Arnold Schwarzenegger
Governor

NATURAL GAS VARIABILITY IN CALIFORNIA: ENVIRONMENTAL IMPACTS AND DEVICE PERFORMANCE

EXPERIMENTAL EVALUATION OF POLLUTANT EMISSIONS FROM RESIDENTIAL APPLIANCES

APPENDIX I. SUMMARY REPORTS FOR STORAGE WATER HEATERS

PIER INTERIM PROJECT REPORT

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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.

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1.0 Water Heater WH01

1.1. Experimental information for WH01

This water heater was purchased new and instrumented for energy efficiency testing under CEC contract 500-06-036. It was installed in one of the two test bays that were being used for LNG interchangeability experiments. It was operated for several weeks of energy efficiency testing prior to initial evaluation for fuel interchangeability.

Two sets of experiments were conducted with this unit. In autumn 2007, experiments were conducted on the same day with fuel mixture 3A (WN = 1414) and 3A diluted with N_2 (WN = 1380); an experiment was conducted with PG&E line gas (WN = 1327) two days later. Environmental conditions were similar on both days. For these experiments, several parameters that were typically recorded during our experiments were already being monitored with the data system for energy efficiency testing (e.g. appliance manifold pressure); these data can be accessed but have not been incorporated into the LNG data record. In this set of experiments the aerosol dilution system inlet heater was not functioning; the inlet was therefore heated only by the exhaust gas stream. Formaldehyde samples were collected and analyzed during these experiments; however, it was determined subsequently that the critical orifices used in the sampling system had reduced flow. Sample flow rates were not measured during these experiments. Aldehyde results are not presented owing to uncertainty in sample flow rates, concentrations, and emission rates.

NO_X concentrations and emission rates measured in this first set of experiments were lower than expected for this type of burner by about a factor of two. This discrepancy suggests a possible problem with the sampling configuration or analytical instrumentation, but the specific cause has not been identified. The Horiba PG250 analyzer used to measure direct NO was calibrated with the same method that was used in other experiments and the available records indicate no major change in instrument response that could account for the factor-of-two discrepancy in NO_X results for these experiments. One possible contributing factor is that the exhaust gases were sampled at a single location in the central flue of the water heater, below the opening for exhaust dilution. It is known that the exhaust plume can be stratified in the central flue. However, we have not found that this stratification can differentially affect NO_X relative to other exhaust gases to the extent observed. Typically the stratification affects overall mixing of exhaust with excess combustion air, leading to proportional changes in all exhaust constituents.

A second set of experiments was conducted in on March 27, 2008: this pair included PG&E line gas (WN = 1328) and fuel 3C (WN = 1419). In these experiments, NO_X air-free concentrations and emission rates for this pair of experiments were at expected levels for this type of burner.

Table 1. Appliance and burner information.

Burner ID	WH01
Burner category	Storage water heater
Burner technology	Flammable vapor ignition resistant with pilot, natural draft; aluminized steel multiport low NO_X burner; certified to meet 40 ng/J NO_X standard (labeled for SCAQMD).
Appliance manufacturer	American
Model	Proline Flame Guard (Model BFG61-40S40-3NOV)
Serial number	0719105745 (Product number 0732032)
Capacity	40 gal.
Recovery rating	33.9 gal per h
Energy factor rating	0.59
Design manifold P	5 in. W.C.
Burner ratings (Btu/h)	40,000
Age (years)	New
Test location	Laboratory
History notes	Procured as new commercial unit for energy efficiency testing under CEC contract 500-06-036.

Table 2. Interchangeability experiments for storage water heater WH01.

Exp.	Fuel	Date	Burner operation
L041	PG&E	10/30/07	L041-L043: Data collected for 2 burns initiated by drawing 10 gal of water (25% of tank volume). Time between burns was about 8 min. Each experiment started with a purge burn.[1] L041 included one additional burn. Burn times provided in table below. L080-L081: Start each experiment with purge burn of several min. Draw water prior to burns and use gas control valve (switch between "on" and "pilot" to start and stop main burner for 15-min burns.
L042	3A	11/01/07	
L043	$3A+N_2$	11/01/07	
L080	PG&E	03/27/08	
L081	3C	03/27/08	

[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 3. Fuel analysis for interchangeability experiments with storage water heater WH01.

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
L041	PG&E	-	96.6	1.36	0.31	0.11	0.32	1.33	1011	1327
L042	3A	post	90.6	5.48	2.82	1.06	-	-	1118	1415
	3A	pre	90.9	5.40	2.72	1.02	-	-	1115	1413
L043	$3A+N_2$	post	88.9	5.37	2.72	1.01	1.97	-	1095	1379
	$3A+N_2$	pre	88.9	5.38	2.73	1.02	1.93	-	1096	1380
L080	PG&E	L080	96.7	1.27	0.26	0.14	0.34	1.25	1011	1328
L081	3C	Cylinder	86.4	12.0	1.60	-	-	-	1125	1419

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

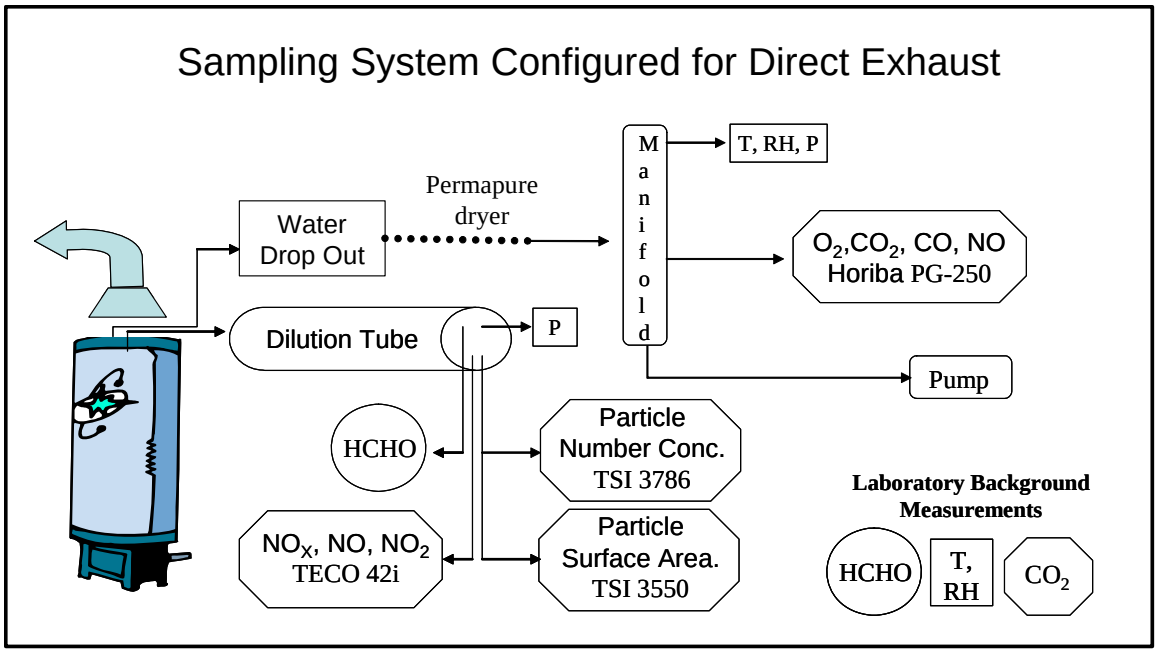

Figure 1. Pollutant sampling configuration for storage water heater WH01.

Table 4. Analyte ranges and calibration levels for experiments with storage water heater WH01, autumn 2007.

Analyte	**Sample location[1]**	**Equipment[2]**	**Range**	**Calibration levels**
Carbon dioxide (CO_2)	3" below top of central flue	Horiba PG-250	0-20%,	0, 10%
Oxygen (O_2)	3" below top of central flue	Horiba PG-250	0-25%	0, 20.95%
Carbon monoxide (CO)	3" below top of central flue	Horiba PG-250	0-200 ppm	0, 50 ppm
Nitric oxide (NO)	3" below top of central flue	Horiba PG-250	0-25 ppm	0, 5.0 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] Calibrated from mixture of NO in N_2.

