experiments with OV09.

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
L147	PG&E	PG&E[2]	95.4%	2.27%	0.28%	0.11%	1.03%	0.89%	1015	1329
L148	2C	Cylinder[3]	92.0	8.00	-	-	-	-	1071	1390
L149	1C	Cylinder[3]	86.4	12.00	1.60	-	-	-	1125	1419
L150	3C	Cylinder[3]	90.4	7.90	-	-	1.70	-	1053	1359

[1] Calculated using the American Gas Association interchangeability program.
[2] Composition of gas distributed to LBNL, as measured by PG&E online GC.
[3] Certified composition in cylinder (determined by the supplier, AirLiquide).

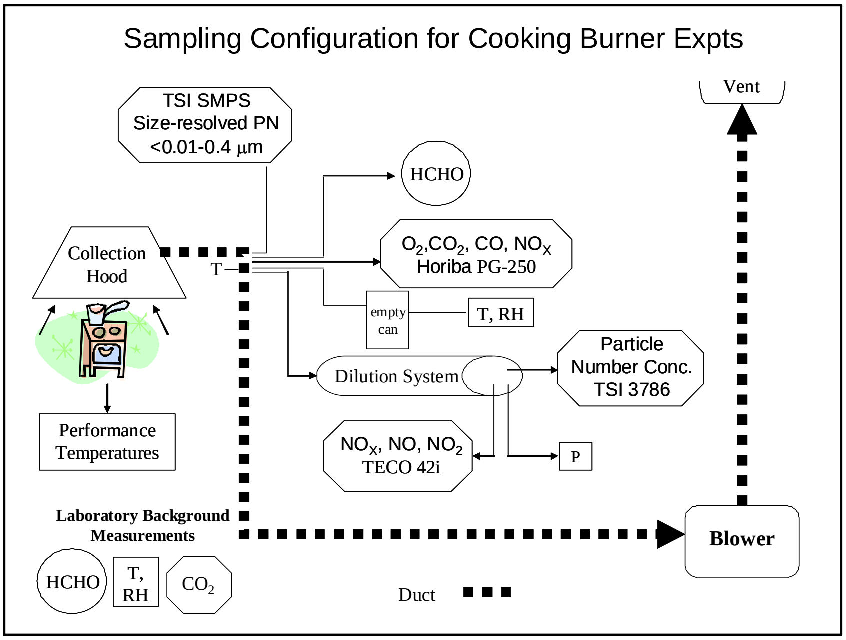

Figure 14. Analytical sampling configuration for OV09.

The empty can is used to measure RH of the airstream from the collection hood at room temperature. This indicates the potential for condensation in sampling system. PG-250 also has water removal system. HCHO sampled through 30-cm Teflon tubing (nominal ¼" diameter) for primary sample, duplicate sampled through 90-cm Teflon tubing.

Table 20. Analyte ranges and calibration levels for experiments with OV09.

Analyte	**Sample location**	**Equipment[1]**	**Range**	**Calibration levels**
Carbon dioxide (CO_2)	outlet of collection hood	Horiba PG-250	0-5%	0, 1%
Oxygen (O_2)			0-25%	0, 20.95%
Carbon monoxide (CO)			0-200 ppm	0, 40 ppm
Nitrogen oxides (NO_X)			0-25 ppm	0, 2.0 ppm[3]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-5 ppm	0, 2.0 ppm[3]
Carbon dioxide (CO_2)	laboratory air	PP Systems EGM-4	5000 ppm	Periodic[2]

[1] Horiba Environmental and Process Instruments (environ.hii.horiba.com); Thermo Fisher Scientific (thermo.com); PP Systems (ppsystems.com). [2] Not checked daily; observed to remain within 10s of ppm at ambient conditions.

Table 21. Aerosol instrumentation used for OV09.

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 part. mode	±12%
PN resolved by aerodynamic diameter	TSI 3071A classifier, TSI 3025A CPC	Sort using electrostatic classifier, count with CPC	3 nm	10^5 cm^{-3}	±10%

[1]TSI Instruments, Shoreview, MN (tsi.com). CPC = condensation particle counter. Detailed information provided in product literature. [2]50% detection. [3] Product 3001788, purchased from TSI.

Table 22. Other measurements for experiments with OV09.

Measured Quantity	Location(s)	Device(s)[1]
Fuel pressure	Gas supply line	Model 264 transducer (Setra)
Fuel volume & flow	Fuel flow to appliance during burner operation	AC-250-TC T-compensating dry gas meter with 1- and ¼-ft dials (American Meter); flow rate timed by stopwatch
Fuel flow rate	Fuel flow to appliance during burner operation	Pulse counter for AC-250-TC, 10 counts per rev (Riotronics)
Dilution sampler vacuum	Dilution tube	Setra Model 264 transducer
Temperature, combustion air	In vicinity of range	Precision NTC thermistor (APT)
Relative humidity, combustion air	In vicinity of range	Thermostet polymer based capacitance RH sensor (APT)
Temperature, air sample location in hood	At point of air sampling in duct connected to hood	Thermocouple (K), probe, Omega KQSS-18E-12
Temperature, oven	Oven interior, shelf lower and upper halves of oven	Thermocouple (K), screw-mount, Omega XCIB-K-4-2-3

[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 OV09

For each fuel, full-burn CO emissions were the highest during the initial burn – heating to 350 F – resulting from the large peak that occurred at the start of burner firing; emission rates for this burn were roughly 300-400 ng/J. Full-burn CO was lower for the ramp burn to 425 F (roughly 110-250 ng/J) and lower again for the burn to reach 500 F (85-150 ng/J). End of burn air-free CO concentrations were highest at 425 F in all four experiments (300-500 ppm). CO concentrations and emissions were similar for PG&E and mix 1C, lower for 2C and highest for mix 3C; these results indicate an unclear dependence on fuel Wobbe number for CO emissions from this burner. End of burn NO_X concentrations were higher for the 350 and 500 F burns relative to 425 F but NO_X emission rates increased with oven temperature. Full-burn NO_X emission rates were 22-26 ng/J at 350 F and 27-30 ng/J at 500 F. Full-burn NO_2 emission rates were in the range of 11-12 ng/J for all fuels and temperature settings. PN emission rates were low for all burns and all fuels with the exception of the 500 F burn with fuel 2C; PN did not start high in the first experiment and decrease throughout the day as observed in some other cooking burner experiments. Formaldehyde emission rates were lowest and similar for PG&E and fuel 3C (at roughly 0.6 ng/J), slightly higher for fuel 1C (0.7 ng/J) and substantially higher for fuel 2C (1.1 ng/J). These results do not follow the trend of the CO results.

Table 23. Burner operating parameters for experiments with oven OV09. Information provided for first burner firing at each temperature setting.

Experiment	Burn	Start Time	End Time	Firing Rate, Stopwatch[1] (kBTU h^{-1})	Supply P (in. H_2O)[2]
L147	350F	08:38	08:45	18	7.6
L147	425F	08:53	08:57		7.7
L147	500F	09:04	09:07		7.7
L148	350F	09:52	09:59	18	7.8
L148	425F	10:07	10:10		7.8
L148	500F	10:17	10:20		7.8
L149	350F	11:26	11:33	17	7.8
L149	425F	11:40	11:43		7.8
L149	500F	11:49	11:52		7.8
L150	350F	12:37	12:43	20	7.8
L150	425F	12:34	12:53		7.9
L150	500F	13:00	13:03		7.9

[1] Fuel flow calculated from stopwatch timing of 1/4-foot dial of gas meter, one timing event for the first burn at each temperature setting (n=3 per experiment). Firing rate calculated from measured fuel flow rate and higher heating value from fuel composition.

[2] Pressure in fuel supply line during burn. Pressure at outlet of appliance regulator was not readily accessible without dismantling the fuel transfer lines within the appliance, and was therefore not measured.

Table 24. Environmental conditions[1] for experiments with OV09.

Exp.	Fuel	T (°C)	RH (%)
L147	PG&E	22.4 ± 0.1	25 ± 0
L148	1C	22.7 ± 0.1	24 ± 0
L149	3C	23.3 ± 0.1	23 ± 0
L150	2C	23.2 ± 0.2	24 ± 0

[1] Measured over period of formaldehyde sample.

Table 25. Sample location temperatures and dilution ratios for each burn.

	Sample location T (°C)[1]			Dilution ratio[2]		
Exp.	350 F	425 F	500 F	350 F	425 F	500 F
L147	30 ± 1	38 ± 0	43 ± 0	24	22	23
L148	35 ± 1	43 ± 0	48 ± 0	25	24	25
L149	35 ± 0	42 ± 0	46 ± 0	24	24	24
L150	34 ± 0	40 ± 1	46 ± 0	24	24	23

[1] Measured in exhaust duct from collection hood alongside pollutant sampling inlets. Mean ± standard deviation measured over last min of each burn to achieve new temperature setting.

[2] Calculated by comparing NO_X measured in gas manifold (PG-250) and dilution sampler (Thermo 42i) over last min of each burn.

Table 26. Measured RH of sample stream at room temperature. [1]

Exp.	Gas manifold T (°C)			Gas manifold RH (%)		
	350 F	425 F	500 F	350 F	425 F	500 F
L147	20.3 ± 0	20.3 ± 0	20.4 ± 0	40 ± 1	39 ± 0	38 ± 1
L148	20.8 ± 0	20.8 ± 0	20.9 ± 0	40 ± 1	36 ± 0	36 ± 0
L149	21.1 ± 0	21.1 ± 0	21.3 ± 0	37 ± 0	36 ± 0	36 ± 0
L150	21.7 ± 0	21.6 ± 0	21.7 ± 0	38 ± 0	36 ± 0	36 ± 1

[1] Measured in 1-gal vessel in parallel sample stream from hood outlet; measured to confirm that hood dilution is sufficient to avoid condensation in sampling stream for PG-250.

Table 27. Aldehyde samples for experiments with oven OV09.

Exp(s)	Location	Date	Sample start/end time		Flow (L/min)	Air vol. (L)	HCHO extract conc. (ng/μL)	Acet. extract conc. (ng/μL)	HCHO air conc.[1] (μg/m³)	Acet. air conc.[1] (μg/m³)
Bkg	Lab air	01/15/09	8:35	13:10	1.03	283	0.346	0.181	2	1
L147a	Collection hood outlet	01/15/09	8:35	9:16	1.06	44	0.924	0.141	42	6
L147b			8:35	9:16	1.12	46	0.975	0.146	42	6
L148			9:49	10:28	1.04	41	1.500	0.150	74	7
L149			11:23	11:59	1.06	38	1.032	0.125	54	7
L150			12:34	13:10	1.05	38	0.895	0.149	47	8

[1] Concentration in the air stream being sampled for other gaseous analytes.

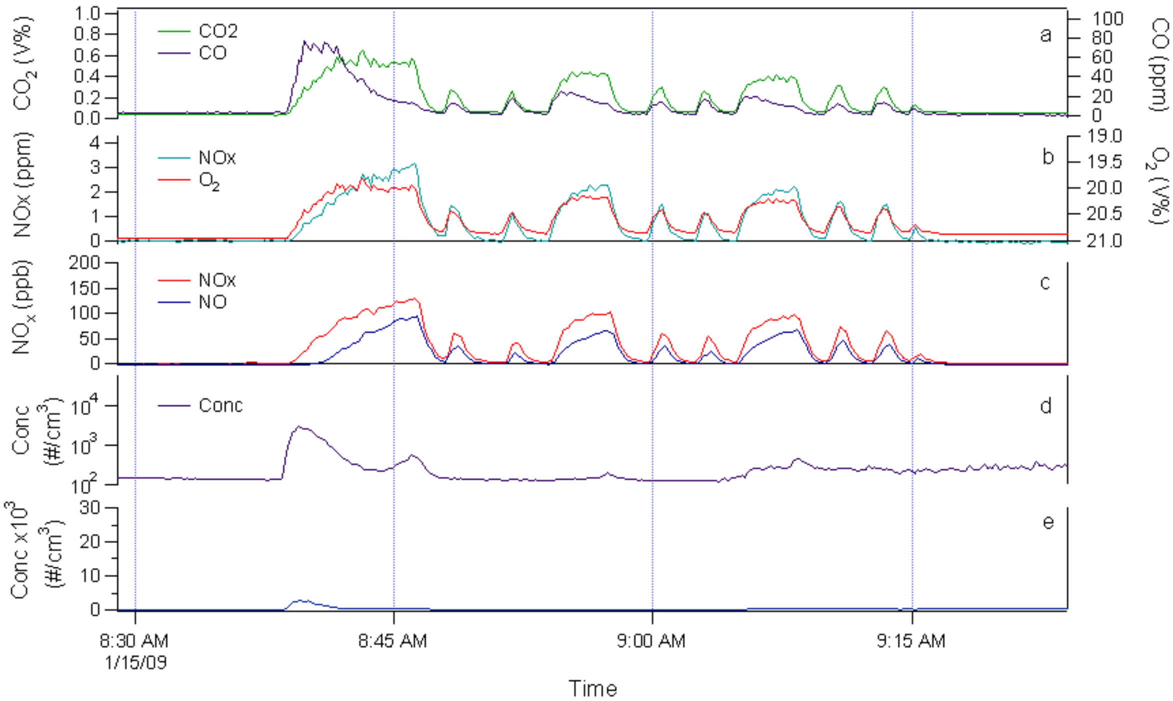

Figure 15. Measured analyte concentrations for oven OV09 with PG&E line gas (L147).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

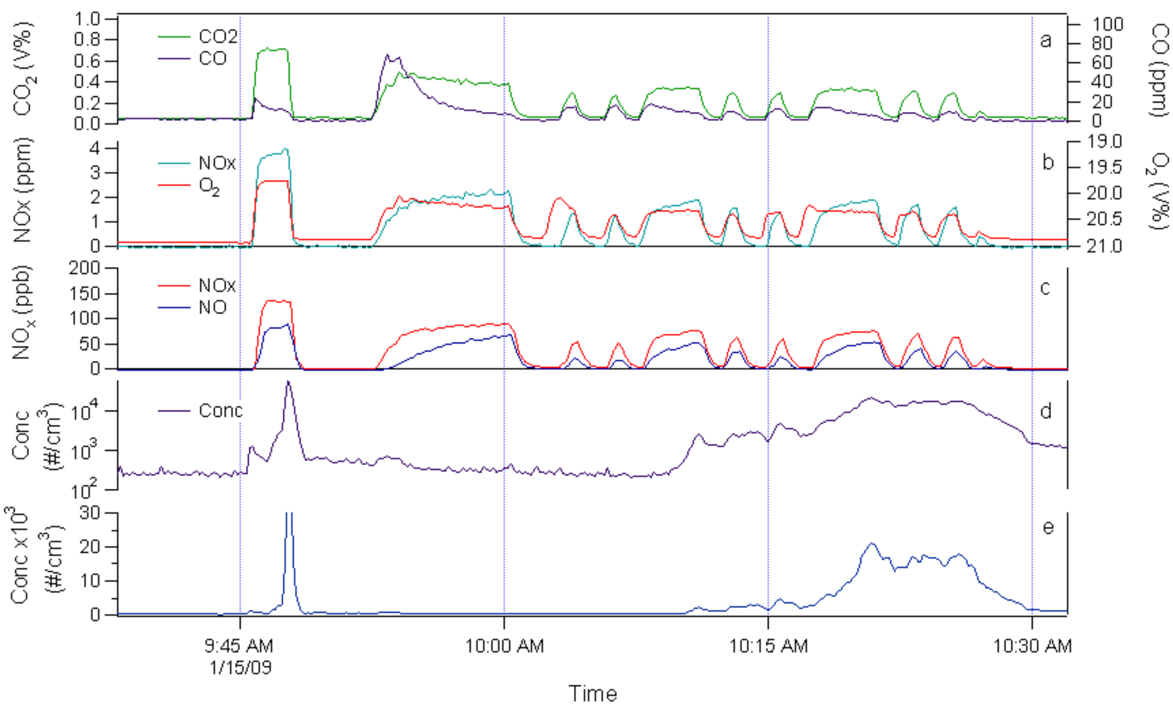

Figure 16. Measured analyte concentrations for oven OV09 with fuel 2C (L148).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

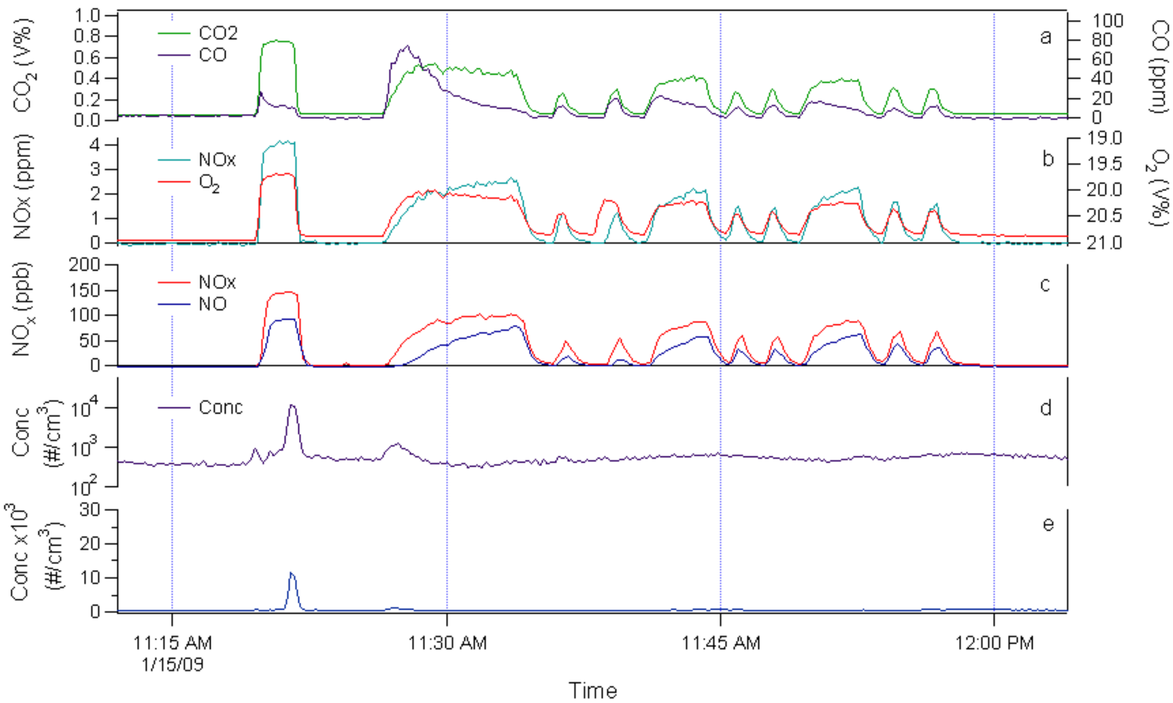

Figure 17. Measured analyte concentrations for oven OV09 with fuel 3C (L149).