Table 5. Analyte ranges and calibration levels for experiments with storage water heater WH01, spring 2008.

.Analyte	Sample location[1]	Equipment[2]	Range	Calibration levels
Carbon dioxide (CO_2)	3" below top of central flue	Horiba PG-250	0-10%	0, 10%
Oxygen (O_2)	3" below top of central flue	Horiba PG-250	0-25%	0, 20.95%
Carbon monoxide (CO)	3" below top of central flue	Horiba PG-250	0-200 ppm	0, 40 ppm
Nitrogen oxides (NO_X)	3" below top of central flue	Horiba PG-250	0-50 ppm	0, 50 ppm[3]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-10 ppm	0, 2.4 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.

Table 6. Aerosol instrumentation used for storage water heater WH01.

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 7. Other measurements for experiments with storage water heater WH01.
Additional measurements were made with data system installed for energy efficiency testing.

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	Upstream of appliance in lab	Pulse counter for AC-250-TC, 10 counts per rev (Riotronics)
Dilution sampler vacuum	Dilution tube	Magnehelic gauge (early expts); Setra Model 264 transducer
Temperature, air	In vicinity of appliance	Precision NTC thermistor (APT)
Relative humidity	In vicinity of appliance	Thermostet polymer based capacitance RH sensor (APT)

[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 WH01

During both sets of experiments, CO levels in the flue were equal to or lower than background and mostly within the noise level of the instrument after a small spike at ignition. NO_X was almost entirely in the form of NO. In the first set of experiments, NO_X air-free concentrations and emissions were much lower than expected for a conventional storage WH burner. In the second set of experiments, NO_X air-free concentrations and emissions were at levels expected for this type of burner. In both sets of experiments, NO_X did not vary with fuel WN. Thus, while the absolute emission levels of the first set are in doubt, the lack of a trend with fuel WN is a valuable result. In all experiments, PN emissions were consistent between burns at each fuel and increased with increasing fuel WN. Absolute levels were higher during the second set of experiments and PN emissions were generally low. PN concentrations increased over the course of each burn and for higher WN fuels, the flue concentrations of PN leveled off. HCHO emission rates were extremely low at <0.1 ng/J.

Table 8. Burner operating parameters for experiments with storage water heater WH01, autumn 2007.

Exp.	Burn	Start time	End time	Fuel used. (ft^3)	Firing rate[1] (kBtu/h)	Man. P (in. H_2O)
	Purge[2]	14:31:40	14:43:00			
L041	B1[3]	15:26:10	15:42:40	NA[4]	NA[4]	NA[4]
10/30/07	B2[3]	15:50:10	16:06:50	NA[4]	33.6	NA[4]
	Purge[2]	11:48:50	12:08:40			
L042	B1	12:41:20	12:56:20	8.0	35.3	NA[4]
11/1/07	B2	13:04:20	13:19:30	8.0	35.0	NA[4]
	Purge[2]	14:02:30	14:12:20			
L043	B1	14:32:10	14:48:10	8.2	34.0	NA[4]
11/1/07	B2	14:56:10	15:11:40	8.1	34.3	NA[4]

[1] Fuel flow rate ($ft^3\ h^{-1}$) calculated from measured fuel use over entire period of burner operation; firing rate calculated from measured fuel flow rate and higher heating value from fuel composition.
[2] The "purge" burn is used to flush fuel from the previous experiment. For experiments L041 and L043, the purge burn was initiated by drawing 6 gal of water. For experiment L042 the purge burn started automatically upon ignition of the pilot (tank water temperature sufficiently below set-point).
[3] In experiment L041, there were three sample burns following the purge burn. The first occurred from 15:02:10 to 15:18:50. Since the formaldehyde sample was not started prior to this first sample burn, a third sample burn was added. The burns listed in the table are for the second and third burns that corresponded to the period of HCHO sampling.
[4] Fuel volume and flow rate not measured in L041, burn 1; volume and flow measurement started during early part of L041, burn 2. Manifold pressure not measured with interchangeability data system; may be available from energy efficiency data system.

Table 9. Burner operating parameters for experiments with storage water heater WH01, spring 2008.

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)
L080	B1	12:27	12:41	NA[2]	NA[2]	7.4	4.9
L080	B2	12:57	13:11	NA[2]	NA[2]	7.4	5
L081	B1	14:11	14:25	NA[2]	NA[2]	7.8	5.2
L081	B2	14:41	14:55	NA[2]	NA[2]	7.8	5.1

[1] Fuel flow rate ($ft^3\ h^{-1}$) calculated by stopwatch timing of dial on gas meter.
[2] Data not available.

Table 10. Lab / Combustion air conditions[1] for experiments with water heater WH04.

Exp.	Fuel	T (°C)	RH (%)
L041	PG&E	23.0 ± 0.1	48 ± 0
L042	3A	23.0 ± 0.1	52 ± 0
L043	3A+N_2	23.9 ± 0.1	51 ± 1
L080	PG&E	20.5 ± 0.1	28 ± 1
L081	3C	21.0 ± 0.2	28 ± 0

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

Table 11. Sampling system conditions for experiments with water heater WH04.

Exp.	Sample Location T (°C)[1]		Dilution Ratio[2]	
	Burn 1	Burn 2	Burn 1	Burn 2
L041	NA	NA	19	18
L042	NA	NA	18	18
L043	NA	NA	18	18
L080	293 ± 0	292 ± 0	34	34
L081	299 ± 0	300 ± 0	34	34

[1] Mean ± standard deviation measured during each burn.
[2] Calculated by comparing NO measured in gas manifold (PG-250) and dilution sampler (Thermo 42i) for each burn.

Table 12. Formaldehyde samples for experiments with storage water heater WH04.

Exp(s)	Location	Date	Sample start/end time		Air vol. (L)	Extract conc. (ng/μL)	Air conc.[1] (μg/m^3)
Bkg	Lab air	03/27/2008	12:17:00	14:56:00	181	0.215	2.38
L080	Dilution Tube	03/27/2008	12:25:40	13:12:00	47	0.046	1.94
L081			14:08:00	14:56:00	49	0.046	1.87

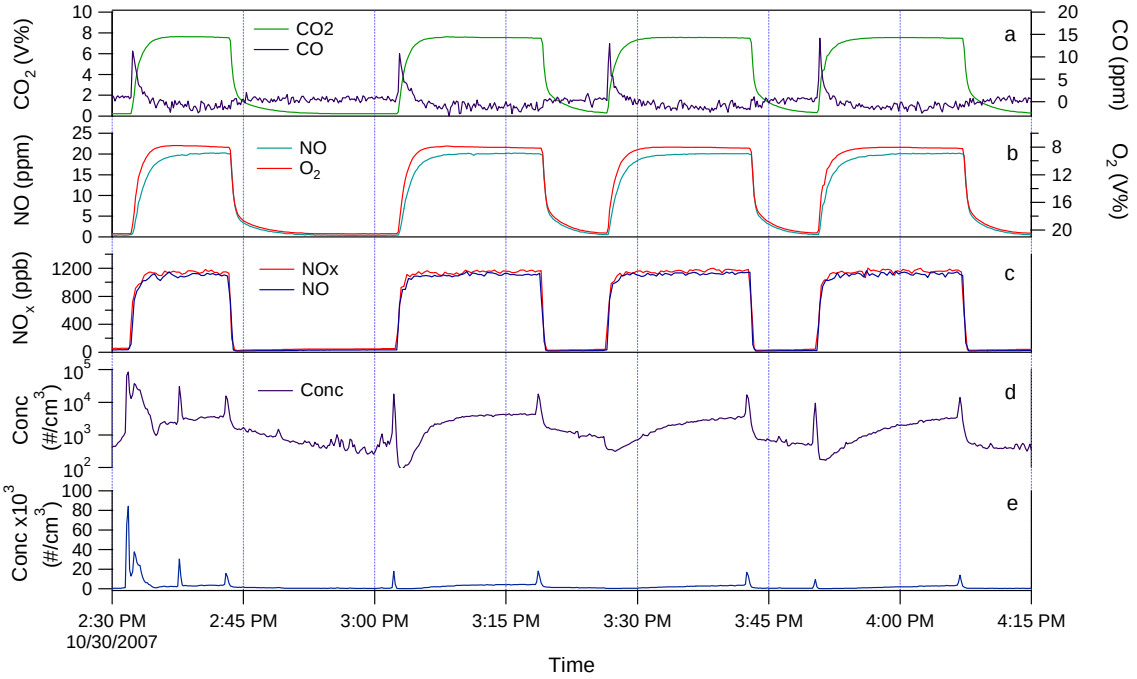

Figure 2. Measured analyte concentrations for storage water heater WH01 with PG&E line gas (L041). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. "Conc" refers to particle number concentration.

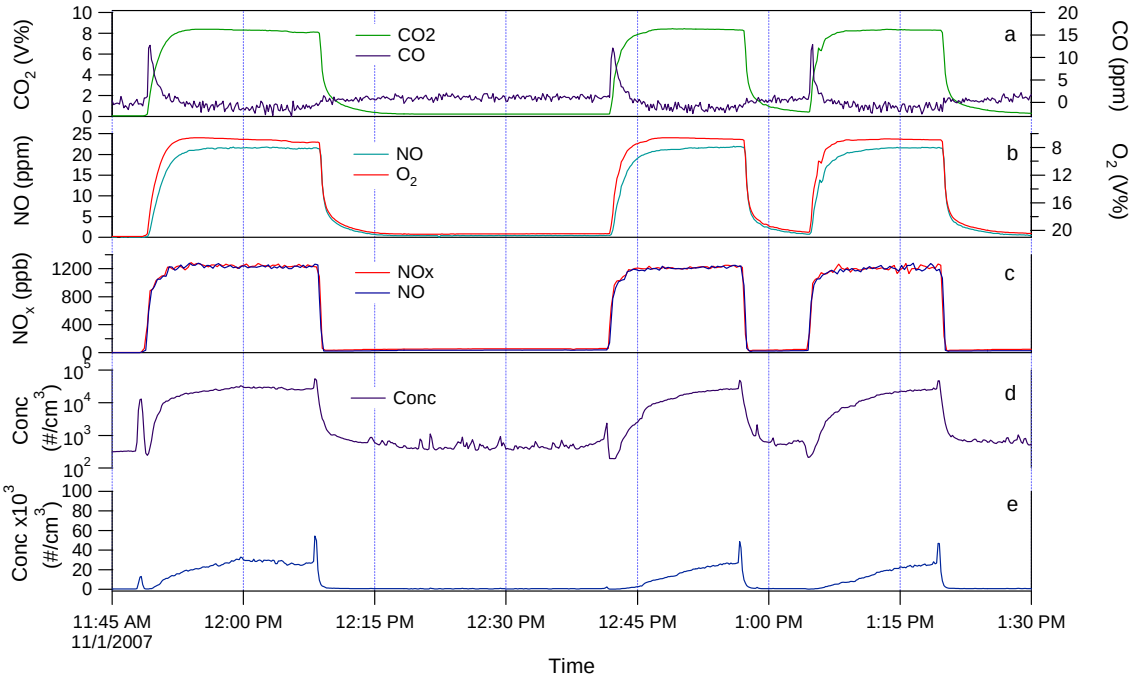

Figure 3. **Measured analyte concentrations for storage water heater WH01 with fuel 3A (L042).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. "Conc" refers to particle number concentration.

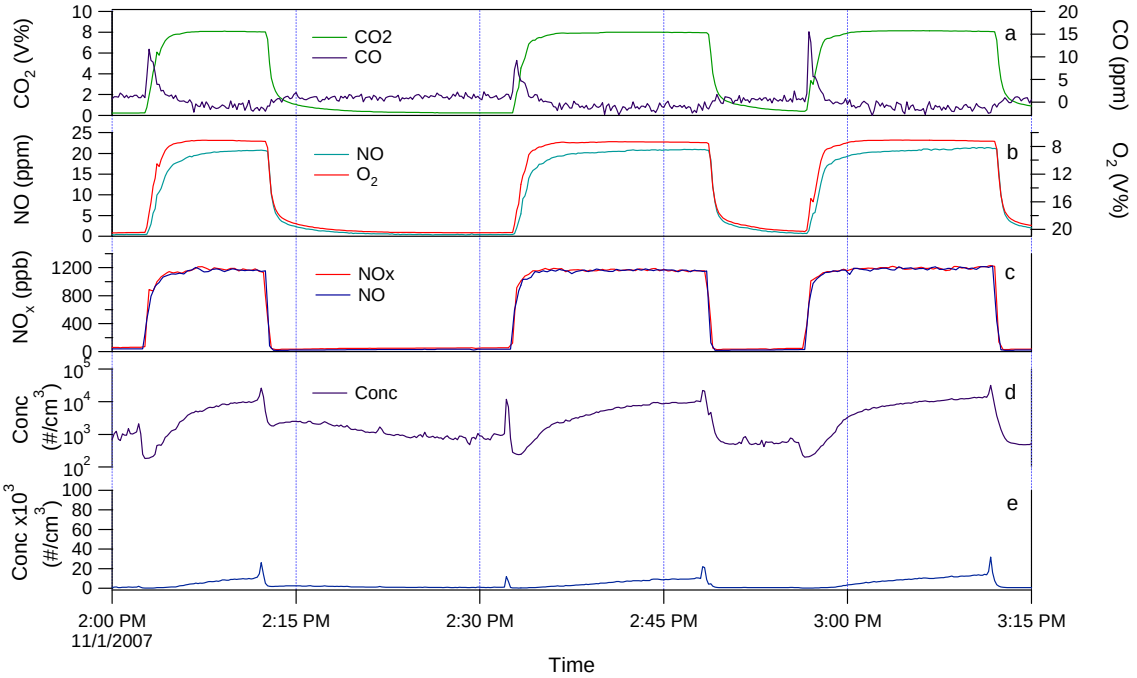

Figure 4. **Measured analyte concentrations for storage water heater WH01 with fuel 3A + N_2 (L043).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. "Conc" refers to particle number concentration.

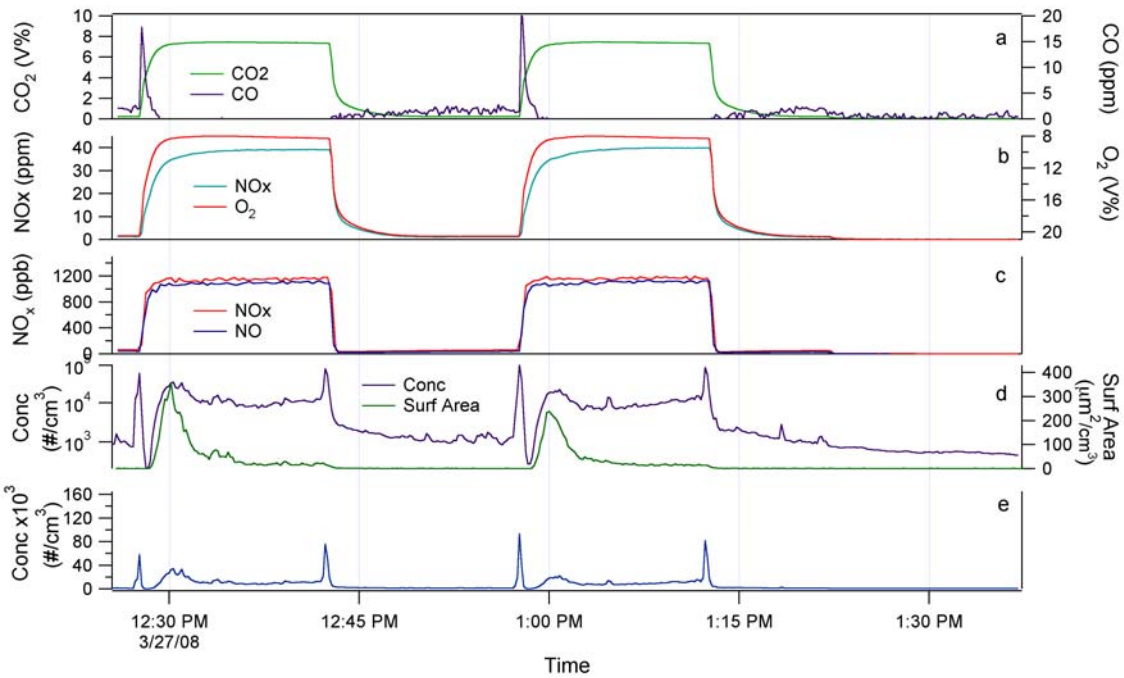

Figure 5. **Measured analyte concentrations for storage water heater WH01 with PG&E line gas (L080).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. "Conc" refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