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.

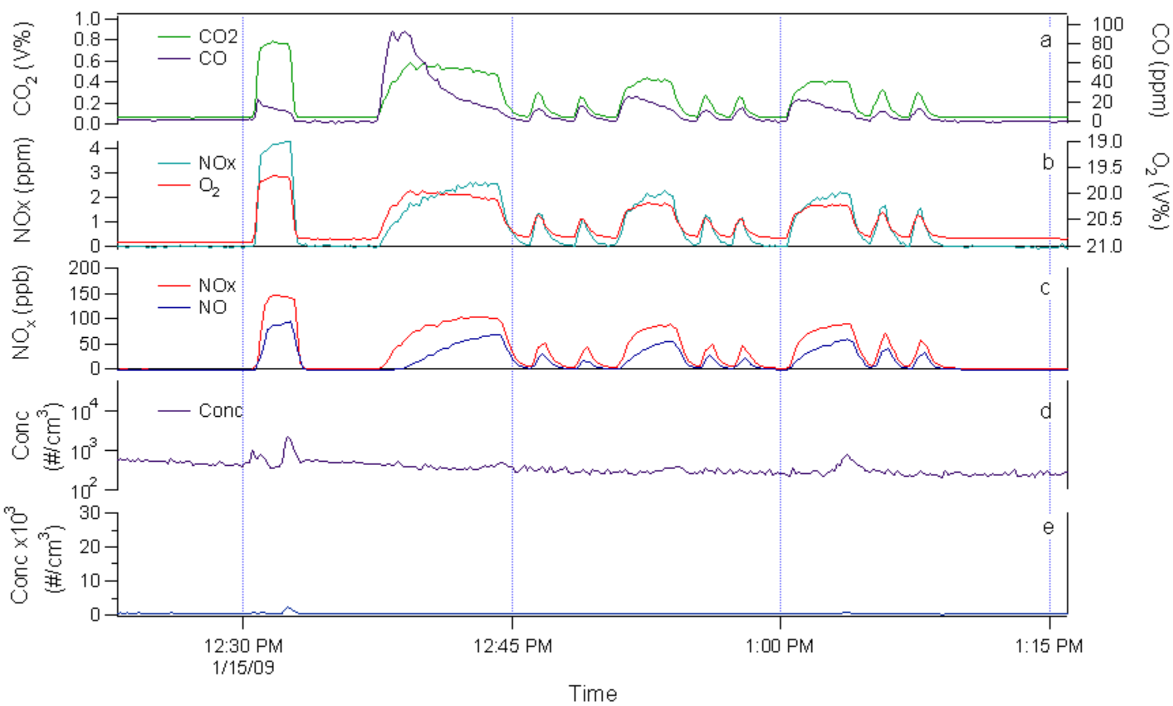

Figure 18. Measured analyte concentrations for oven OV09 with fuel 1C (L150).

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.

Table 28. Calculated air-free concentrations (using CO_2) over last 1 min of each burn; results for CO, PG250 NO and PN.

Exp.	Fuel	Wobbe	CO (ppm)			PG250 NO_X (ppm)			PN (10^5 cm^{-3})		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L147	PG&E	1329	280	369	302	71	67	71	0.7	-0.4	0.6
L148	2C	1359	205	298	206	76	71	77	-0.1	1.9	130
L149	1C	1390	261	381	330	71	66	70	-0.9	0.8	-0.2
L150	3C	1419	392	510	395	66	64	66	-0.2	-0.8	-0.8

Table 29. Calculated air-free concentrations (using CO_2) over last 1 min of each burn; results for NO_X, NO, and NO_2 (NO_X-NO) measured with Thermo 42i.

Exp.	Fuel	Wobbe	NO_X (ppm)			NO (ppm)			NO_2 (ppm)		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L147	PG&E	1329	71	67	71	51	41	48	19.9	25.4	22.3
L148	2C	1359	76	71	77	56	46	54	20.4	24.8	22.8
L149	1C	1390	71	66	70	53	42	46	18.8	23.8	24.2
L150	3C	1419	66	64	66	42	38	42	23.4	25.6	24.9

Table 30. Calculated emission rates over entirety of first burn at each temperature setting; results for CO, PG250 NO and PN.

Exp.	Fuel	Wobbe	CO (μg KJ^{-1})			PG250 NO_X (μg KJ^{-1})			PN (10^7 KJ^{-1})		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L147	PG&E	1329	275	135	113	25	28	29	10	-1	1.5
L148	2C	1359	204	107	86	26	29	30	1.2	11	270
L149	1C	1390	230	139	112	25	27	29	0.2	2.4	0.1
L150	3C	1419	305	246	147	22	22	27	-0.1	-0.8	-1

Table 31. Calculated emission rates over entirety of first burn at each temperature setting; results for NO_X, NO, and NO_2 (NO_X-NO) measured with Thermo 42i.

Exp.	Fuel	Wobbe	NO_X (μg KJ^{-1})			NO (μg KJ^{-1})			NO_2 (μg KJ^{-1})		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L147	PG&E	1329	25	28	29	13.4	16.4	18.5	11.3	11.6	11.0
L148	2C	1359	26	29	30	14.8	17.4	18.9	11.4	11.7	11.2
L149	1C	1390	25	27	29	13.9	15.7	18.2	10.9	11.1	10.9
L150	3C	1419	22	22	27	10.4	10.8	16.1	11.7	11.2	11.3

Table 32. Calculated formaldehyde emission rates over entire period of burner operation.

Exp.	Fuel	Wobbe	HCHO (μg KJ^{-1})
L147	PG&E	1329	0.61, 0.60
L148	2C	1359	1.11
L149	1C	1390	0.73
L150	3C	1419	0.63

3.0 Oven OV10

3.1. Experimental information for OV10

Five experiments were conducted on the same day, in the following order: PG&E line gas (WN = 1333), mix 2C (WN = 1390), mix 1C (WN = 1359), mix 3C (WN = 1419), and mix 2C (which was repeated because of a sampling issue with the aldehyde sample for the first fuel experiments with OV10 using fuel 2C. The heater for the dilution sampler inlet was set to automatic mode. The SMPS was used to collect size-resolved particle number concentrations in the ultrafine mode (<100 nm particle diameter). Appliance manifold pressure was not measured because access was not possible without dismantling the internal fuel transfer lines. This range is the same as OV07.

Table 33. Appliance and burner information OV10.

Burner ID	OV10
Appliance manufacturer	General Electric
Model number	JGB520BEW2WH (XL44)
Serial number	DS121180R
Year of manufacture	1997
Burner technologies	Hot surface ignition; single tube-type oven burner
Burner rating (Btu/h)	18,000
Other information	Procured January 2009
Test location	Laboratory
History notes	Identified via Craig's List. Seller was selling on behalf of family member. Frequency of use unknown.

Figure 19. Range containing OV10.

Figure 20. Oven compartment for OV10.

Figure 21. Oven bottom burner OV10.

Figure 22. Spreader plate for oven bottom burner OV10.

Table 34. Interchangeability experiments for oven bottom burner OV10.

Exp.	Fuel	Date	Burner operation
L155	PG&E	01/22/2009	Purge burn with each fuel change using cooktop burners. Operate oven through initial ramp plus 2 maintenance cycles at 350, 425 and 500F. Cool to touch between experiments.
L156	2C		
L157	1C		
L158	3C		
L159	2C		

Table 35. Fuel analysis for interchangeability experiments with OV10.

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
L155	PG&E	PG&E[2]	95.3	2.41	0.32	0.12	0.98	0.82	1018	1333
L156, L159	2C	Cylinder[3]	90.4	7.90	-	-	1.70	-	1053	1359
L157	1C	Cylinder[3]	92.0	8.00	-	-	-	-	1071	1390
L158	3C	Cylinder[3]	86.4	12.00	1.60	-	-	-	1125	1419

[1] Calculated using the American Gas Association interchangeability program.
[2] Composition of gas distributed to LBNL, as measured by PG&E online GC.
[3] Certified composition in cylinder (determined by the supplier, AirLiquide).

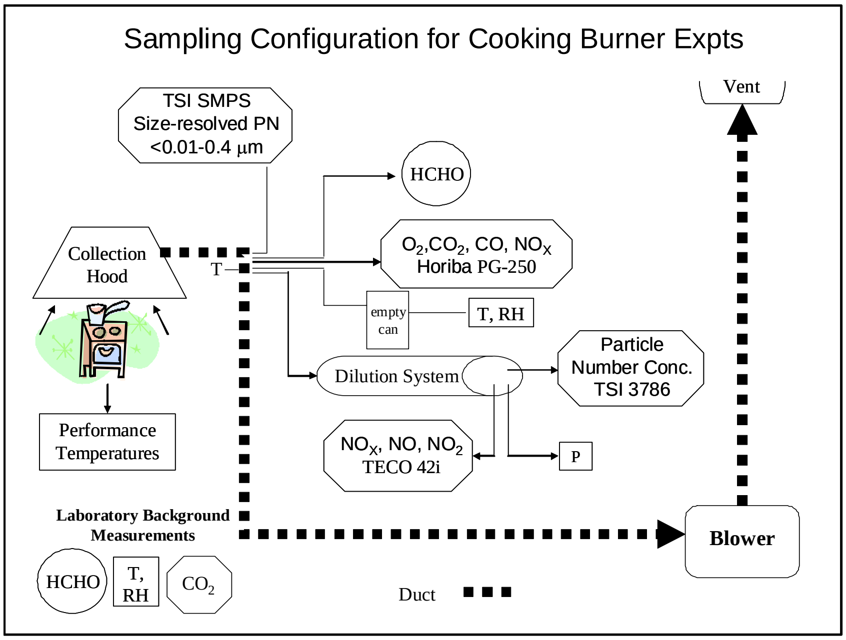

Figure 23. Analytical sampling configuration for OV10.

The empty can is used to measure RH of the airstream from the collection hood at room temperature. This indicates the potential for condensation in sampling system. PG-250 also has water removal system. HCHO sampled through 30-cm Teflon tubing (nominal ¼" diameter) for primary sample, duplicate sampled through 90-cm Teflon tubing.

Table 36. Analyte ranges and calibration levels for experiments with OV10.

Analyte	Sample location	Equipment[1]	Range	Calibration levels
Carbon dioxide (CO_2)	outlet of collection hood	Horiba PG-250	0-5%	0, 1%
Oxygen (O_2)			0-25%	0, 20.95%
Carbon monoxide (CO)			0-200 ppm	0, 40 ppm
Nitrogen oxides (NO_X)			0-25 ppm	0, 4.0 ppm[3]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-5 ppm	0, 2.0 ppm[3]
Carbon dioxide (CO_2)	laboratory air	PP Systems EGM-4	5000 ppm	Periodic[2]

[1] Horiba Environmental and Process Instruments (environ.hii.horiba.com); Thermo Fisher Scientific (thermo.com); PP Systems (ppsystems.com). [2] Not checked daily; observed to remain within 10s of ppm at ambient conditions.

Table 37. Aerosol instrumentation used for OV10.

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 part. mode	±12%
PN resolved by aerodynamic diameter	TSI 3071A classifier, TSI 3025A CPC	Sort using electrostatic classifier, count with CPC	3 nm	10^5 cm^{-3}	±10%

[1]TSI Instruments, Shoreview, MN (tsi.com). CPC = condensation particle counter. Detailed information provided in product literature. [2]50% detection. [3] Product 3001788, purchased from TSI.

Table 38. Other measurements for experiments with OV10.

Measured Quantity	Location(s)	Device(s)[1]
Fuel pressure	Gas supply line	Model 264 transducer (Setra)
Fuel volume & flow	Fuel flow to appliance during burner operation	AC-250-TC T-compensating dry gas meter with 1- and ¼-ft dials (American Meter); flow rate timed by stopwatch
Fuel flow rate	Fuel flow to appliance during burner operation	Pulse counter for AC-250-TC, 10 counts per rev (Riotronics)
Dilution sampler vacuum	Dilution tube	Setra Model 264 transducer
Temperature, combustion air	In vicinity of range	Precision NTC thermistor (APT)
Relative humidity, combustion air	In vicinity of range	Thermostet polymer based capacitance RH sensor (APT)
Temperature, air sample location in hood	At point of air sampling in duct connected to hood	Thermocouple (K), probe, Omega KQSS-18E-12
Temperature, oven	Oven interior, shelf lower and upper halves of oven	Thermocouple (K), screw-mount, Omega XCIB-K-4-2-3

[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 OV10

CO concentrations and emissions were highest at the lowest temperature setting (first burn) with each fuel. End of burn air-free CO concentrations were similar for burns at 350 and 425 F and somewhat lower at 500 F within each experiment; end-of-burn air-free CO was in the range of 93 to 220 ppm. CO increased monotonically with fuel Wobbe number. CO was roughly 40-70% higher for fuel (3C) compared to PG&E line gas. PN end-of-burn concentrations and full-burn emission rates were of similar order for 350 F and 425 F burns, and more than an order of magnitude higher for 500 F burns. As observed for many cooking burners, PN concentrations and emissions were highest in the first experiment, which again used PG&E fuel. PN decreased over the next several experiments which featured an increasing progression of Wobbe number fuels. PN increased slightly (likely not a robust effect given the variation in PN) when going from fuel 3C (L158) to fuel 2C in L159. Full-burn NO_2 emissions appear to increase with fuel Wobbe number whereas there is not a clear trend for NO_X. Formaldehyde emissions were similar for all fuels. Full burn emission rates were 94-132 ng/J for CO (350 F setting; highest for CO), 35-37 ng/J for NO_X (500 F setting; highest for NO_X), 310-890 x 10^4 J^{-1} for PN at 500 F setting, and 0.30-0.35 ng/J for HCHO.

Table 39. Burner operating parameters for experiments with oven OV10.

Experiment	Burn	Start Time	End Time	Firing Rate, Stopwatch[1] (kBTU h^{-1})	Supply P (in. H_2O)[2]
L155	350F	08:09	08:20		7.7
L155	425F	08:26	08:32	15	7.7
L155	500F	08:38	08:46		7.7
L156	350F	09:30	09:41		7.8
L156	425F	09:48	09:53	17	7.8
L156	500F	09:59	10:06		7.8
L157	350F	10:47	10:58		7.8
L157	425F	11:04	11:09	17	7.8
L157	500F	11:15	11:22		7.8
L158	350F	12:21	12:31		7.8
L158	425F	12:37	12:42	16	7.8
L158	500F	12:47	12:54		7.8
L159	350F	13:37	13:48		7.8
L159	425F	13:54	13:59	15	7.8
L159	500F	14:05	14:13		7.8

[1] Fuel flow calculated from stopwatch timing of 1/4-foot dial of gas meter. Firing rate calculated from measured fuel flow rate and higher heating value from fuel composition.
[2] Pressure in fuel supply line during burn. Pressure at outlet of appliance regulator was not readily accessible without dismantling the fuel transfer lines within the appliance, and was therefore not measured.

Table 40. Environmental conditions[1] for experiments with OV10.

Exp.	Fuel	T (°C)	RH (%)
L155	PG&E	20.7 ± 0.4	56 ± 1
L156	2C	21.2 ± 0.2	55 ± 1
L157	1C	21.4 ± 0.1	54 ± 0
L158	3C	21.8 ± 0.3	54 ± 1
L159	2C	22.0 ± 0.3	54 ± 1

[1] Measured over period of formaldehyde sample.

Table 41. Sample location temperatures and dilution ratios for each burn.