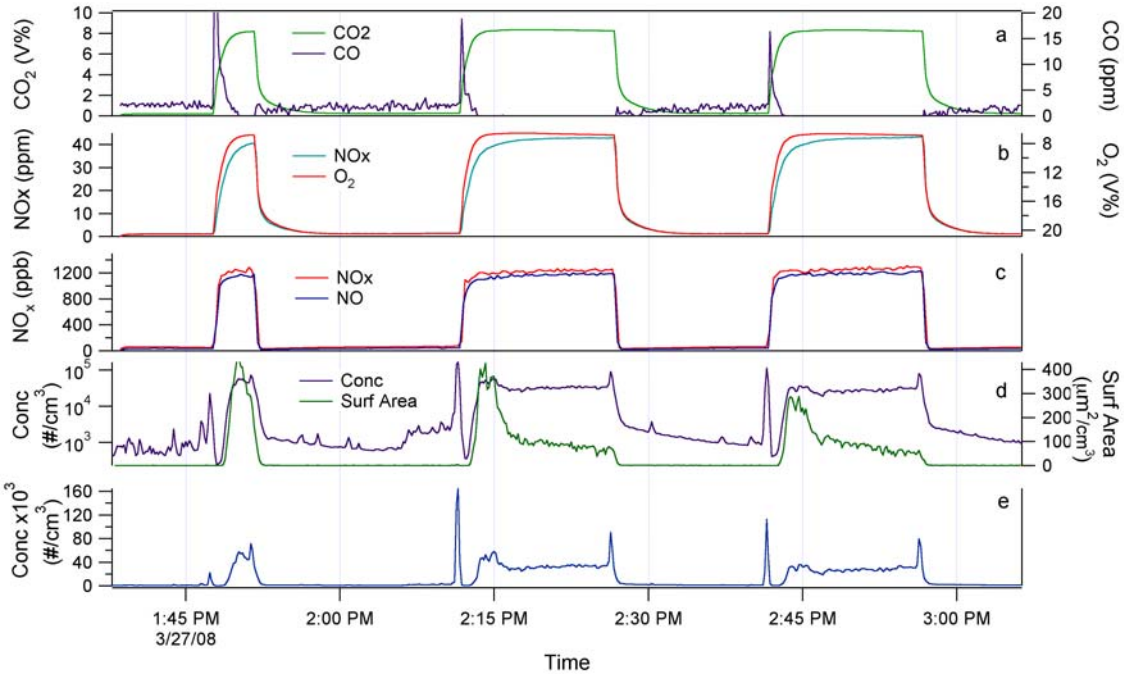

Figure 6. **Measured analyte concentrations for storage water heater WH01 with fuel 3C (L081).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. "Conc" refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

Table 13. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, water heater WH01.

Exp	Fuel	Wobbe	CO (ppm)		NO_X (ppm)		NO (ppm)		NO_2 (ppm)		PN (10^5 cm^{-3})	
			B1	B2	B1	B2	B1	B2	B1	B2	B1	B2
L041	PG&E	1348	-1	-1	33	33	32	32	0.8	0.8	1.1	0.8
L042	3A	1414	-2	-1	31	31	31	31	0	-0.2	6	6
L043	3A+N_2	1379	-1	-1	31	31	31	31	-0.1	0	2.3	3
			CO (ppm)		NO_X (ppm)		NO (ppm)		NO_2 (ppm)		PN (10^5 cm^{-3})	
L080	PG&E	1328	-4	-5	63	64	60	61	2.8	3	5.3	5.5
L081	3C	1419	-5	-5	62	63	59	59	2.9	3.5	16	14

Table 14. Calculated emission rates over entirety of each burn, water heater WH01.

Exp	Fuel ID	Wobbe	CO (μg KJ^{-1})		NO_X (μg KJ^{-1})		NO (μg KJ^{-1})		NO_2 (μg KJ^{-1})		PN (10^7 KJ^{-1})		HCHO (μg KJ^{-1})
			B1	B2	B1	B2	B1	B2	B1	B2	B1	B2	
L041	PG&E	1348	0	0	13.6	13.6	13.3	13.3	0.3	0.3	2	1.2	
L042	3A	1414	0	0	13.2	13.2	13.1	13.2	0.1	0.0	8.3	8.4	
L043	3A+N_2	1379	0	0	13.1	13.2	13.0	13.0	0.1	0.2	3.2	4.3	
			CO (μg KJ^{-1})		NO_X (μg KJ^{-1})		NO (μg KJ^{-1})		NO_2 (μg KJ^{-1})		PN (10^7 KJ^{-1})		HCHO (μg KJ^{-1})
L080	PG&E	1328	-1	-1	26	26	24	25	1.6	1.5	16	15	0.04
L081	3C	1419	-1	-1	26	27	25	25	1.4	1.5	39	30	0.03

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2.0 Water Heater WH02

2.1. Experimental information for WH02

This was the second appliance and the first water heater tested with simulated LNG blends to evaluate interchangeability at a residence. Experiments were conducted on the same day with PG&E line gas (WN = 1322), fuel mix 1C (WN = 1390) and fuel 3C (WN = 1419). 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. During set-up it was observed that PN concentration spikes resulted when the match used to light the pilot was inserted into the combustion chamber while still smoldering.

Table 15. Appliance and burner information.

Burner ID	WH02
Burner category	Storage water heater
Technology	Conventional stamped sheet metal burner; pre-FVIR (open combustion chamber); natural draft w/pilot
Appliance manufacturer	General Electric
Model	Profile SmartWater™ (Model PG4059XB)
Serial number	GELN0701142770
Capacity	40 gal.
Recovery rating	33.9 gal per h
Energy factor rating	0.59
Design manifold P	4 in. H_2O
Burner ratings (Btu/h)	40,000
Age	6 years at time of testing (installed 2001)
Test location	As installed on ground floor garage of residence
History notes	Unit installed by current homeowner in 2001; used by family of 2 adults and 2 children.

FVIR = Flammable vapor ignition resistant.

Table 16. Interchangeability experiments for storage water heater WH02.

Exp.	Fuel	Date	Burner operation
F014	PG&E	11/21/07	Start with purge burn[1]. Minimum of two experimental burns each initiated by drawing 10 gal of water (25% of tank volume). Time between burns was 9-20 min.
F015	1C	11/21/07	
F016	3C	11/21/07	

[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 17. Fuel analysis for interchangeability experiments with storage water heater WH02.

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
F014	Line	B1	95.9%	1.65%	0.30%	0.11%	0.80%	1.21%	1009	1322
F015	1C	B2	91.9%	8.11%	0.00%	0.00%	0.00%	0.00%	1072	1390
F016	3C	B2	86.4%	12.0%	1.57%	0.00%	0.00%	0.00%	1125	1419

[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.

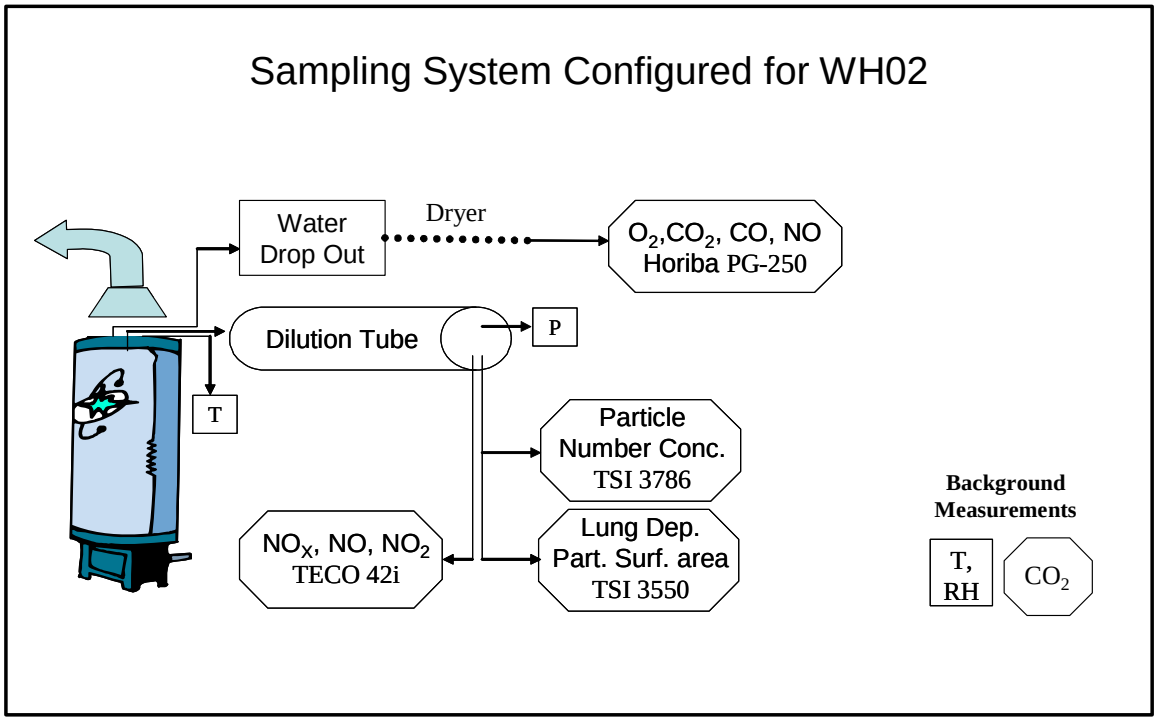

Figure 7. Pollutant sampling configuration for storage water heater WH02; there was no sampling fir formaldehyde in experiments F014-F016.

Figure 8. Experimental apparatus installed for storage water heater WH02.
From left: cylinder containing simulated LNG, low pressure regulator (on floor, next to cylinder cart), gas meter (on floor), water heater, cart containing analytical instrumentation, dilution sampler (background, above cart), and blowers for dilution sampler (on floor behind cart).

Table 18. Analyte ranges and calibration levels for experiments with storage water heater WH02.

Analyte	Sample location[1]	Equipment[2]	Range	Calibration levels
Carbon dioxide (CO_2)	3" below top of central flue	Horiba PG-250	0-20%	0, 10%
Oxygen (O_2)	3" below top of central flue	Horiba PG-250	0-25%	0, 20.95% check at 8%
Carbon monoxide (CO)	3" below top of central flue	Horiba PG-250	0-1000 ppm	0, 50 ppm
Nitrogen oxide (NO)	3" below top of central flue	Horiba PG-250	0-100 ppm	0, 50 ppm [(3)]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-10 ppm	0, 2.5 ppm
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] Calibrated from mixture of NO in N_2. Insufficient quantity of gas to complete calibration; use instrument response setting from calibration at 50 ppm conducted one day earlier.

Table 19. Aerosol instrumentation used for storage water heater WH02.

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 20. Other measurements for experiments with storage water heater WH02.

Measured Quantity	Location(s)	Device(s) [1]
Fuel pressure	Inlet to appliance regulator Outlet of appliance regulator	Magnehelic gauge; 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	Magnehelic gauge (early expts); Setra Model 264 transducer
Temperature, air	Air inlet underneath WH	Precision NTC thermistor (APT)
Relative humidity	Air inlet underneath WH	Thermostet polymer based capacitance RH sensor (APT)
Temperature, exhaust	At exhaust sampling location, 3” below top of WH central flue	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 WH02

CO emission rates during main burner operation were very low. During these burns, CO spiked a bit on ignition then quickly dropped below pilot burner levels and in some cases even below background levels. PN emissions were also extremely low and during several burns PN dropped below background levels. NO_X emissions varied by <10% among experiments. NO_X was overwhelmingly (>90%) in the form of NO. For this burner, pollutant emissions were not impacted substantially by fuel variability. Full burn emission rates were <1 ng/J for CO, 31-34 ng/J for NO_X, and -1 to 2.5 x10^4 J^{-1} for PN.

Table 21. Burner operating parameters for experiments with storage water heater WH02.

Exp.	Burn times			Fuel flow rate (ft^3 h^{-1})		Firing rate[1] (kBtu/h)		Manifold pressure (in. H_2O)	
	Purge[2]	Burn 1	Burn 2	B1	B2	B1	B2	B1	B2
F014	10:12:40–10:16:30	10:40:00–10:54:50	11:18:20–11:31:30	36.0	35.1	36.3	35.4	3.4	3.4
F015[2]	12:15:40–12:25:20	12:47:20–13:01:20	13:10:20–13:24:20	34.7	34.7	37.2	37.2	3.4	3.4
F016	14:26:20–14:36:40	14:58:20–15:11:20	15:21:00–15:32:10	33.7	34.4	37.9	38.7	3.4	3.3

[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.
[2] The "purge" burn is used to flush fuel from the previous experiment. Formal purge for F014 started with lighting of pilot, no water draw required; range finding run from 9:54 to 10:09 used same fuel. Purge burns for F015 and F016 initiated by drawing 6 and 6.5 gal of water.

Table 22. Combustion air conditions[1] for experiments with water heater WH02.

Exp.	T, burn 1 (°C)	T, burn 2 (°C)	RH, burn 1 (%)	RH, burn 2 (%)
F014	26 ± 4	25 ± 3	32 ± 7	32 ± 6
F016	28 ± 4	29 ± 3	27 ± 6	24 ± 3
F015	26 ± 3	27 ± 3	28 ± 6	23 ± 3

[1] Mean ± standard deviation measured over period of two sampling burns. Probes placed at air inlet below water heater and thus impacted by heating with burner on.

Table 23. Sampling system conditions for experiments with storage water heater WH02.

Exp.	Exhaust sample location T (°C) [1]		Dilution Ratio (2 burns)[2]	
F014	225 ± 35	160 ± 20	20	16
F015	255 ± 40	255 ± 40	17	17
F016	250 ± 40	250 ± 40	17	17

[1] Measured in gas sampling manifold 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.