	Sample location T (°C)[1]			Dilution ratio[2]		
Exp.	350 F	425 F	500 F	350 F	425 F	500 F
L155	44 ± 1	53 ± 0	61 ± 0	28	27	27
L156	47 ± 1	55 ± 0	62 ± 0	29	28	28
L157	47 ± 1	54 ± 1	61 ± 0	29	28	28
L158	47 ± 0	54 ± 0	61 ± 0	29	28	28
L159	47 ± 1	54 ± 1	62 ± 0	29	29	28

[1] Measured in exhaust duct from collection hood alongside pollutant sampling inlets. Mean ± standard deviation measured over last min of each burn to achieve new temperature setting.
[2] Calculated by comparing NO_X measured in gas manifold (PG-250) and dilution sampler (Thermo 42i) over last min of each burn.

Table 42. Measured RH of sample stream at room temperature. [1]

Exp.	Gas manifold T (°C)			Gas manifold RH (%)		
	350 F	425 F	500 F	350 F	425 F	500 F
L155	19.3 ± 0	19.7 ± 0	20 ± 0	57 ± 0	56 ± 0	55 ± 0
L156	19.8 ± 0	20.1 ± 0	20.3 ± 0	56 ± 0	55 ± 0	55 ± 0
L157	20.1 ± 0	20.2 ± 0	20.5 ± 0	54 ± 0	54 ± 0	54 ± 0
L158	20.0 ± 0	20.2 ± 0	20.5 ± 0	54 ± 0	54 ± 0	54 ± 0
L159	20.2 ± 0	20.4 ± 0	20.7 ± 0	54 ± 0	54 ± 0	54 ± 0

[1] Measured in 1-gal vessel in parallel sample stream from hood outlet; measured to confirm that hood dilution is sufficient to avoid condensation in sampling stream for PG-250.

Table 43. Aldehyde samples for experiments with oven OV10.

Exp(s)	Location	Date	Sample start/end time		Flow (L/min)	Air vol. (L)	HCHO extract conc. (ng/μL)	Acet. extract conc. (ng/μL)	HCHO air conc.[1] (μg/m³)	Acet. air conc.[1] (μg/m³)
Bkg	Lab air	01/22/09	8:05	14:21	1.05	396	0.609	0.329	3	2
L155a	Collection hood outlet	01/22/09	8:05	8:55	1.09	55	1.143	0.259	42	9
L155b			8:05	8:55	1.23	62	1.101	0.272	36	9
L156[2]			-	-	-	-	-	-	-	-
L157			10:44	11:30	1.04	48	0.918	0.191	38	8
L158			12:17	13:02	1.07	49	0.961	0.207	40	9
L159			13:34	14:21	1.07	50	0.964	0.196	38	8

[1] Concentration in the air stream being sampled for other gaseous analytes.
[2] L156 sample not valid.

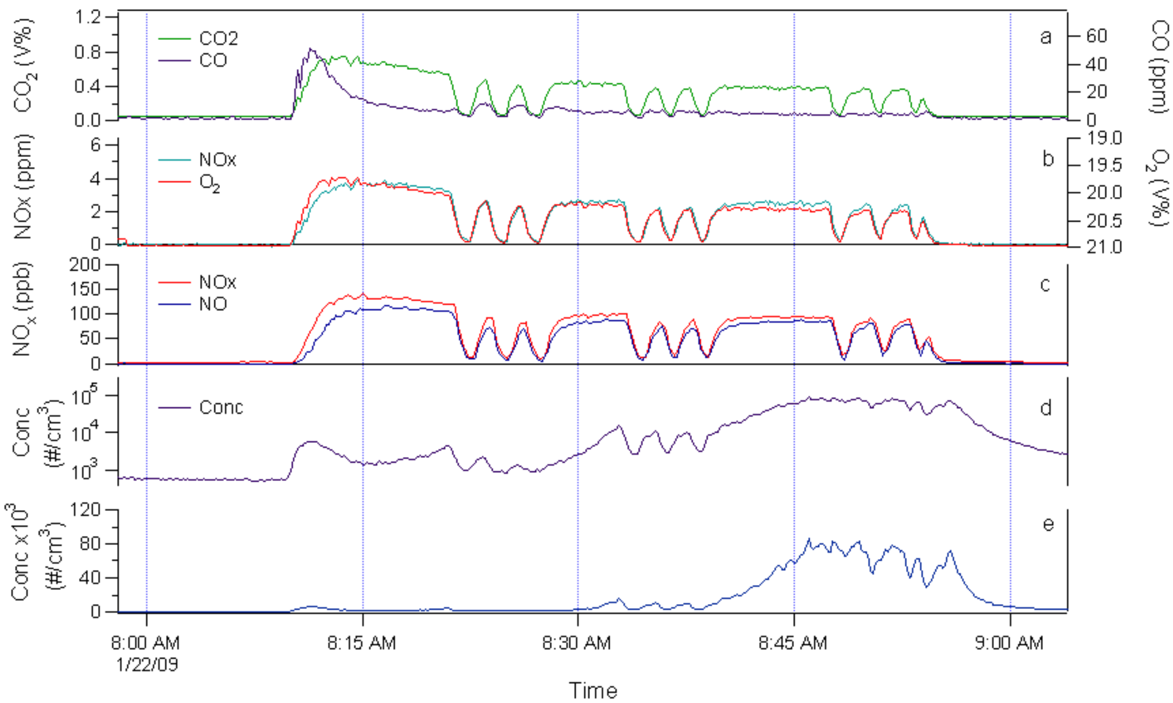

Figure 24. **Measured analyte concentrations for oven OV10 with PG&E line gas (L155).**
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

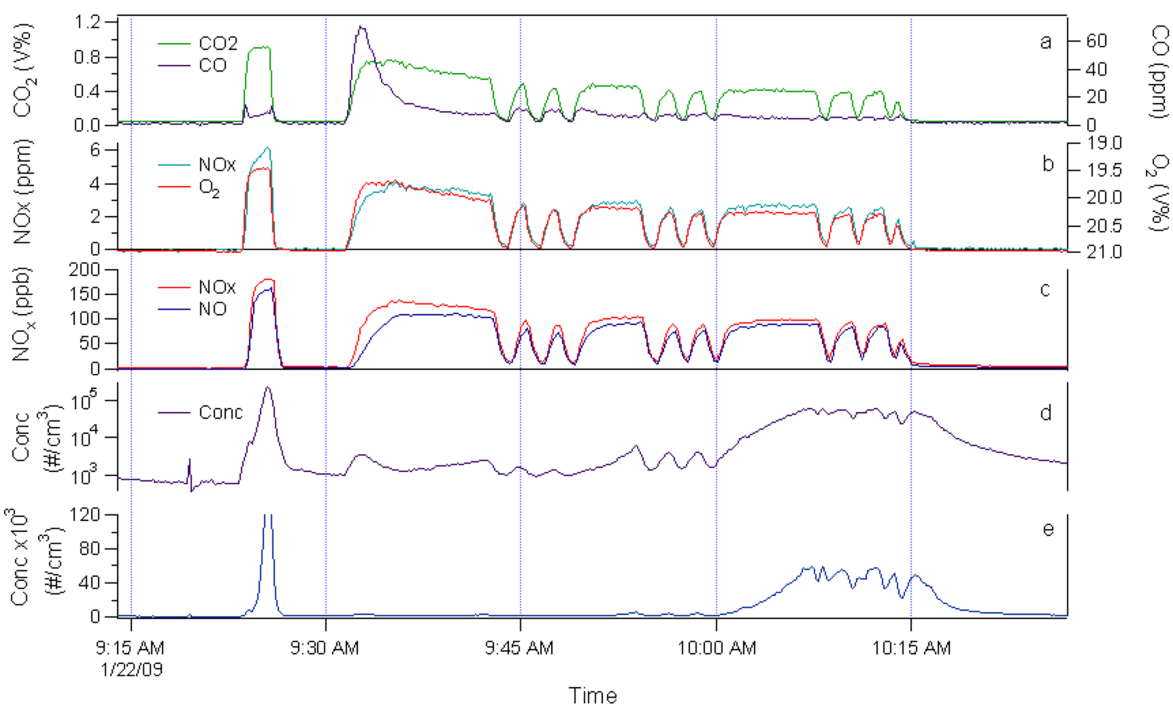

Figure 25. **Measured analyte concentrations for oven OV10 with fuel 2C (L156).**
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

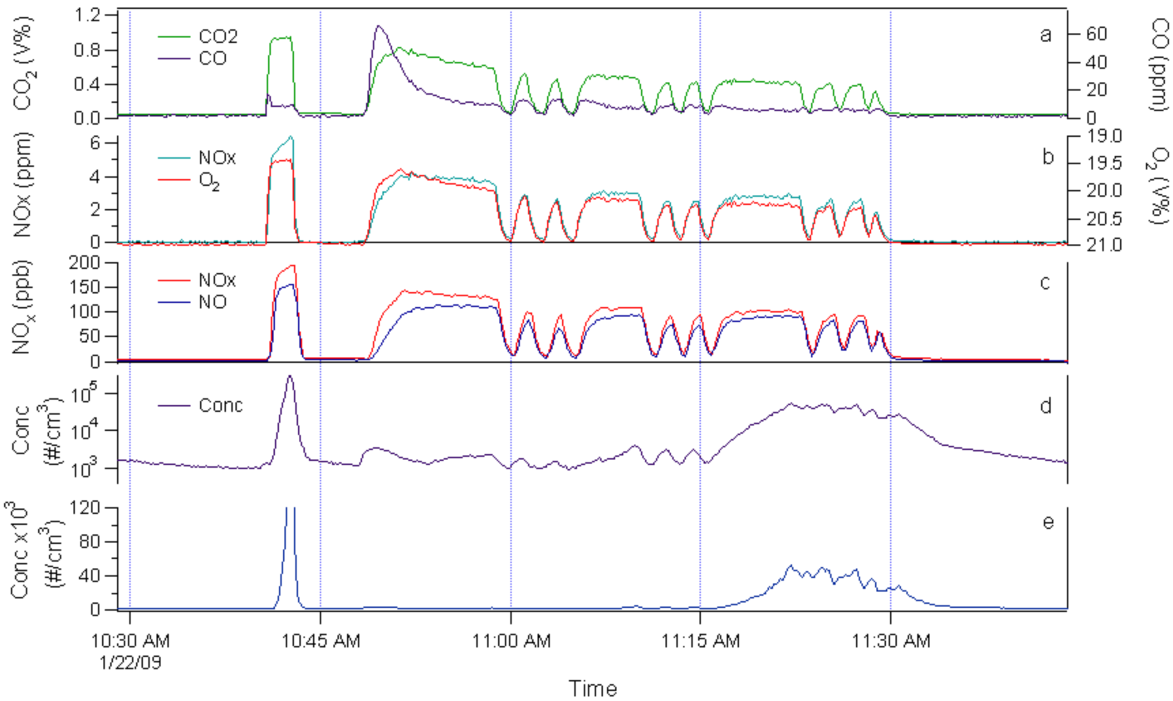

Figure 26. Measured analyte concentrations for oven OV10 with fuel 1C (L157).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

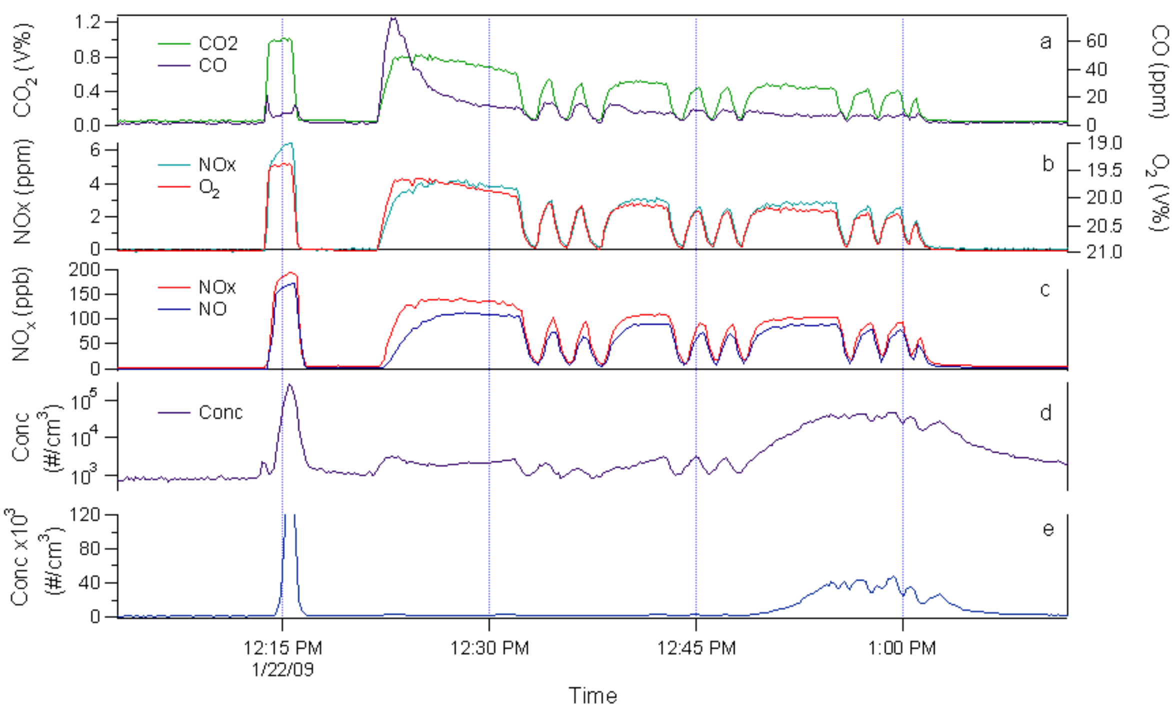

Figure 27. Measured analyte concentrations for oven OV10 with fuel 3C (L158).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

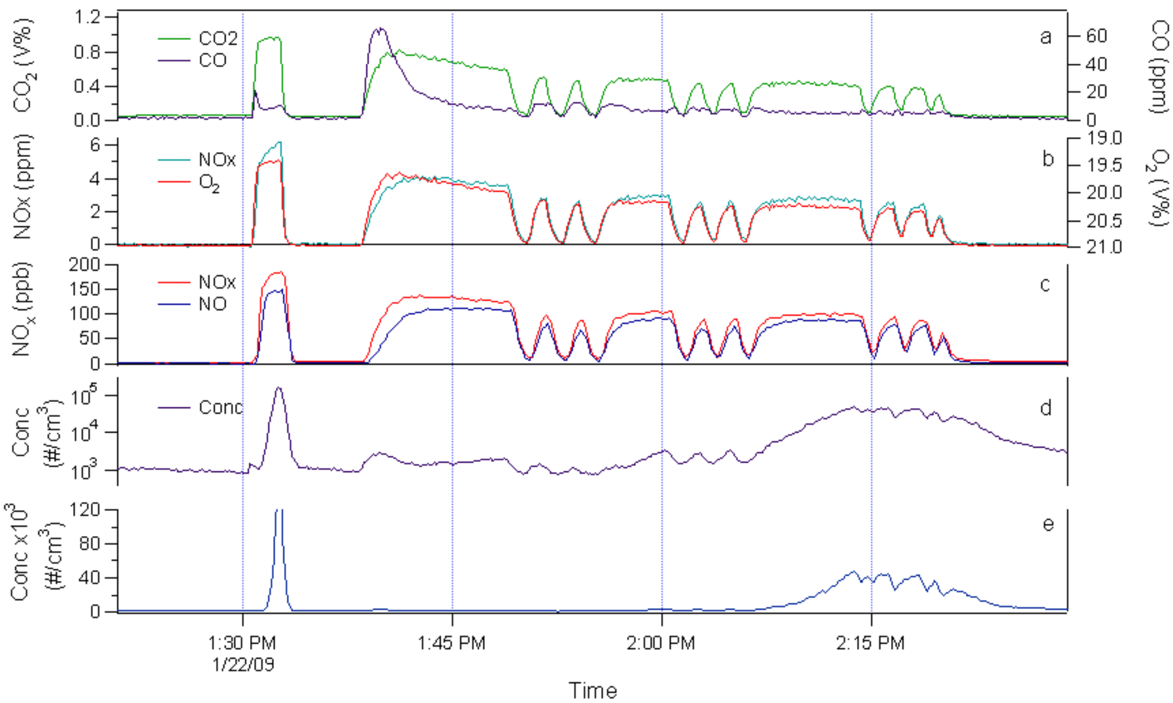

Figure 28. Measured analyte concentrations for oven OV10 with fuel 2C (L159).

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.

Table 44. Calculated air-free concentrations (using CO_2) over last 1 min of each burn; CO, NO_x, PN.

Exp.	Fuel	Wobbe	CO (ppm)			PG250 NO_X (ppm)			PN (10^5 cm^{-3})		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L155	PG&E	1333	130	135	95	77	79	87	14	57	690
L156	2C	1359	142	135	93	77	81	86	8.8	18	410
L157	1C	1390	174	155	114	77	80	87	7.2	10	300
L158	3C	1419	220	200	162	75	79	85	8.3	10	240
L159	2C	1359	141	135	99	76	80	86	5.7	10	310

Table 45. Calculated air-free concentrations (using CO_2) over last 1 min of each burn; NO_x, NO, and NO_2 (NO_x-NO) measured with Thermo 42i.