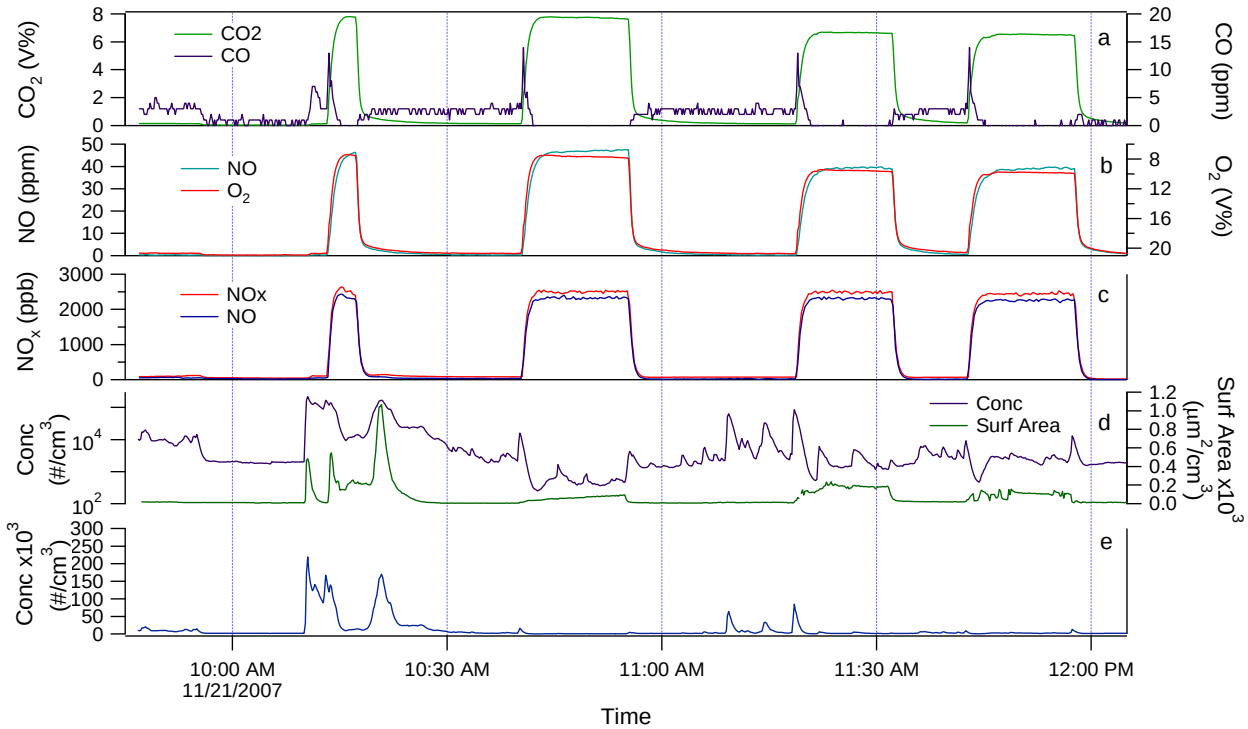

Figure 9. **Measured analyte concentrations for storage water heater WH02 with PG&E line gas (F014).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(d) present measurements from the dilution system PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

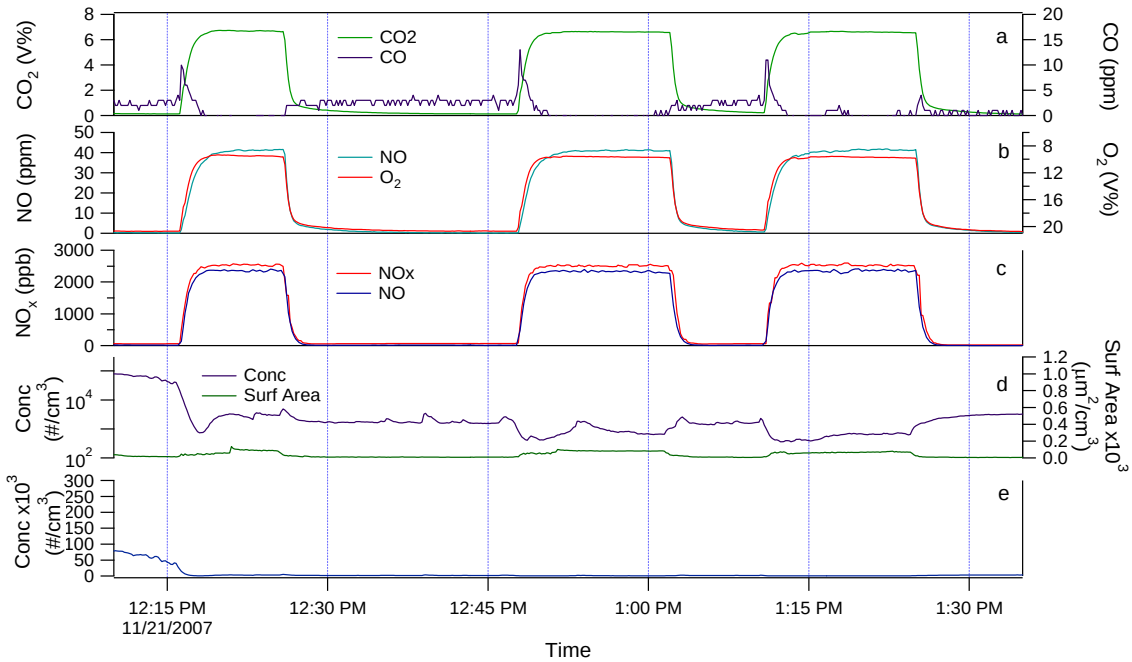

Figure 10. Measured analyte concentrations for storage water heater WH02 with fuel 1C (F015). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(d) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

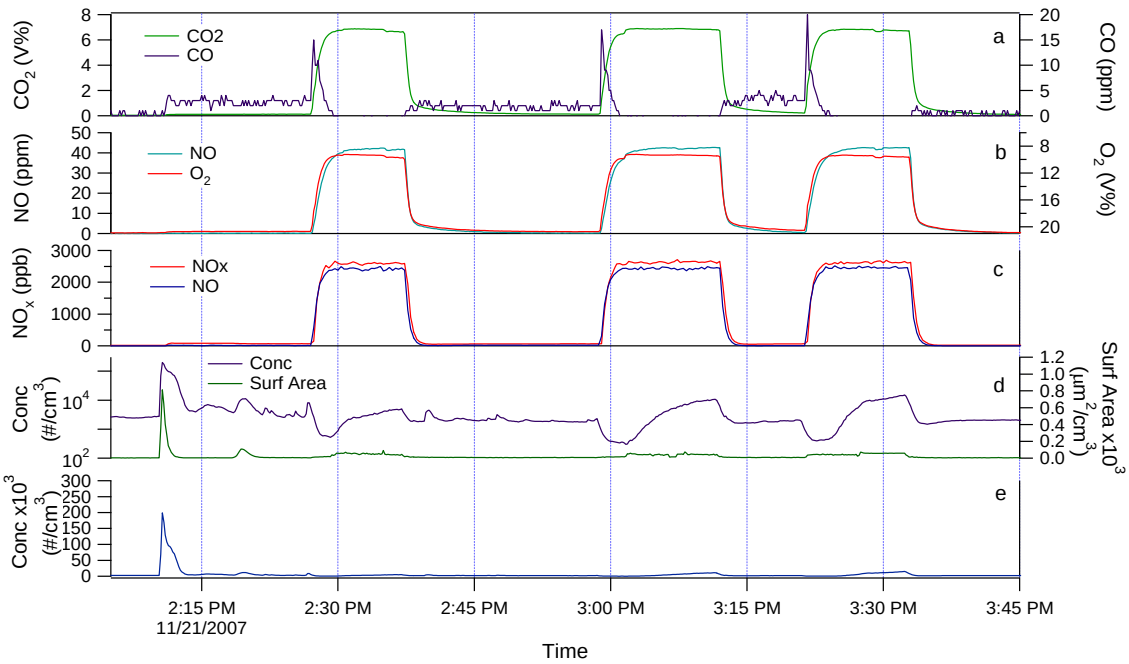

Figure 11. Measured analyte concentrations for storage water heater WH02 with fuel 3C (F016). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(d) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

Table 24. Preliminary results for storage water heater WH02: calculated air-free concentrations (using CO_2) over last 5 min of each burn. Uncertainty will be addressed in subsequent reporting.

Exp.:	F014		F016		F015	
Fuel:	PG&E		1C		1C	
Wobbe:	1322		1390		1419	
CO, ppm	-4	-2	-2	-4	-2	-2
PG-250 NO, ppm	73	71	75	76	74	75
NO_X, ppm	78	75	81	81	79	79
NO, ppm	73	71	75	76	74	75
NO_2, ppm	5.1	4.8	6.2	4.8	5.5	4.3
PN, 10^5 cm^{-3}	-0.6	-0.0	0.2	0.2	-0.5	-0.5

Table 25. Preliminary results for storage water heater WH02: calculated emission rates over entirety of each burn. Uncertainty will be addressed in subsequent reporting.