Exp.	Fuel	Wobbe	NO_X (ppm)			NO (ppm)			NO_2 (ppm)		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L155	PG&E	1333	77	79	87	68	72	81	8.8	7.0	6.0
L156	2C	1359	77	81	86	69	73	81	8.6	8.1	5.3
L157	1C	1390	77	80	87	66	69	78	11.4	11.2	8.3
L158	3C	1419	75	79	85	62	67	74	13.2	12.2	11.5
L159	2C	1359	76	80	86	67	70	76	8.7	10.2	9.7

Table 46. Calculated emission rates over entirety of first burn at each temperature setting; CO, NO_X, PN.

Exp.	Fuel	Wobbe	CO ($\mu g\ KJ^{-1}$)			PG250 NO_X ($\mu g\ KJ^{-1}$)			PN ($10^7\ KJ^{-1}$)		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L155	PG&E	1333	94	46	33	29	33	37	29	84	890
L156	2C	1359	108	53	37	30	34	36	15	31	490
L157	1C	1390	117	58	42	30	35	37	16	22	390
L158	3C	1419	132	68	52	29	34	35	17	20	310
L159	2C	1359	108	52	35	29	34	36	11	16	360

Table 47. Calculated emission rates over entirety of first burn at each temperature setting; NO_X, NO, and NO_2 (NO_X-NO) measured with Thermo 42i.

Exp.	Fuel	Wobbe	NO_X ($\mu g\ KJ^{-1}$)			NO ($\mu g\ KJ^{-1}$)			NO_2 ($\mu g\ KJ^{-1}$)		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L155	PG&E	1333	29	33	37	24	29	33	5.6	4.3	3.3
L156	2C	1359	30	34	36	23	29	33	6.1	4.3	3.2
L157	1C	1390	30	35	37	23	29	33	6.9	5.4	4.1
L158	3C	1419	29	34	35	22	28	30	7.5	6.0	5.0
L159	2C	1359	29	34	36	23	29	32	6.4	4.8	4.2

Table 48. Calculated formaldehyde emission rates over entire period of burner operation.

Exp.	Fuel	Wobbe	HCHO ($\mu g\ KJ^{-1}$)
L155	PG&E	1333	0.30, 0.35
L156	2C	1359	Not measured
L157	1C	1390	0.30
L158	3C	1419	0.30
L159	2C	1359	0.29

4.0 Oven OV11

4.1. Experimental information for OV11

Four experiments were conducted on the same day, in the following order: PG&E line gas (WN = 1334), mix 1C (WN = 1390), mix 3C (WN = 1419), and mix 2C (WN = 1359). The heater for the dilution sampler inlet was set to automatic mode. The heater for the dilution sampler inlet was set to automatic mode. The SMPS was used to sample size-resolved particle number concentrations in the ultrafine mode (<100 nm particle diameter). Appliance manifold pressure was not measured because access was not possible without dismantling the internal fuel transfer lines. To assess the potential for condensation in gas sampling lines, RH was measured in an air sampling stream allowed to come to room temperature by pulling a sample stream through a using a 1-gal vessel; this sample was drawn parallel to the sampling stream of the PG-250 gas analyzer.

Table 49. Appliance and burner information OV11.

Burner ID	OV11
Appliance manufacturer	General Electric
Model number	JGBP35BEA5BB (Spectra)
Serial number	DA245208P
Manufacture year	2001
Burner technologies	Hot surface ignition; single tube-type oven burner
Burner rating (Btu/h)	16,000
Other information	Procured January 2009
Test location	Laboratory
History notes	Procured from used appliance dealer in San Jose, California. History unknown but seller provided 90-day warranty.

Figure 29. **Oven compartment for OV11.**


Figure 30. Oven bottom burner OV11.


Figure 31. Spreader plate for oven bottom burner OV11.

Table 50. Interchangeability experiments for oven bottom burner OV11.

Exp.	Fuel	Date	Burner operation
L164	PG&E	01/27/2009	This burner was unusual in that the setting temperatures were was not achieved in many cases.[1] As a result, the burner did not cycle on/off. OV11 was operated at each temperature setting (350, 425, 500 °F) for 15 min regardless of cycling. A purge burn occurred with each fuel change using cooktop burners as usual. Oven was cooled to touch between experiments.
L165	1C		
L166	3C		
L167	2C		

[1]Based on measured gas flow rate, it appears the problem was insufficient gas supply / firing rate.

Table 51. Fuel analysis for interchangeability experiments with OV11.

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
L164	PG&E	PG&E [2]	95.4	2.41	0.32	0.11	0.90	0.82	1018	1334
L165	1C	Cylinder[3]	92.0	8.00	-	-	-	-	1071	1390
L166	3C	Cylinder[3]	86.4	12.00	1.60	-	-	-	1125	1419
L167	2C	Cylinder[3]	90.4	7.90	-	-	1.70	-	1053	1359

[1] Calculated using the American Gas Association interchangeability program.
[2] Composition of gas distributed to LBNL, as measured by PG&E online GC.
[3] Certified composition in cylinder (determined by the supplier, AirLiquide).

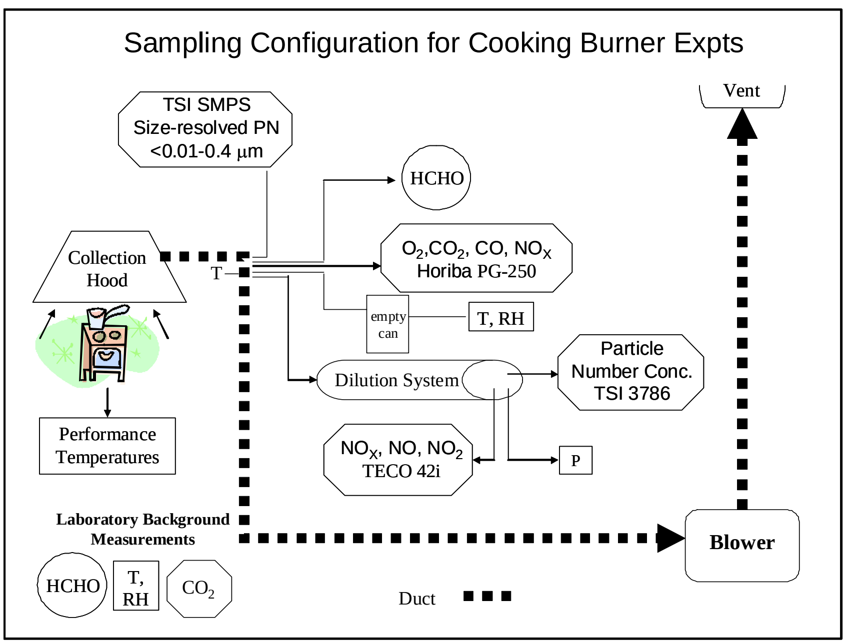

Figure 32. Analytical sampling configuration for OV11.

The empty can is used to measure RH of the airstream from the collection hood at room temperature. This indicates the potential for condensation in sampling system. PG-250 also has water removal system. HCHO sampled through 30-cm Teflon tubing (nominal ¼" diameter) for primary sample, duplicate sampled through 90-cm Teflon tubing.

Table 52. Analyte ranges and calibration levels for experiments with OV11.

Analyte	Sample location	Equipment[1]	Range	Calibration levels
Carbon dioxide (CO_2)	outlet of collection hood	Horiba PG-250	0-5%	0, 1%
Oxygen (O_2)			0-25%	0, 20.95%
Carbon monoxide (CO)			0-200 ppm	0, 40 ppm
Nitrogen oxides (NO_X)			0-25 ppm	0, 2.0 ppm[3]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-5 ppm	0, 2.0 ppm[3]
Carbon dioxide (CO_2)	laboratory air	PP Systems EGM-4	5000 ppm	Periodic[2]

[1] Horiba Environmental and Process Instruments (environ.hii.horiba.com); Thermo Fisher Scientific (thermo.com); PP Systems (ppsystems.com). [2] Not checked daily; observed to remain within 10s of ppm at ambient conditions.

Table 53. Aerosol instrumentation used for OV11.

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 part. mode	±12%
PN resolved by aerodynamic diameter	TSI 3071A classifier, TSI 3025A CPC	Sort using electrostatic classifier, count with CPC	3 nm	10^5 cm^{-3}	±10%

[1]TSI Instruments, Shoreview, MN (tsi.com). CPC = condensation particle counter. Detailed information provided in product literature. [2]50% detection. [3] Product 3001788, purchased from TSI.

Table 54. Other measurements for experiments with OV11.

Measured Quantity	Location(s)	Device(s)[1]
Fuel pressure	Gas supply line	Model 264 transducer (Setra)
Fuel volume & flow	Fuel flow to appliance during burner operation	AC-250-TC T-compensating dry gas meter with 1- and ¼-ft dials (American Meter); flow rate timed by stopwatch
Fuel flow rate	Fuel flow to appliance during burner operation	Pulse counter for AC-250-TC, 10 counts per rev (Riotronics)
Dilution sampler vacuum	Dilution tube	Setra Model 264 transducer
Temperature, combustion air	In vicinity of range	Precision NTC thermistor (APT)
Relative humidity, combustion air	In vicinity of range	Thermostet polymer based capacitance RH sensor (APT)
Temperature, air sample location in hood	At point of air sampling in duct connected to hood	Thermocouple (K), probe, Omega KQSS-18E-12
Temperature, oven	Oven interior, shelf lower and upper halves of oven	Thermocouple (K), screw-mount, Omega XCIB-K-4-2-3

[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 OV11

This burner exhibited impaired operation as indicated by the low measured firing rates and failure to reach temperatures of 350 and 500 °F during the 15-min interval allowed for each setting (425 °F was achieved for all fuels except PG&E line gas). There was no obvious indication of tampering or changes to fuel supply system. While the observed performance clearly indicates a problem for a trained technician or knowledgeable user, it is not known whether the delay in reaching each temperature setting would be observed by most users, and if observed, would this observation lead to repair or removal of the appliance. It is assumed that since the over burner starts reliably, remains lit and provides heat to the oven, at least some users would continue to operate such an appliance in their homes. For this reason, the results are retained as relevant to the population of in-use appliances.

Owing to the impaired burner operation and lack of typical cycling behavior, this oven did not show typical patterns of transient pollutant emissions. End-of-burn results were calculated for the last one minute of operation at a given temperature setting if there was not a discernible first burn followed by cycling. As shown in the figures below, exhaust concentrations were at stable levels during each temperature setting, following an initial broad peak after the initial ignition. The breadth of the initial peak may be an indicator of a longer time required for the burner and/or spreader to achieve a stable operating temperature, resulting in turn from the lower firing rate. Full-burn emissions were calculated over the entire period of operation.

Full-burn CO emission rates were highest at 350 F for all fuels but there was not a consistent pattern for 425 and 500 F burns. Full-burn CO emissions appeared to decrease with fuel Wobbe number for 350 F and 425 F but not 500 F burns. PN emissions were much higher at 500 F than at 350 F or 425 F, but there were no clear trends of PN varying with Wobbe number. NO_X emissions were similar at 425 F and 500 F and higher at these temperature settings than at 350 F; this is consistent with the hypothesis that the burner and/or spreader were not fully warmed during the 350 F burns (also consistent with the higher CO during these burns). NO_2 absolute emission levels varied with the same pattern but to a lesser extent, resulting in higher NO_2/NO_X fractions for the 350 F burns. Neither NOX nor NO2 appeared to be strongly impacted by fuel Wobbe number. Overall, both CO and NO_2 levels were higher than expected for a well-functioning burner (and higher than most other ovens tested in this study). Formaldehyde emissions were the highest for any oven but did not vary with fuel Wobbe number. Full burn emission rates were 540-790 ng/J for CO (350 F setting; highest for CO), 41-47 ng/J for NO_X (500 F setting; highest for NO_X), 240-2800 x 10^4 J^{-1} for PN at 500 F setting, and 5.1-5.8 ng/J for HCHO.

Table 55. Burner operating parameters for experiments with oven OV11.

Experiment	Burn	Start Time	End Time	Firing Rate, stopwatch[2] (kBTU h^{-1})	Supply P (in. H_2O)[3]
L164	350F	08:46	08:59	8.6	7.7
L164	425F	09:01	09:14		7.7
L164	500F	09:16	09:40		7.9
L165	350F	10:07	10:20	9.3	7.9
L165	425F	10:22	10:32		7.9
L165	500F	10:37	10:50		7.9
L166	350F	12:41	12:54	10.5	7.9
L166	425F	12:56	13:04		7.9
L166	500F	13:11	13:25		7.9
L167	350F	14:02	14:15	9.5	7.9
L167	425F	14:17	14:25		7.9
L167	500F	14:32	14:46		7.9

[1] Fuel flow calculated from stopwatch timing of 1/4-foot dial of gas meter. Firing rate calculated from measured fuel flow rate and higher heating value from fuel composition.
[2] Pressure in fuel supply line during burn. Pressure at outlet of appliance regulator was not readily accessible without dismantling the fuel transfer lines within the appliance, and was therefore not measured.

Table 56. Environmental conditions[1] for experiments with OV11.

Exp.	Fuel	T (°C)	RH (%)
L164	PG&E	21.2 ± 0.1	21 ± 0
L165	1C	21.6 ± 0.2	22 ± 0
L166	3C	22.6 ± 0.2	24 ± 0
L167	2C	23 ± 0.1	23 ± 0

[1] Measured over period of formaldehyde sample.

Table 57. Sample location temperatures and dilution ratios for each burn.

	Sample location T (°C)[1]			Dilution ratio[2]		
Exp.	350 F	425 F	500 F	350 F	425 F	500 F
L164	37 ± 0	48 ± 0	52 ± 0	25	26	26
L165	39 ± 1	50 ± 0	55 ± 0	26	26	27
L166	41 ± 0	49 ± 0	54 ± 0	25	26	26
L167	42 ± 0	49 ± 0	53 ± 0	27	26	26

[1] Measured in exhaust duct from collection hood alongside pollutant sampling inlets. Mean ± standard deviation measured over last min of each burn to achieve new temperature setting.
[2] Calculated by comparing NO_X measured in gas manifold (PG-250) and dilution sampler (Thermo 42i) over last min of each burn.

Table 58. Measured RH of sample stream at room temperature.[1]

Exp.	Gas manifold T (°C)			Gas manifold RH (%)		
	350 F	425 F	500 F	350 F	425 F	500 F
L164	19.1 ± 0	19.1 ± 0	20.3 ± 0.1	34 ± 0	33 ± 0	34 ± 0
L165	19.3 ± 0	19.3 ± 0	19.4 ± 0	35 ± 0	35 ± 0	35 ± 0
L166	20.1 ± 0	20.2 ± 0	20.5 ± 0	37 ± 0	36 ± 0	36 ± 0
L167	20.6 ± 0	20.6 ± 0	20.7 ± 0	37 ± 0	37 ± 0	35 ± 0

[1] Measured in 1-gal vessel in parallel sample stream from hood outlet; measured to confirm that hood dilution is sufficient to avoid condensation in sampling stream for PG-250.

Table 59. Aldehyde samples for experiments with oven OV11.

Exp(s)	Location	Date	Sample start/end time		Flow (L/min)	Air vol. (L)	HCHO extract conc. (ng/μL)	Acet extract conc. (ng/μL)	HCHO air conc.[1] (μg/m^3)	Acet. air conc.[1] (μg/m^3)
Bkg	Lab air	01/27/2009	8:43	14:49	1.09	399	1.446	0.420	7	2
L164a	Collection hood outlet	01/27/2009	8:43	9:34	1.06	54	8.622	0.712	319	26
L164b			8:43	9:34	1.13	57	8.713	0.715	303	25
L165			10:04	10:54	1.06	53	9.002	0.788	341	30
L166			12:38	13:28	1.07	53	7.780	0.852	292	32
L167			13:59	14:49	1.06	53	9.518	0.819	360	31

[1] Concentration in the air stream being sampled for other gaseous analytes.

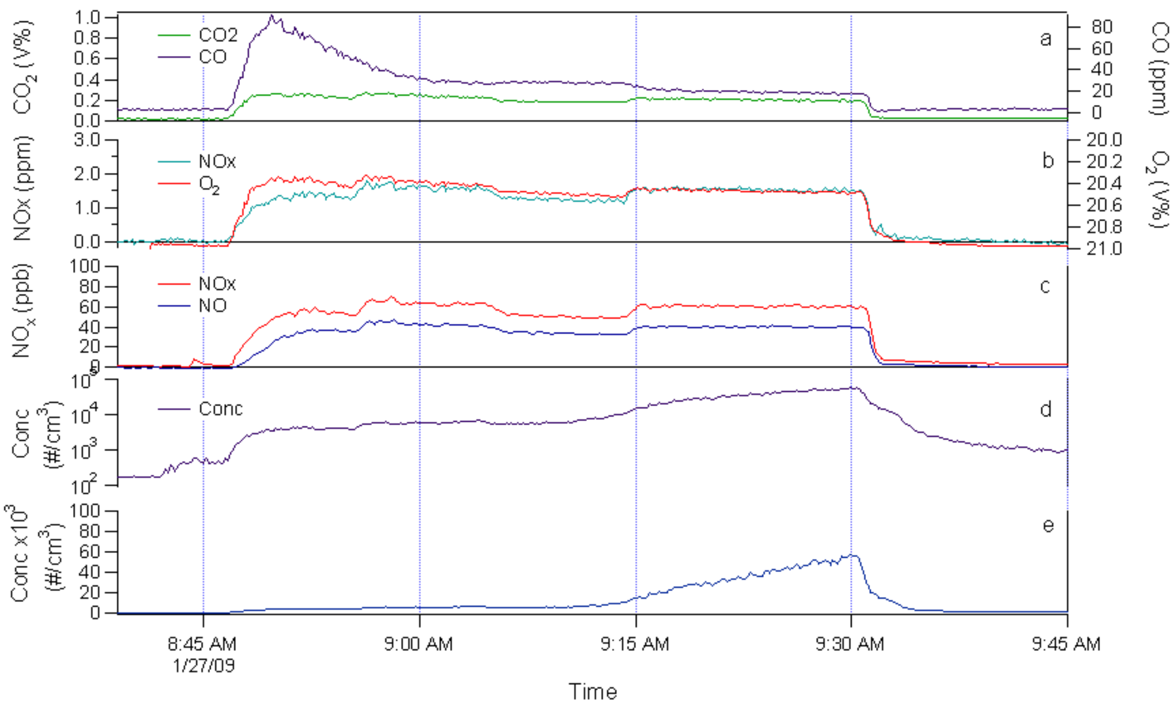

Figure 33. Measured analyte concentrations for oven OV11 with PG&E line gas (L164).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Note the lack of burner cycling (temperature not achieved) at any setting.

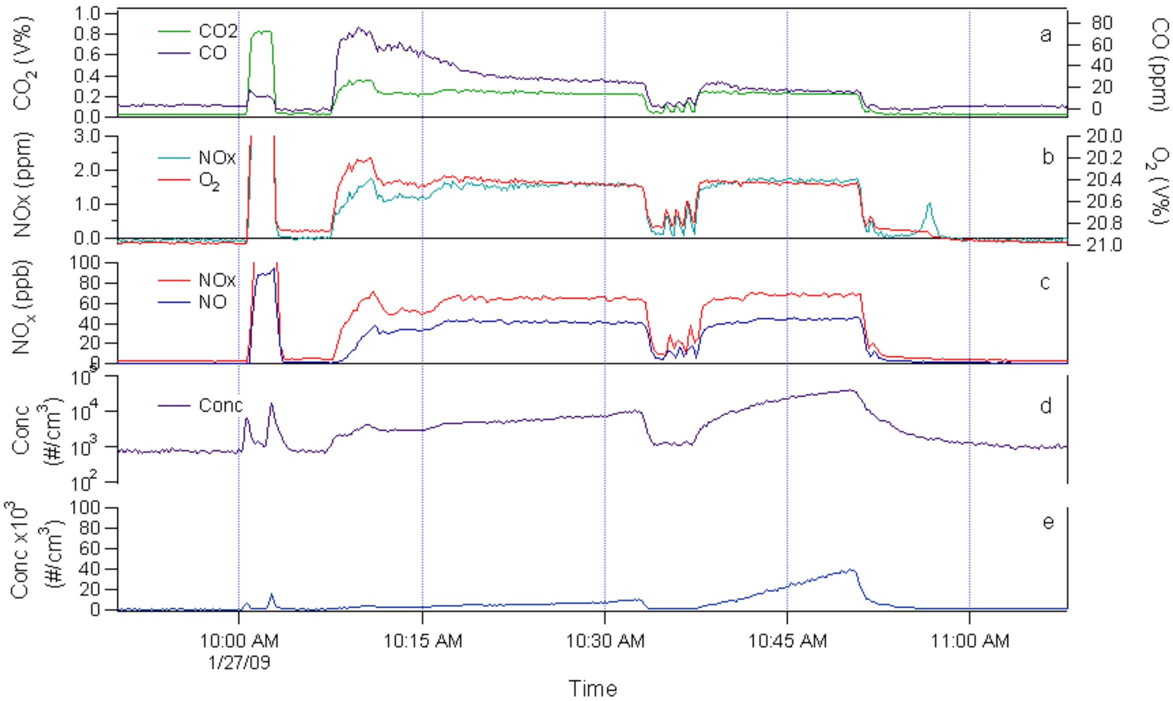

Figure 34. Measured analyte concentrations for oven OV11 with fuel 1C (L165).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Note that temperature setting was achieved (indicated by burner cycling) only at the 425 °F setting.

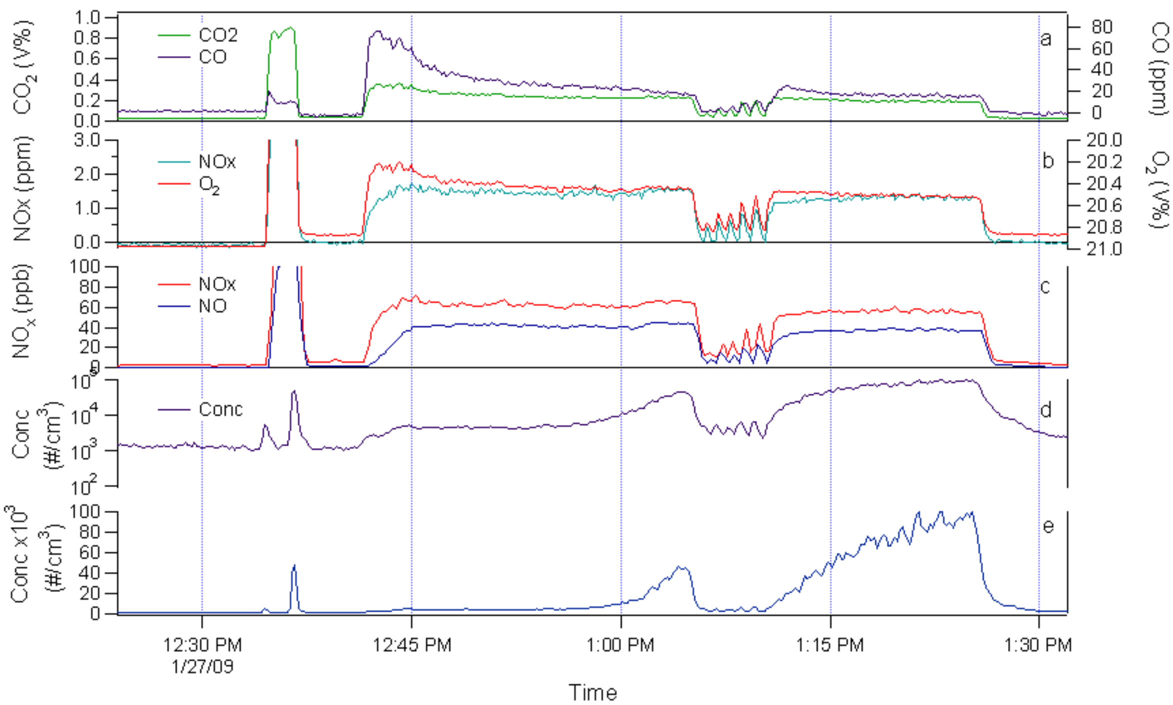

Figure 35. Measured analyte concentrations for oven OV11 with fuel 3C (L166).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Note that temperature setting was achieved (indicated by burner cycling) only at the 425 °F setting.

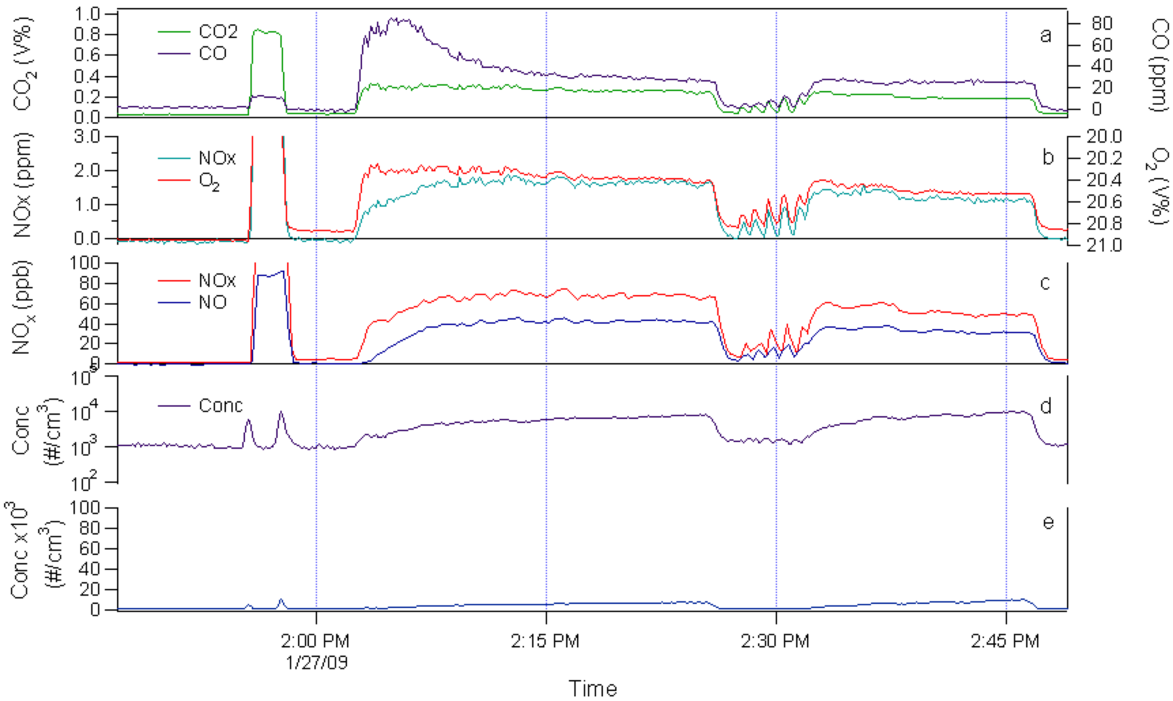

Figure 36. Measured analyte concentrations for oven OV11 with fuel 2C (L167).

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. Note that temperature setting was achieved (indicated by burner cycling) only at the 425 °F setting.

Table 60. Calculated air-free concentrations (using CO_2) over last 1 min of each burn; results for CO, PG250 NO_x and PN.

Exp.	Fuel	Wobbe	CO (ppm)			PG250 NO_X (ppm)			PN (10^5 cm^{-3})		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L164	PG&E	1334	1700	1770	1150	88	100	107	80	210	680
L165	1C	1390	1620	1420	850	91	105	113	61	150	620
L166	3C	1419	1540	1060	1150	92	102	111	54	600	1900
L167	2C	1359	1490	1490	1950	89	96	101	65	100	180

Table 61. Calculated air-free concentrations (using CO_2) over last 1 min of each burn; results for NO_x, NO, and NO_2 (NO_x-NO) measured with Thermo 42i.

Exp.	Fuel	Wobbe	NO_X (ppm)			NO (ppm)			NO_2 (ppm)		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L164	PG&E	1334	88	100	107	61	68	74	28	32	33
L165	1C	1390	91	105	113	62	69	76	29	36	36
L166	3C	1419	92	102	111	63	70	76	30	32	35
L167	2C	1359	89	96	101	57	63	67	32	33	33

Table 62. Calculated emission rates over entirety of first burn at each temperature setting; results for CO, PG250 NO_X and PN.

Exp.	Fuel	Wobbe	CO (μg KJ^{-1})			PG250 NO_X (μg KJ^{-1})			PN (10^7 KJ^{-1})		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L164	PG&E	1334	790	475	318	34	42	46	140	290	1200
L165	1C	1390	677	398	254	34	45	47	93	230	750
L166	3C	1419	536	345	332	34	43	46	89	620	2800
L167	2C	1359	621	401	462	33	41	41	95	190	240

Table 63. Calculated emission rates over entirety of first burn at each temperature setting; results for NO_X, NO, and NO_2 (NO_X-NO) measured with Thermo 42i.

Exp.	Fuel	Wobbe	NO_X (μg KJ^{-1})			NO (μg KJ^{-1})			NO_2 (μg KJ^{-1})		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L164	PG&E	1334	34	42	51	22	29	31	12.0	13.0	14.6
L165	1C	1390	34	45	47	21	30	31	13.5	15.3	16.1
L166	3C	1419	34	43	46	21	30	31	12.9	13.4	14.3
L167	2C	1359	33	41	41	19	27	27	13.8	14.6	14.3

Table 64. Calculated formaldehyde emission rates over entire period of burner operation.

Exp.	Fuel	Wobbe	HCHO (μg KJ^{-1})
L164	PG&E	1334	5.65, 5.36
L165	1C	1390	5.81
L166	3C	1419	5.14
L167	2C	1359	5.83

5.0 Oven OV12

5.1. Experimental information for OV12

Four experiments were conducted on the same day, in the following order: PG&E line gas (WN = 1329), mix 1C (WN = 1390), mix 2C (WN = 1359), and mix 3C (WN = 1419). The heater for the dilution sampler inlet was set to automatic mode. The SMPS was used to sample size-resolved particle number concentrations in the ultrafine mode (<100 nm particle diameter). Appliance manifold pressure was not measured because access was not possible without dismantling the internal fuel transfer lines. To assess the potential for condensation in gas sampling lines, RH was measured in an air sampling stream allowed to come to room temperature by pulling a sample stream through a using a 1-gal vessel; this sample was drawn parallel to the sampling stream of the PG-250 gas analyzer.

Table 65. Appliance and burner information OV12.

Burner ID	OV12
Appliance manufacturer	Maytag
Model number	CRG860A
Serial number	100551FK
Manufacture year	1992
Burner technologies	Hot surface ignition; single tube-type oven burner
Burner rating (Btu/h)	16,000
Other information	Procured January 2009
Test location	Laboratory
History notes	Identified via craigslist.org. Reported reason for sale was kitchen remodel.

Figure 37. Oven compartment for OV12.

Figure 38. Oven bottom burner OV12.

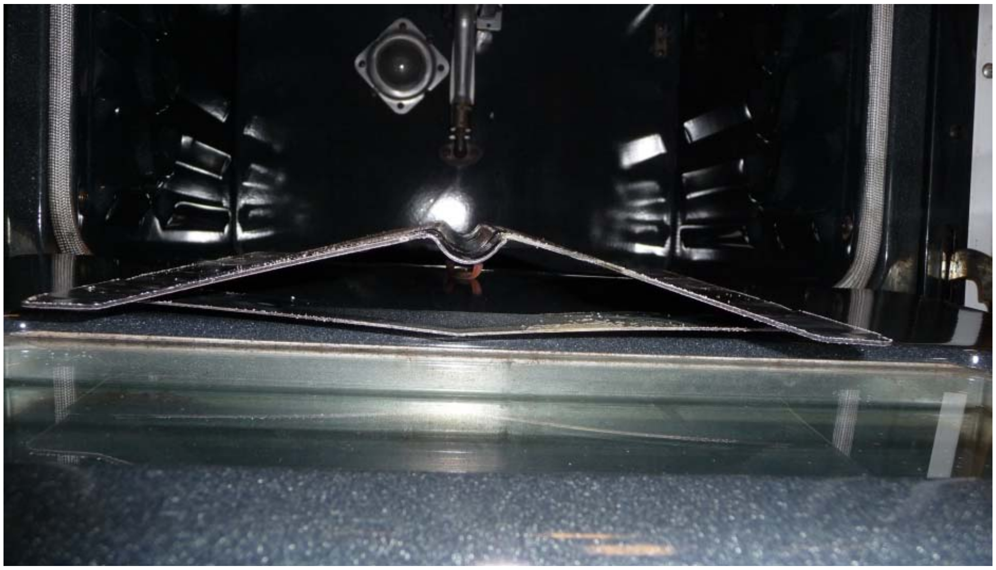

Figure 39. Spreader plate for oven bottom burner OV12.

Table 66. Interchangeability experiments for oven bottom burner OV12.

Exp.	Fuel	Date	Burner operation
L172	PG&E	02/11/2009	Purge burn with each fuel change using cooktop burners. Operate oven through initial ramp plus 2 maintenance cycles at 350, 425 and 500F. Cool to touch between experiments.
L173	1C		
L174	2C		
L175	3C		

Table 67. Fuel analysis for interchangeability experiments with OV12.

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
L172	PG&E	PG&E [2]	95.9	1.76	0.39	0.18	0.42	1.32	1016	1329
L173	1C	Cylinder[3]	92.0	8.00	-	-	-	-	1071	1390
L174	2C	Cylinder[3]	90.4	7.90	-	-	1.70	-	1053	1359
L175	3C	Cylinder[3]	86.4	12.00	1.60	-	-	-	1125	1419

[1] Calculated using the American Gas Association interchangeability program.
[2] Composition of gas distributed to LBNL, as measured by PG&E online GC.
[3] Certified composition in cylinder (determined by the supplier, AirLiquide).