Exp.:	F014		F016		F015	
Fuel:	PG&E		1C		1C	
Wobbe:	1322		1390		1419	
CO, $\mu g\ KJ^{-1}$	-0.7	-0.1	0.1	-0.1	-0.1	0.0
PG-250 NO, $\mu g\ KJ^{-1}$	30.2	29.3	31.5	31.7	31.5	31.7
NO_X, $\mu g\ KJ^{-1}$	32.3	31.3	34.1	33.9	34.1	34.1
NO, $\mu g\ KJ^{-1}$	30.1	29.1	31.6	31.7	31.4	31.6
NO_2, $\mu g\ KJ^{-1}$	2.2	2.2	2.5	2.2	2.4	2.5
PN, 10^7 KJ^{-1}	-0.8	2.5	1.1	2.5	-1.2	-1.3

3.0 Water Heater WH03

3.1. Experimental information for WH03

This water heater is located in a crawl space with height (floor to bottom of joists) <6 feet. The testing occurred the day after central furnace CF02, at the same residence. This crawl space floor contained some sections of unpaved dirt and there was concern that particles suspended from researcher activity in the crawl space may have contributed to some of the particle number peaks observed during the furnace experiment. Several measures were taken to mitigate the suspension of particles and their entry into the combustion zone of the water heater. These included placing a tarp underneath the main area of activity and hanging painter's plastic sheeting from ground to joists at a radial distance of 0.5-1 m around the water heater to create a more tortuous path for large soil particles to traverse in approaching the water heater. A portable HEPA air filtration unit was placed nearby to the water heater to reduce the number concentration of all particles entering into the combustion air of the water heater. 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 26. Appliance and burner information.

Burner ID	WH03
Burner category	Storage water heater
Technology	Conventional stamped sheet metal burner; pre-FVIR (open combustion chamber); natural draft w/pilot; certified to 40 ng/J
Appliance manufacturer	Rheem
Model	Professional 50 (Model RHGPRO50-40N)
Serial number	RHLN1101114357
Capacity	50 gal.
Recovery rating	40.4 gal per h
Energy factor rating	0.62
Design manifold P	4 in. H_2O
Burner ratings (Btu/h)	40,000
Age	4 years at time of testing (installed 2003)
Test location	As installed in garage / crawl space of residence
History notes	Unit installed in 2003; used by family of 2 adults and 2 toddlers

FVIR = Flammable vapor ignition resistant.

Table 27. Interchangeability experiments for storage water heater WH03.

Exp.	Fuel	Date	Burner operation
F022	PG&E	11/29/07	Start with purge burn[1]. Minimum of two experimental burns, each preceded by drawing 10 gal of water (20% of tank volume) with burner control set to "pilot"; following draw, control set to "on" to initiate burn. Approximately 15 min of cooling time preceded each burn.
F023	1C	11/29/07	
F024	3C	11/29/07	

[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 28. Fuel analysis for interchangeability experiments with storage water heater WH03.

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
F022	Line	B2	95.6	2.28	0.30	0.09	1.00	0.74	1016	1333
F022	Line	Pre	95.5	2.44	0.26	0.06	0.99	0.73	1017	1333
F023	3C	B1	86.3	12.1	1.61	0.00	0.00	0.00	1127	1420
F023	3C	B2	86.2	12.2	1.59	0.00	0.00	0.00	1126	1420
F024	1C	B1	91.9	8.07	0.00	0.00	0.00	0.00	1071	1390
F024	1C	B2	92.1	7.94	0.00	0.00	0.00	0.00	1070	1389

[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.

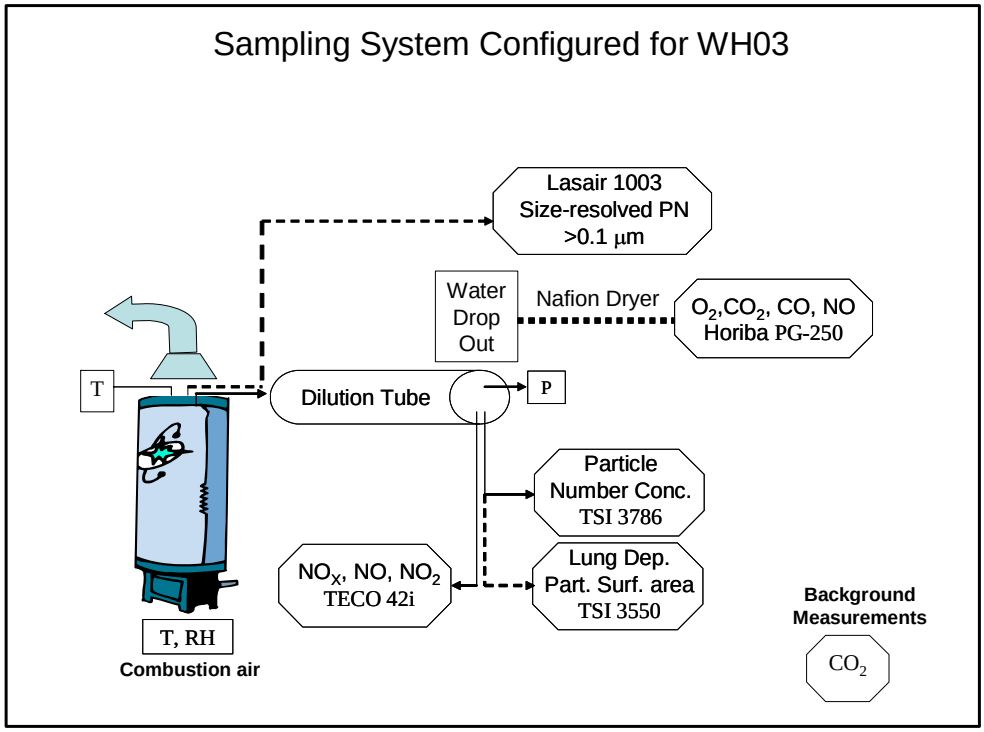

Figure 12. Pollutant sampling configuration for storage water heater WH03; formaldehyde sampling did not occur for experiments F022-F024.

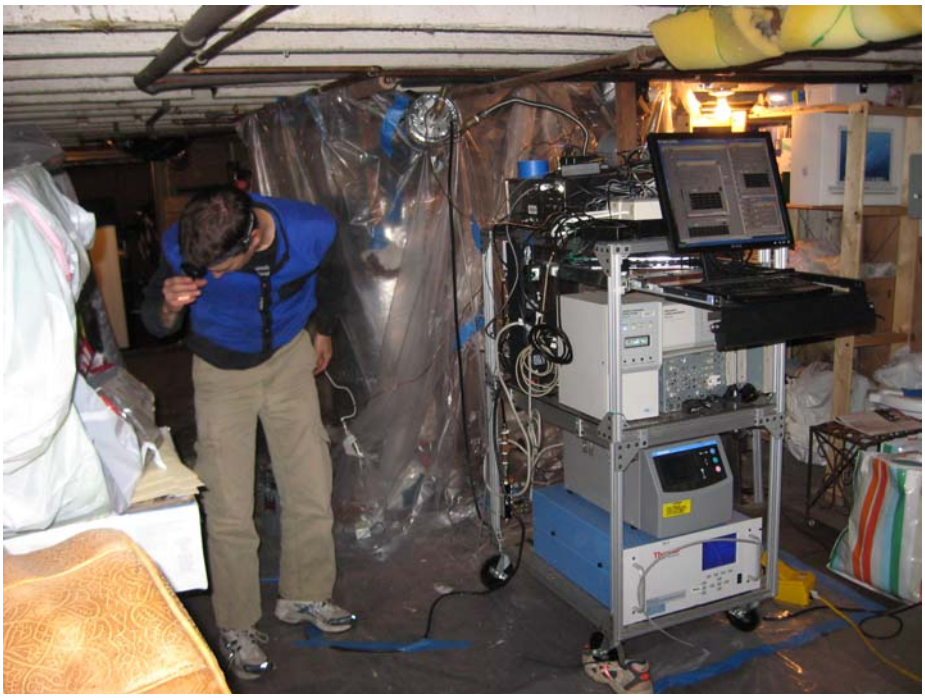

Figure 13. **Experimental apparatus installed for storage water heater WH03.**
Appliance is obscured by plastic sheeting used to create a barrier to mitigate the entrainment into the combustion zone of large particles that may be suspended by walking on concrete floor (nearby areas are unpaved dirt). On the floor/ground, plastic sheeting overlaying a tarp was used to mitigate particle suspension from researcher movement. Dilution sampling tube is shown at top middle of picture, oriented into the picture, toward water heater central flue.