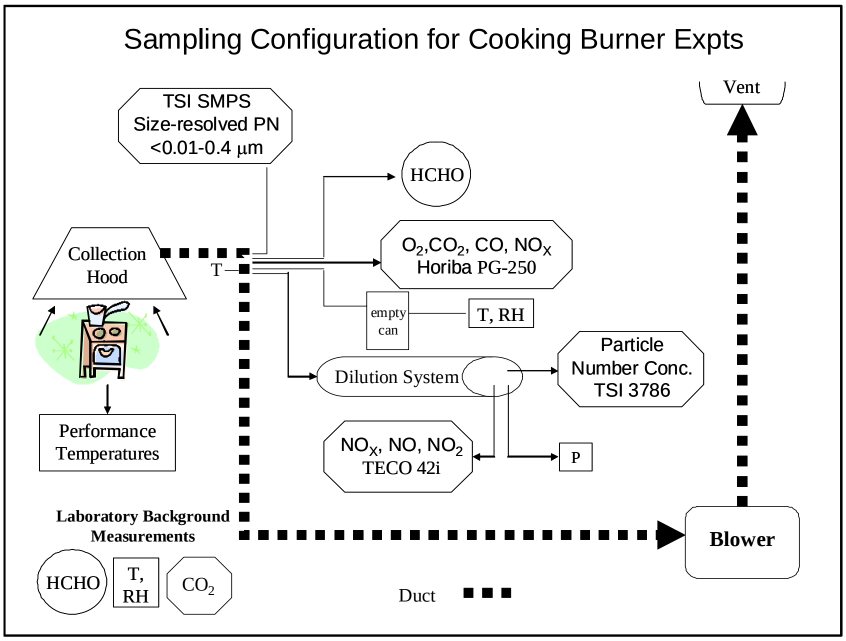

Figure 40. Analytical sampling configuration for OV12.

The empty can is used to measure RH of the airstream from the collection hood at room temperature. This indicates the potential for condensation in sampling system. PG-250 also has water removal system. HCHO sampled through 30-cm Teflon tubing (nominal ¼” diameter) for primary sample, duplicate sampled through 90-cm Teflon tubing.

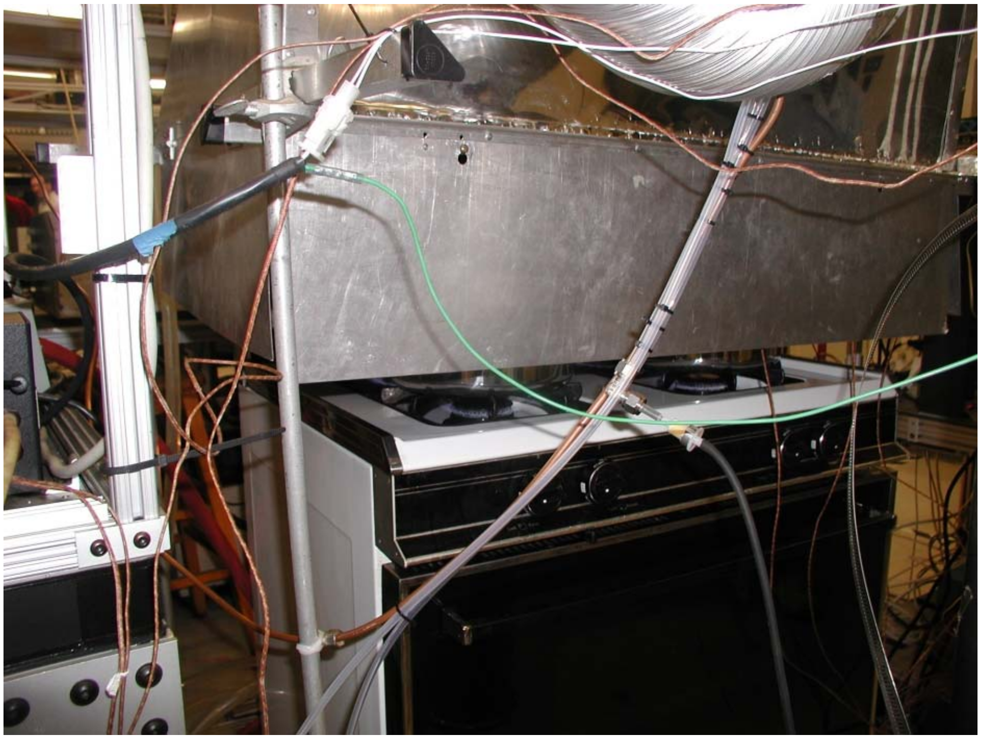

Figure 41. Installation of OV12.

Table 68. Analyte ranges and calibration levels for experiments with OV12.

Analyte	**Sample location**	**Equipment[1]**	**Range**	**Calibration levels**
Carbon dioxide (CO_2)	outlet of collection hood	Horiba PG-250	0-5%	0, 1%
Oxygen (O_2)			0-25%	0, 20.95%
Carbon monoxide (CO)			0-200 ppm	0, 40 ppm
Nitrogen oxides (NO_X)			0-25 ppm	0, 4.0 ppm[3]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-5 ppm	0, 2.0 ppm[3]
Carbon dioxide (CO_2)	laboratory air	PP Systems EGM-4	5000 ppm	Periodic[2]

[1] Horiba Environmental and Process Instruments (environ.hii.horiba.com); Thermo Fisher Scientific (thermo.com); PP Systems (ppsystems.com). [2] Not checked daily; observed to remain within 10s of ppm at ambient conditions.

Table 69. Aerosol instrumentation used for OV12.

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 part. mode	±12%
PN resolved by aerodynamic diameter	TSI 3071A classifier, TSI 3025A CPC	Sort using electrostatic classifier, count with CPC	3 nm	10^5 cm^{-3}	±10%

[1]TSI Instruments, Shoreview, MN (tsi.com). CPC = condensation particle counter. Detailed information provided in product literature. [2]50% detection. [3] Product 3001788, purchased from TSI.

Table 70. Other measurements for experiments with OV12.

Measured Quantity	**Location(s)**	**Device(s)[1]**
Fuel pressure	Gas supply line	Model 264 transducer (Setra)
Fuel volume & flow	Fuel flow to appliance during burner operation	AC-250-TC T-compensating dry gas meter with 1- and ¼-ft dials (American Meter); flow rate timed by stopwatch
Fuel flow rate	Fuel flow to appliance during burner operation	Pulse counter for AC-250-TC, 10 counts per rev (Riotronics)
Dilution sampler vacuum	Dilution tube	Setra Model 264 transducer
Temperature, combustion air	In vicinity of range	Precision NTC thermistor (APT)
Relative humidity, combustion air	In vicinity of range	Thermostet polymer based capacitance RH sensor (APT)
Temperature, air sample location in hood	At point of air sampling in duct connected to hood	Thermocouple (K), probe, Omega KQSS-18E-12
Temperature, oven	Oven interior, shelf lower and upper halves of oven	Thermocouple (K), screw-mount, Omega XCIB-K-4-2-3

[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 OV12

As with other ovens, full-burn CO emission rates were higher during the first burn of the cycle (temperature set to 350 F) than during the initial burns at each of the other temperature settings (425 and 500 F). Full-burn CO increased with Wobbe number at 350 F (by about 30% from PG&E to fuel 3C) but not at the other temperatures. Overall, CO emission rates were low. Full-burn NO_X emissions increased slightly with temperature setting for each fuel. There were no clear trends between NO_X emissions and Wobbe number. NO_2 full-burn emissions rates were somewhat higher for the higher Wobbe fuels but the increase was not monotonic (the statistical discernability will be evaluated in separate analysis). Formaldehyde emission rates did not vary with fuel Wobbe number. Full burn emission rates were 48-65 ng/J for CO (350 F setting; highest for CO), 34-37 ng/J for NO_X (500 F setting; highest for NO_X), 70-90 x 10^4 J^{-1} for PN at 500 F setting, and 0.23-0.25 ng/J for HCHO.

Table 71. Burner operating parameters for experiments with oven OV12.

Experiment	Burn	Start Time	End Time	Firing Rate, stopwatch[1] (kBTU h^{-1})	Supply P (in. H_2O)[2]
L172	350F	08:06	08:14	16	7.7
L172	425F	08:29	08:33		7.8
L172	500F	08:42	08:47		7.8
L173	350F	09:22	09:29	16	7.8
L173	425F	09:44	09:48		7.8
L173	500F	09:57	10:02		7.8
L174	350F	10:41	10:49	16	7.8
L174	425F	11:03	11:07		7.9
L174	500F	11:17	11:21		7.9
L175	350F	12:21	12:29	17	7.8
L175	425F	12:44	12:48		7.9
L175	500F	12:57	13:02		7.9

[1] Fuel flow calculated from stopwatch timing of 1/4-foot dial of gas meter, one timing event for the first burn at each temperature setting (n=9,9,7,7 per experiment). Firing rate calculated from measured fuel flow rate and higher heating value from fuel composition.

[2] Pressure in fuel supply line during burn. Pressure at outlet of appliance regulator was not readily accessible without dismantling the fuel transfer lines within the appliance, and was therefore not measured.

Table 72. Environmental conditions[1] for experiments with OV12.

Exp.	Fuel	T (°C)	RH (%)
L172	PG&E	20.2 ± 0.1	46 ± 1
L173	1C	20.6 ± 0.1	46 ± 1
L174	2C	20.9 ± 0.1	46 ± 1
L175	3C	20.9 ± 0.1	46 ± 1

[1] Measured over period of formaldehyde sample.

Table 73. Sample location temperatures and dilution ratios for each burn.

	Sample location T (°C)[1]			Dilution ratio[2]		
Exp.	350 F	425 F	500 F	350 F	425 F	500 F
L172	33 ± 1	40 ± 1	44 ± 0	28	30	31
L173	36 ± 1	40 ± 0	45 ± 0	32	31	31
L174	36 ± 1	40 ± 0	45 ± 0	30	30	31
L175	35 ± 1	40 ± 0	45 ± 1	30	31	31

[1] Measured in exhaust duct from collection hood alongside pollutant sampling inlets. Mean ± standard deviation measured over last min of each burn to achieve new temperature setting.

[2] Calculated by comparing NO_X measured in gas manifold (PG-250) and dilution sampler (Thermo 42i) over last min of each burn.

Table 74. Measured RH of sample stream at room temperature. [1]

Exp.	Gas manifold T (°C)			Gas manifold RH (%)		
	350 F	425 F	500 F	350 F	425 F	500 F
L172	19 ± 0	18.9 ± 0	19.1 ± 0	64 ± 1	59 ± 1	60 ± 1
L173	19.2 ± 0	19.2 ± 0	19.3 ± 0	63 ± 1	59 ± 1	60 ± 0
L174	19.3 ± 0	19.2 ± 0	19.3 ± 0	64 ± 0	60 ± 1	61 ± 1
L175	19.2 ± 0	19.4 ± 0	19.4 ± 0	66 ± 0	59 ± 1	60 ± 1

[1] Measured in 1-gal vessel in parallel sample stream from hood outlet; measured to confirm that hood dilution is sufficient to avoid condensation in sampling stream for PG-250.

Table 75. Aldehyde samples for experiments with oven OV12.

Exp(s)	Location	Date	Sample start/end time		Flow (L/min)	Air vol. (L)	HCHO extract conc. (ng/µL)	Acet extract conc. (ng/µL)	HCHO air conc.[1] (µg/m³)	Acet. air conc.[1] (µg/m³)
Bkg	Lab air	02/11/2009	8:01	13:11	1.07	331	0.382	0.194	2	1
L172a	Collection hood outlet		8:03	8:56	1.03	55	0.505	0.073	18	3
L172b			8:03	8:56	1.10	59	0.528	0.090	18	3
L173			9:19	10:12	1.05	56	0.478	0.077	17	3
L174			10:38	11:30	1.05	55	0.475	0.074	17	3
L175			12:18	13:11	1.04	55	0.503	0.085	18	3

[1] Concentration in the air stream being sampled for other gaseous analytes.

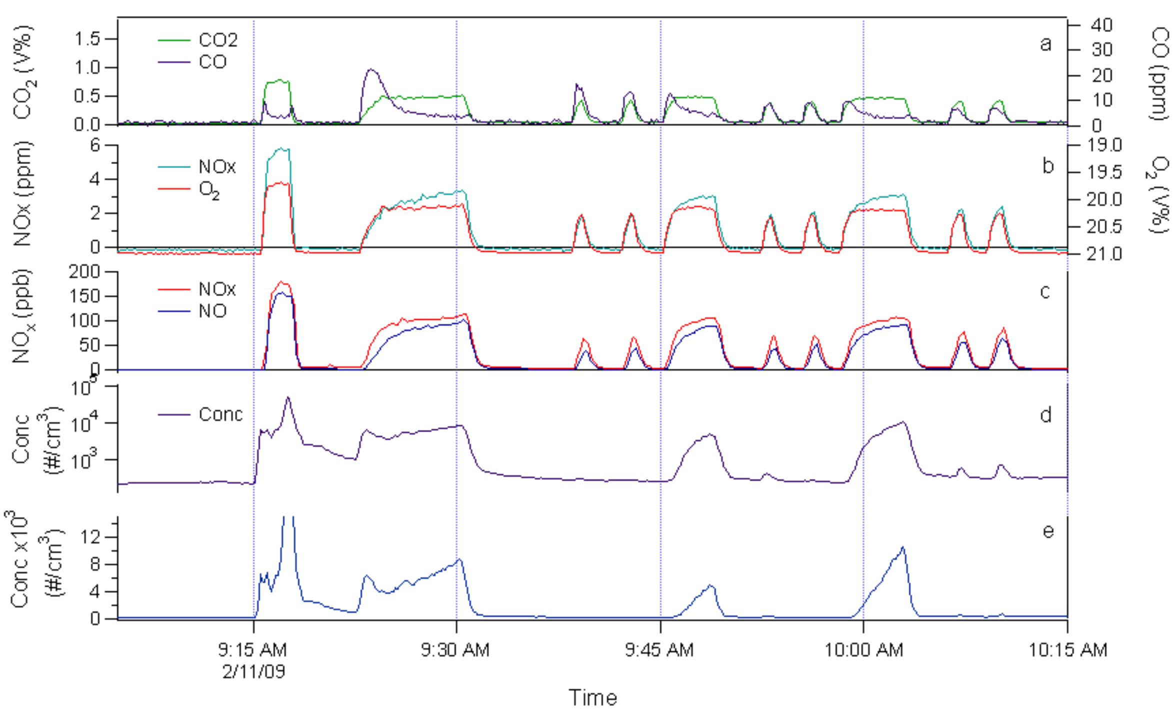

Figure 42. Measured analyte concentrations for oven OV12 with PG&E line gas (L172).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

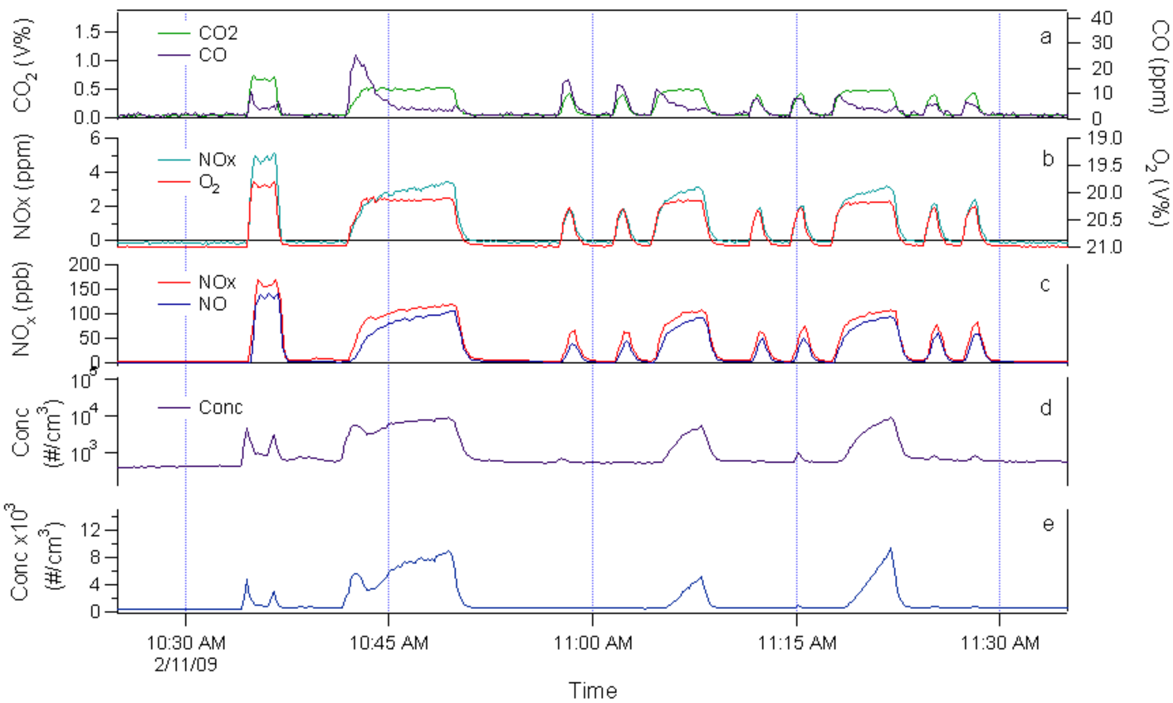

Figure 43. Measured analyte concentrations for oven OV12 with fuel 1C (L173).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

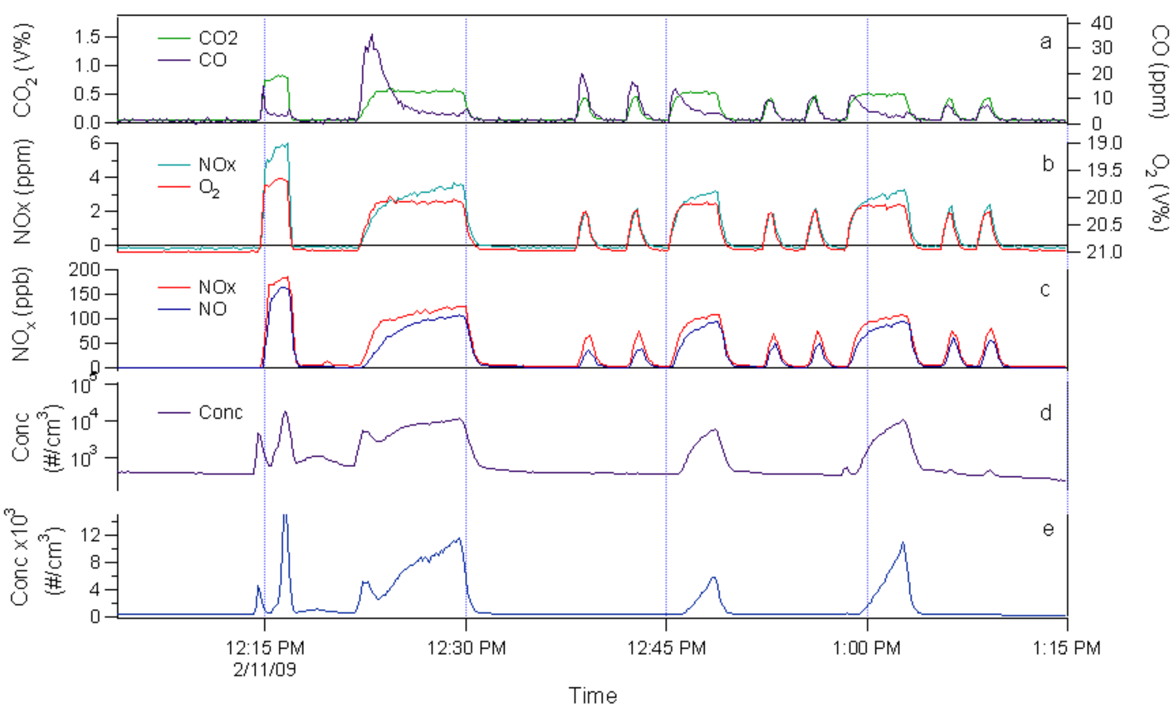

Figure 44. Measured analyte concentrations for oven OV12 with fuel 2C (L174).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

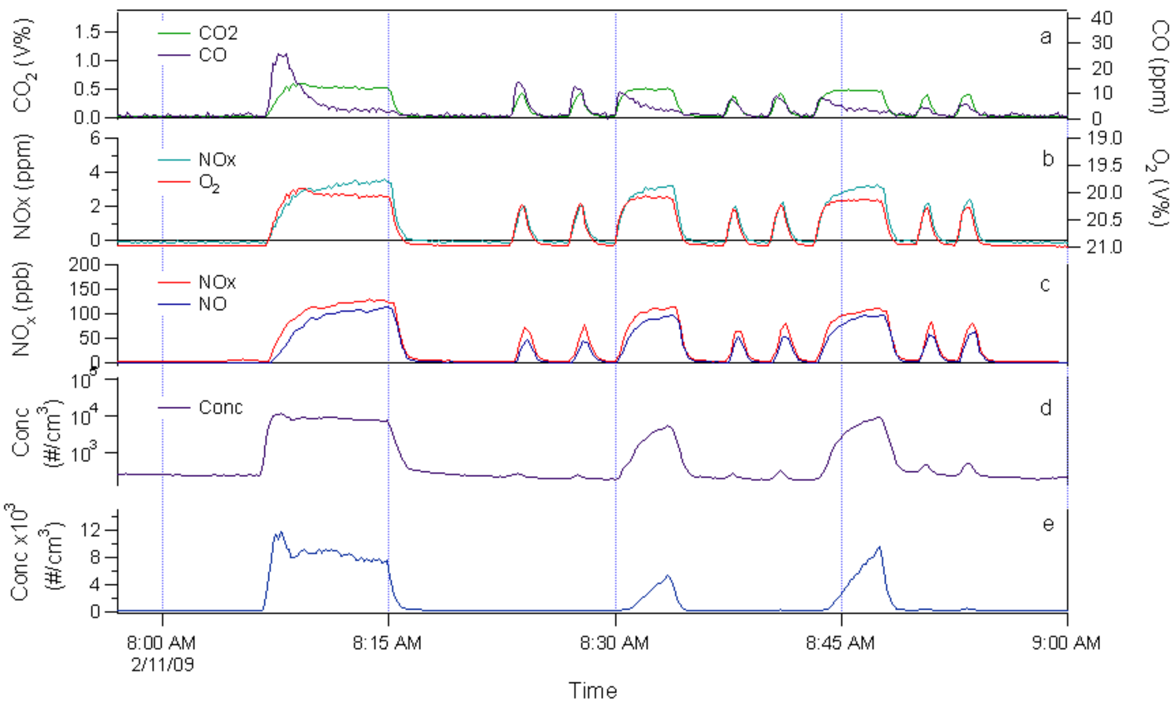

Figure 45. Measured analyte concentrations for oven OV12 with fuel 3C (L175).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

Table 76. Calculated air-free concentrations (using CO_2) over last 1 min of each burn; results for CO, PG250 NO_X and PN.

Exp.	Fuel	Wobbe	CO (ppm)			PG250 NO_X (ppm)			PN (10^5 cm^{-3})		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L172	PG&E	1329	58	72	61	89	82	88	53	22	52
L173	1C	1390	59	101	49	87	81	89	58	19	57
L174	2C	1359	52	71	59	86	80	84	57	19	41
L175	3C	1419	60	84	53	83	76	82	66	17	42

Table 77. Calculated air-free concentrations (using CO2) over last 1 min of each burn; results for NOX, **NO, and NO_2 (NO_X-NO) measured with Thermo 42i.**

Exp.	Fuel	Wobbe	NO_X (ppm)			NO (ppm)			NO_2 (ppm)		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L172	PG&E	1329	89	82	88	76	70	80	12.8	12.4	8.1
L173	1C	1390	87	81	89	76	67	77	10.5	13.9	11.7
L174	2C	1359	86	80	84	74	66	72	11.8	13.4	11.4
L175	3C	1419	83	76	82	71	64	71	11.8	12.3	11.7

Table 78. Calculated emission rates over entirety of first burn at each temperature setting; results for CO, PG250 NO_X and PN.

Exp.	Fuel	Wobbe	CO (μg KJ^{-1})			PG250 NO_X (μg KJ^{-1})			PN (10^7 KJ^{-1})		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L172	PG&E	1329	49	33	26	33	34	36	130	41	83
L173	1C	1390	54	42	28	34	34	37	110	38	89
L174	2C	1359	48	36	28	33	33	35	100	39	71
L175	3C	1419	65	40	31	32	32	34	110	39	76

Table 79. Calculated emission rates over entirety of first burn at each temperature setting; results for NO_X, NO, and NO_2 (NO_X-NO) measured with Thermo 42i.

Exp.	Fuel	Wobbe	NO_X (μg KJ^{-1})			NO (μg KJ^{-1})			NO_2 (μg KJ^{-1})		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L172	PG&E	1329	33	34	36	27	28	31	6.0	6.0	4.9
L173	1C	1390	34	34	37	27	27	30	7.0	7.3	6.2
L174	2C	1359	33	33	35	26	27	29	7.0	6.5	5.6
L175	3C	1419	32	32	34	24	25	28	7.3	6.5	5.9

Table 80. Calculated formaldehyde emission rates over entire period of burner operation.

Exp.	Fuel	Wobbe	HCHO (μg KJ^{-1})
L172	PG&E	1329	0.25, 0.24
L173	1C	1390	0.24
L174	2C	1359	0.23
L175	3C	1419	0.23

6.0 Oven OV13

6.1. Experimental information for OV13

Four experiments were conducted on the same day, in the following order: PG&E line gas (WN = 1332), mix 1C (WN = 1390), mix 3C (WN = 1419), and PG&E line gas (WN = 1332). The heater for the dilution sampler inlet was set to automatic mode. The SMPS was used to sample size-resolved particle number concentrations in the ultrafine mode (<100 nm particle diameter). Appliance manifold pressure was not measured because access was not possible without dismantling the internal fuel transfer lines. To assess the potential for condensation in gas sampling lines, RH was measured in an air sampling stream allowed to come to room temperature by pulling a sample stream through a using a 1-gal vessel; this sample was drawn parallel to the sampling stream of the PG-250 gas analyzer. Starting with the second experiment, recorded PN concentrations deviated substantially from typical patterns. Operational parameters recorded in the instrument data log may provide some insight to explain this questionable data. Pending review and a potentially more definitive resolution of the matter, PN results from these experiments are being excluded from analysis.

Table 81. Appliance and burner information OV13.

Burner ID	OV13
Appliance manufacturer	Frigidaire (Electrolux)
Model number	FGFL66ASD
Serial number	VF31132385
Year of manufacture	2003
Burner technologies	Hot surface ignition; single tube-type oven burner
Burner rating (Btu/h)	18,000
Other information	Procured February 2009
Test location	Laboratory
History notes	Identified via craigslist.org. Seller reported use 3-5x per week for 1 year, 1-4x per month over past 2 years. Reason for sale was upgrade.

Figure 46. **Range containing OV13 on the left, OV09 is on right.**

Figure 47. **Oven compartment for OV13.**

Figure 48. Oven bottom burner OV13.

Figure 49. Spreader plate for oven bottom burner OV13.

Table 82. Interchangeability experiments for oven bottom burner OV13.

Exp.	Fuel	Date	Burner operation
L184	PG&E	02/19/2009	Purge burn with each fuel change using cooktop burners. Operate oven through initial ramp plus 2 maintenance cycles at 350, 425 and 500F. Cool to touch between experiments.
L185	1C		
L186	3C		
L187	PG&E		

Table 83. Fuel analysis for interchangeability experiments with OV13.

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
L184	PG&E	PG&E[2]	95.3	2.35	0.36	0.14	0.98	0.84	1018	1332
L185	1C	Cylinder[3]	92.0	8.00	-	-	-	-	1071	1390
L186	3C	Cylinder[3]	86.4	12.00	1.61	-	-	-	1125	1419
L187	PG&E	PG&E[2]	95.3	2.35	0.36	0.14	0.98	0.84	1018	1332

[1] Calculated using the American Gas Association interchangeability program.
[2] Composition of gas distributed to LBNL, as measured by PG&E online GC.
[3] Certified composition in cylinder (determined by the supplier, AirLiquide).

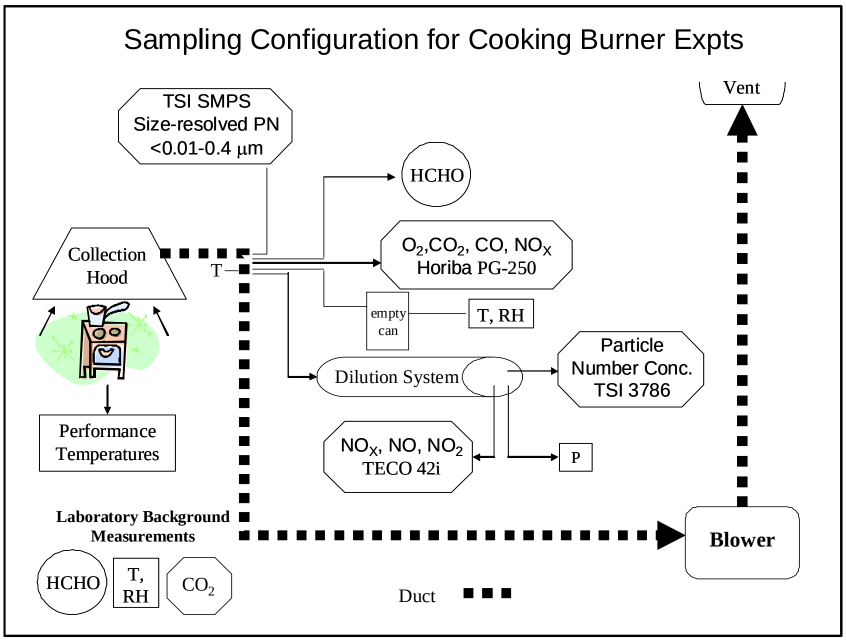

Figure 50. Analytical sampling configuration for OV13.

The empty can is used to measure RH of the airstream from the collection hood at room temperature. This indicates the potential for condensation in sampling system. PG-250 also has water removal system. HCHO sampled through 30-cm Teflon tubing (nominal ¼" diameter) for primary sample, duplicate sampled through 90-cm Teflon tubing.

Table 84. Analyte ranges and calibration levels for experiments with OV13.

Analyte	Sample location	Equipment[1]	Range	Calibration levels
Carbon dioxide (CO_2)	outlet of collection hood	Horiba PG-250	0-5%	0, 1%
Oxygen (O_2)			0-25%	0, 20.95%
Carbon monoxide (CO)			0-200 ppm	0, 40 ppm
Nitrogen oxides (NO_X)			0-25 ppm	0, 4.0 ppm
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-5 ppm	0, 2.0 ppm
Carbon dioxide (CO_2)	laboratory air	Fuji ZFP9-AB21	3000 ppm	0, 470 ppm

[1] Horiba Environmental and Process Instruments (environ.hii.horiba.com); Thermo Fisher Scientific (thermo.com); PP Systems (ppsystems.com).

Table 85. Aerosol instrumentation used for OV13.

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 part. mode	±12%
PN resolved by aerodynamic diameter	TSI 3071A classifier, TSI 3025A CPC	Sort using electrostatic classifier, count with CPC	3 nm	10^5 cm^{-3}	±10%

[1]TSI Instruments, Shoreview, MN (tsi.com). CPC = condensation particle counter. Detailed information provided in product literature. [2]50% detection. [3] Product 3001788, purchased from TSI.

Table 86. Other measurements for experiments with OV13.

Measured Quantity	Location(s)	Device(s)[1]
Fuel pressure	Gas supply line	Model 264 transducer (Setra)
Fuel volume & flow	Fuel flow to appliance during burner operation	AC-250-TC T-compensating dry gas meter with 1- and ¼-ft dials (American Meter); flow rate timed by stopwatch
Fuel flow rate	Fuel flow to appliance during burner operation	Pulse counter for AC-250-TC, 10 counts per rev (Riotronics)
Dilution sampler vacuum	Dilution tube	Setra Model 264 transducer
Temperature, combustion air	In vicinity of range	Precision NTC thermistor (APT)
Relative humidity, combustion air	In vicinity of range	Thermostet polymer based capacitance RH sensor (APT)
Temperature, air sample location in hood	At point of air sampling in duct connected to hood	Thermocouple (K), probe, Omega KQSS-18E-12
Temperature, oven	Oven interior, shelf lower and upper halves of oven	Thermocouple (K), screw-mount, Omega XCIB-K-4-2-3

[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).

6.2. Results for OV13

As with other ovens, full-burn CO emissions were higher during the 350 F burn compared to the 425 and 500 F burns; this result is associated with the large peak that occurs with initial warming of the burner and spreader plate (unclear which is controlling of emissions). Full-burn CO emissions were similar for the replicate experiments with PG&E then progressively higher for fuel 1C and fuel 3C; emissions with 3C were 1.6 to 2.4 times the values calculated for burns with PG&E fuels. End of burn CO concentrations were highest at 425 F and showed the same progression with fuel Wobbe number. NO_X concentrations and emissions were highest at 500 F and showed no trend with fuel Wobbe number. NO_2 emission rates followed a trend similar to CO. Formaldehyde emission rates increased with increasing Wobbe number for the last three experiments, but replicates for the first experiment deviated by a wider margin (0.25 and 0.41

ng/J) than the individual samples from the other three experiments (0.34, 0.41 and 0.45 ng/J). Full burn emission rates were 120-204 ng/J for CO (350 F setting; highest for CO) and 42-45 ng/J for NO_X (500 F setting; highest for NO_X).

Table 87. Burner operating parameters for experiments with oven OV13.

Experiment	Burn	Start Time	End Time	Firing Rate, Stopwatch[1] (kBTU h^{-1})	Supply P (in. H_2O)[2]
L184	350F	08:01	08:09	17	7.7
L184	425F	08:21	08:24		7.8
L184	500F	08:37	08:41		7.7
L185	350F	09:24	09:31	18	7.9
L185	425F	09:44	09:47		7.9
L185	500F	10:00	10:03		7.9
L186	350F	10:47	10:54	19	7.9
L186	425F	11:07	11:09		7.9
L186	500F	11:21	11:24		7.9
L187	350F	12:07	12:14	17	7.7
L187	425F	12:27	12:30		7.7
L187	500F	12:42	12:46		7.7

[1] Fuel flow calculated from stopwatch timing of 1/4-foot dial of gas meter, one timing event for the first burn at each temperature setting (n=3 per experiment). Firing rate calculated from measured fuel flow rate and higher heating value from fuel composition.
[2] Pressure in fuel supply line during burn. Pressure at outlet of appliance regulator was not readily accessible without dismantling the fuel transfer lines within the appliance, and was therefore not measured.

Table 88. Environmental conditions[1] for experiments with OV13.

Exp.	Fuel	T (°C)	RH (%)
L184	PG&E	20.6 ± 0.1	45 ± 0
L185	1C	20.7 ± 0.2	44 ± 1
L186	3C	20.8 ± 0.1	44 ± 1
L187	PG&E	21 ± 0.1	45 ± 1

[1] Measured over period of formaldehyde sample.

Table 89. Sample location temperatures and dilution ratios for each burn.

	Sample location T (°C)[1]			Dilution ratio[2]		
Exp.	350 F	425 F	500 F	350 F	425 F	500 F
L184	32 ± 1	39 ± 1	45 ± 0	29	27	25
L185	35 ± 1	40 ± 1	46 ± 0	27	26	25
L186	35 ± 1	40 ± 0	44 ± 0	30	28	25
L187	35 ± 1	41 ± 1	45 ± 0	27	26	26

[1] Measured in exhaust duct from collection hood alongside pollutant sampling inlets. Mean ± standard deviation measured over last min of each burn to achieve new temperature setting.
[2] Calculated by comparing NO_X measured in gas manifold (PG-250) and dilution sampler (Thermo 42i) over last min of each burn.

Table 90. Measured RH of sample stream at room temperature.[1]

Exp.	Gas manifold T (°C)			Gas manifold RH (%)		
	350 F	425 F	500 F	350 F	425 F	500 F
L184	19.1 ± 0	19 ± 0	19.1 ± 0	63 ± 1	57 ± 1	59 ± 1
L185	19.5 ± 0	19.2 ± 0	19.2 ± 0	62 ± 1	56 ± 1	58 ± 1
L186	19.6 ± 0	19.4 ± 0	19.4 ± 0	61 ± 0	55 ± 1	57 ± 1
L187	19.9 ± 0	19.8 ± 0	19.9 ± 0	62 ± 1	56 ± 1	58 ± 1

[1] Measured in 1-gal vessel in parallel sample stream from hood outlet; measured to confirm that hood dilution is sufficient to avoid condensation in sampling stream for PG-250.

Table 91. Aldehyde samples for experiments with oven OV13.

Exp(s)	Location	Date	Sample start/end time		Flow (L/min)	Air vol. (L)	HCHO extract conc. (ng/μL)	Acet. extract conc. (ng/μL)	HCHO air conc.[1] (μg/m³)	Acet. air conc.[1] (μg/m³)
Bkg	Lab air	02/19/2009	7:58	12:57	1.06	317	0.360	0.200	2	1
L184a	Collection hood outlet	02/19/2009	7:58	8:52	1.02	55	0.416	0.055	15	2
L184b			7:58	8:52	1.09	59	0.701	0.109	24	4
L185			9:21	10:14	1.03	55	0.578	0.080	21	3
L186			10:44	11:36	1.02	53	0.625	0.106	24	4
L187			12:04	12:57	1.03	55	0.488	0.072	18	3

[1] Concentration in the air stream being sampled for other gaseous analytes.
[2] L187 sample not valid.

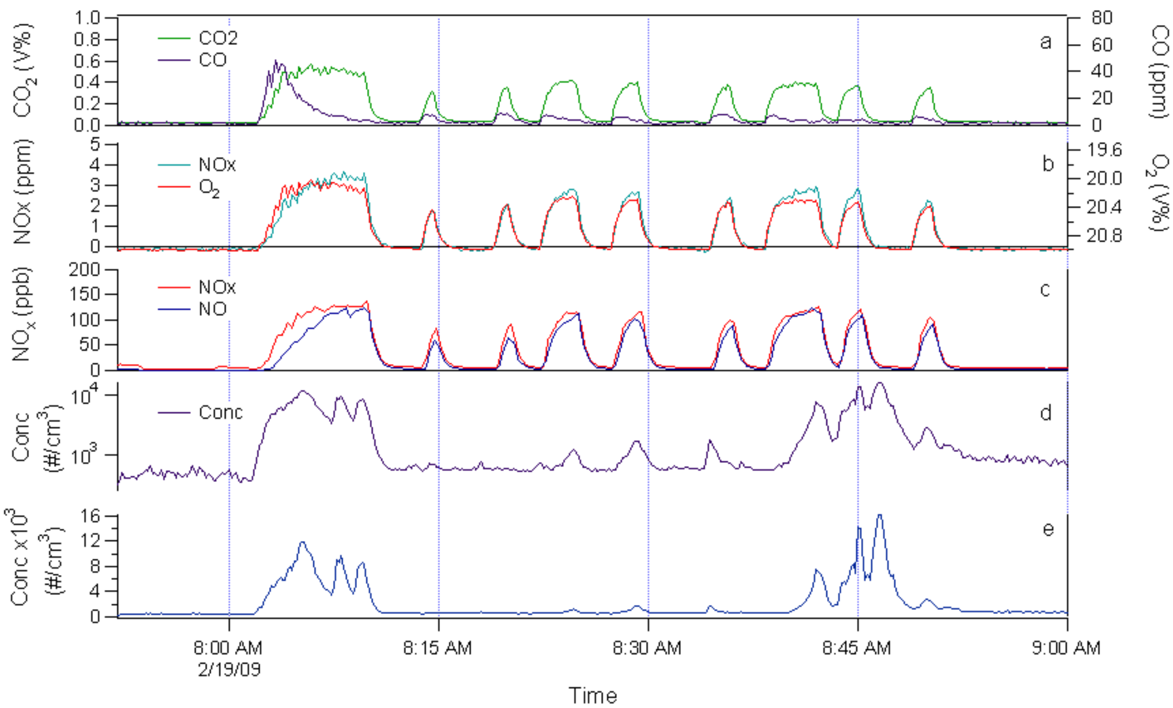

Figure 51. Measured analyte concentrations for oven OV13 with PG&E line gas (L184). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

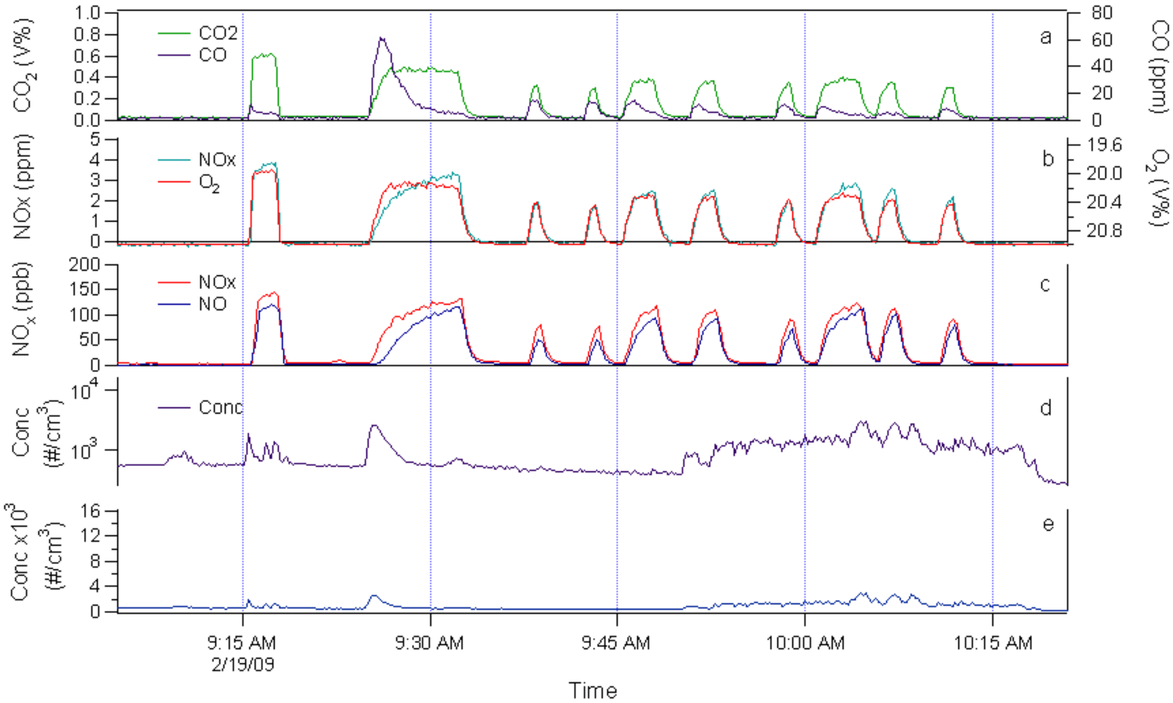

Figure 52. Measured analyte concentrations for oven OV13 with fuel 1C (L185).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

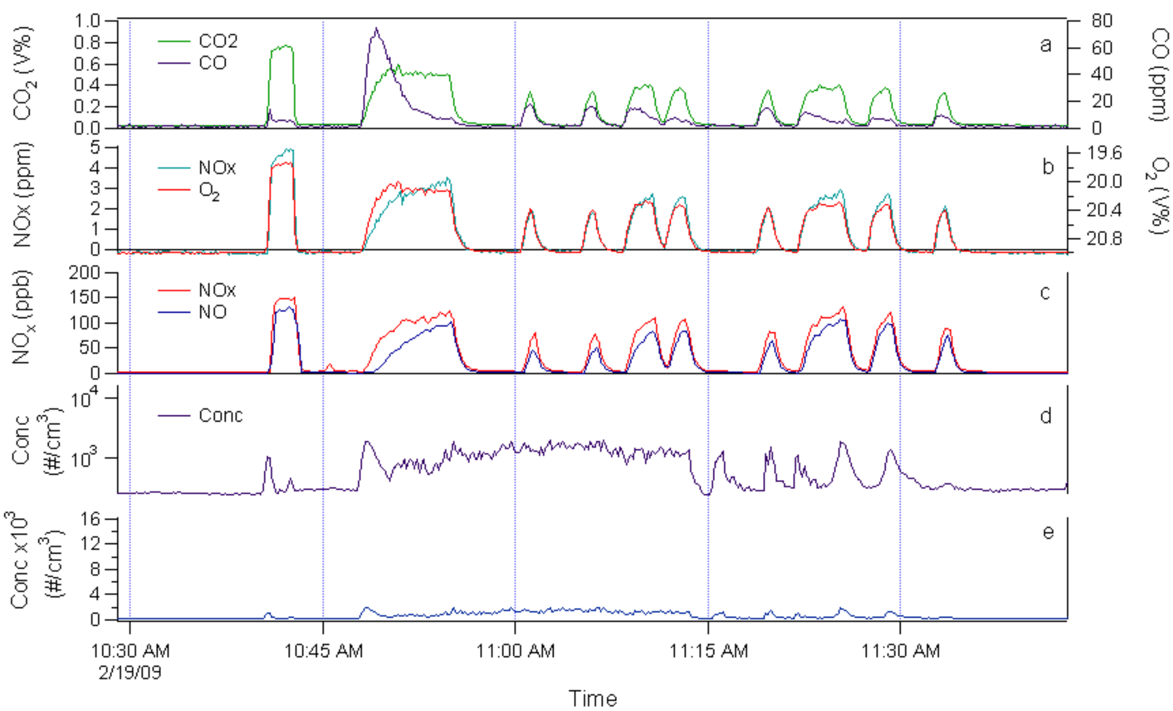

Figure 53. Measured analyte concentrations for oven OV13 with fuel 3C (L186).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

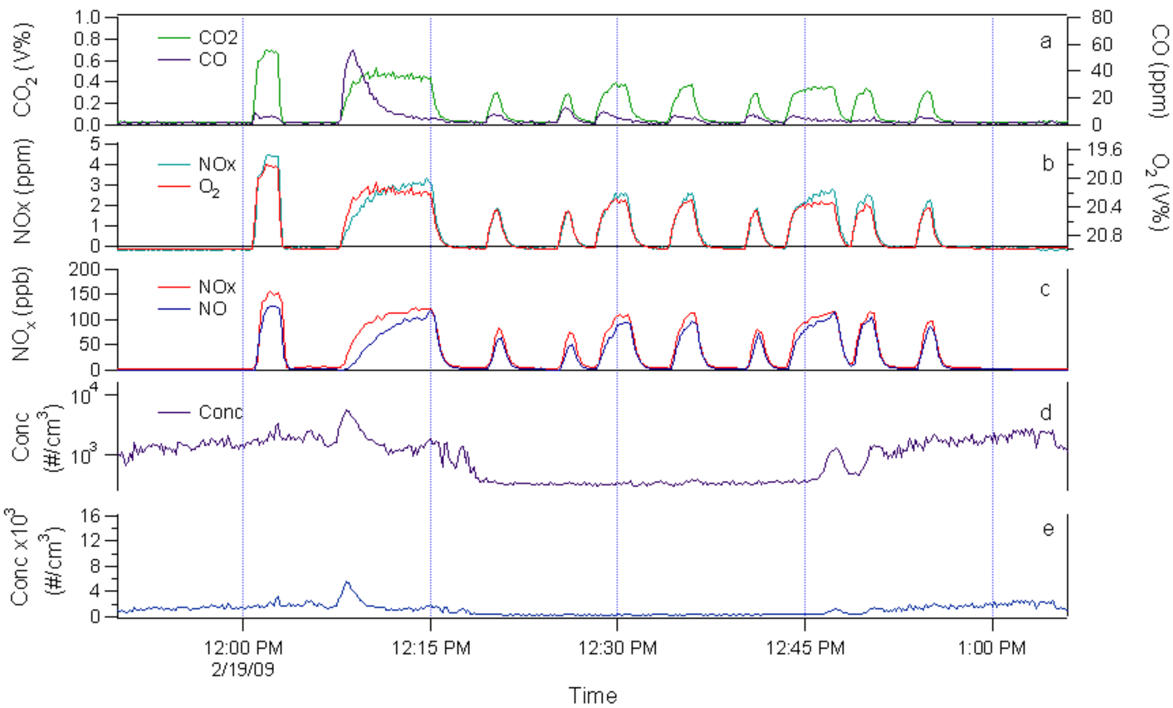

Figure 54. Measured analyte concentrations for oven OV13 with fuel PG&E (L187).
Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

Table 92. Calculated air-free concentrations (using CO_2) over last 1 min of each burn; CO, NO_X, PN.

Exp.	Fuel	Wobbe	CO (ppm)			PG250 NO_X (ppm)			PN (10^5 cm^{-3})		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L184	PG&E	1332	86	129	68	93	86	98	45	0.8	8.6
L185	1C	1390	129	318	111	94	87	97	N/A	N/A	N/A
L186	3C	1419	169	466	184	88	83	97	N/A	N/A	N/A
L187	PG&E	1332	109	185	70	95	91	107	N/A	N/A	N/A

Table 93. Calculated air-free concentrations (using CO_2) over last 1 min of each burn; NO_X, NO, and NO_2 (NO_X-NO) measured with Thermo 42i.

Exp.	Fuel	Wobbe	NO_X (ppm)			NO (ppm)			NO_2 (ppm)		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L184	PG&E	1332	93	86	98	87	75	96	6.1	11.6	1.6
L185	1C	1390	94	87	97	82	63	84	11.8	23.6	12.8
L186	3C	1419	88	83	97	71	52	80	16.1	30.3	17.0
L187	PG&E	1332	95	91	107	81	71	96	14.2	19.3	11.4

Table 94. Calculated emission rates over entirety of first burn at each temperature setting; CO, NO_X, PN.

Exp.	Fuel	Wobbe	CO (μg KJ^{-1})			PG250 NO_X (μg KJ^{-1})			PN (10^7 KJ^{-1})		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L184	PG&E	1332	120	40	31	35	39	42	110	6	36
L185	1C	1390	163	88	51	36	41	43	N/A	N/A	N/A
L186	3C	1419	204	113	68	32	40	43	N/A	N/A	N/A
L187	PG&E	1332	141	55	32	36	41	45	N/A	N/A	N/A

Table 95. Calculated emission rates over entirety of first burn at each temperature setting; NO_X, NO, and NO_2 (NO_X-NO) measured with Thermo 42i.

Exp.	Fuel	Wobbe	NO_X (μg KJ^{-1})			NO (μg KJ^{-1})			NO_2 (μg KJ^{-1})		
			350F	425F	500F	350F	425F	500F	350F	425F	500F
L184	PG&E	1332	35	39	42	27	34	39	7.9	4.6	2.9
L185	1C	1390	36	41	43	26	31	37	9.5	9.8	5.8
L186	3C	1419	32	40	43	21	27	34	11.3	12.3	8.6
L187	PG&E	1332	36	41	45	26	34	40	9.4	7.6	5.3

Table 96. Calculated formaldehyde emission rates over entire period of burner operation.

Exp.	Fuel	Wobbe	HCHO (μg KJ^{-1})
L184	PG&E	1332	0.25, 0.41 [1]
L185	1C	1390	0.41
L186	3C	1419	0.45
L187	PG&E	1332	0.34

[1] The first duplicate (lower value) was collected with the same sampling stream as the samples for other experiments.