Table 29. Analyte ranges and calibration levels for experiments with storage water heater WH03.

Analyte	Sample location[1]	Equipment[2]	Range	Calibration levels
Carbon dioxide (CO_2)	3" below top of central flue	Horiba PG-250	0-10%	0, 10%
Oxygen (O_2)	3" below top of central flue	Horiba PG-250	0-25%	0, 20.95%
Carbon monoxide (CO)	3" below top of central flue	Horiba PG-250	0-200 ppm	0, 40 ppm
Nitrogen oxide (NO)	3" below top of central flue	Horiba PG-250	0-100 ppm	0, 50 ppm[3]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-10 ppm	0, 2.5 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] Calibrated from mixture of NO in N_2.

Table 30. Aerosol instrumentation used for storage water heater WH03.

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 31. Other measurements for experiments with storage water heater WH03.

Measured Quantity	Location(s)	Device(s)[1]
Fuel pressure	Inlet to appliance regulator Outlet of appliance regulator	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, air	Air inlet underneath WH	Precision NTC thermistor (APT)
Relative humidity	Air inlet underneath WH	Thermostet polymer based capacitance RH sensor (APT)
Temperature, exhaust	At exhaust sampling location, 3" below top of WH central flue	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 WH03

CO emission rates during main burner operation were extremely low; in fact, with the main burner on there appears to have been a net decrease in CO compared with combustion air. PN

emissions were substantially higher than for WH02, but still low relative to some cooktop and oven experiments. The number concentration (PN) and volume of larger particles decreased with the burner on. PN air-free concentrations during steady burner operation increased monotonically with fuel Wobbe number and for each experiment steady burner concentrations were similar during the 2 burns. Full-burn PN emission rates do not show a strong trend with fuel Wobbe number. NO_X emissions varied by <5% among experiments. NO_X was overwhelmingly (>95%) in the form of NO. Full burn emission rates were <1 ng/J for CO, 24-25 ng/J for NO_X, and 3-7 x 10^4 J^{-1} for PN.

Table 32. Burner operating parameters for experiments with storage water heater WH03.

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
F022	14:35:40–14:40:30[3]	15:00:10–15:15:30	15:31:10–15:43:30	35.6	37.0	36.2	37.6	3.7	3.7
F023	15:56:00–16:01:00[4]	16:15:10–16:27:50[5]	16:43:20–16:55:10	32.7	34.0	36.9	38.3	3.4[(5)]	3.6
F024	17:08:10–17:12:30	17:28:20–17:40:20	17:55:10–18:08:50	34.5	34.7	37.0	37.2	3.6	3.6

[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. 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.

[3] An initial 5-min purge for F022 occurred between 14:07 and 14:12. When the first burn was attempted at 14:28, the pilot light was extinguished and the main burner ignited then extinguished after approximately 1 min. The pilot was lit at 14:33 and the purge burn was repeated to create a consistent starting condition for the burner. The purge burn was ended by turning the burner control back from "on" to "pilot".

[4] The purge burn for F023 was initiated by briefly turning up the thermostat on the water heater; the purge burn was ended by turning the burner control back from "on" to "pilot".

[5] For FO23 Burn 1, the manifold pressure increased to 0.9 in. H_2O at 16:14:30 and remained at this level until 16:15:10; following this, the manifold pressure was stable at approximately 4 in. H_2O for the remainder of the burn.

Table 33. Combustion air conditions[1] for experiments with water heater WH03.

Exp.	T, burn 1 (°C)	T, burn 2 (°C)	RH, burn 1 (%)	RH, burn 2 (%)
F022	20.2 ± 0.0	20.1 ± 0.1	40 ± <1	41 ± <1
F023	20.2 ± 0.1	20.2 ± 0.1	42 ± <1	43 ± <1
F024	20.0 ± 0.1	19.9 ± 0.1	44 ± <1	43 ± <1

[1] Mean ± standard deviation measured over period of two sampling burns, measured in basement nearby to water heater, but not directly at air intake.

Table 34. Sampling system conditions for experiments with water heater WH03.

Exp.	Sample Location T (°C)[1]		Dilution Ratio[2]	
	Burn 1	Burn 2	Burn 1	Burn 2
F022	149 ± 1	152 ± 1	18	17
F023	156 ± 0	156 ± 1	17	17
F024	156 ± 1	155 ± 0	17	17

[1] Measured at sample location ~3" below top of central flue; mean over last 5 min of each burn.
[2] Calculated by comparing NO measured in gas manifold (PG-250) and dilution sampler (Thermo 42i) over last 5 min of each burn.

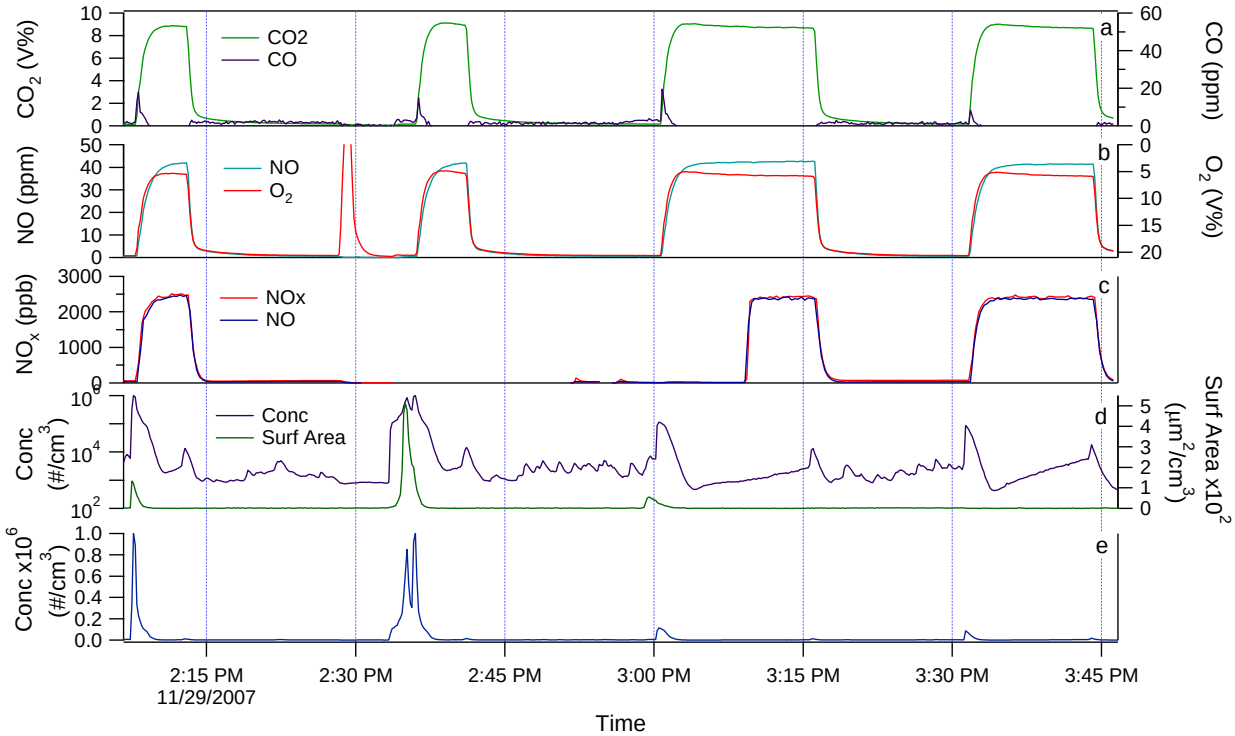

Figure 14. **Measured analyte concentrations for storage water heater WH03 with PG&E line gas (F022).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area. The period of missing data in panel (c) resulted from the Thermo NO_X analyzer being offline after tripping of a GFCI outlet. The first peak shown was a purge burn. Log book includes note that burner started then shut off by itself (with pilot going out) at 14:28; it is unclear why this shows up only in the O_2 data. Pilot was relit at 14:33; large increase in particles at this time likely associated with smoldering match. Following pilot lighting, burner was on until about 14:40.

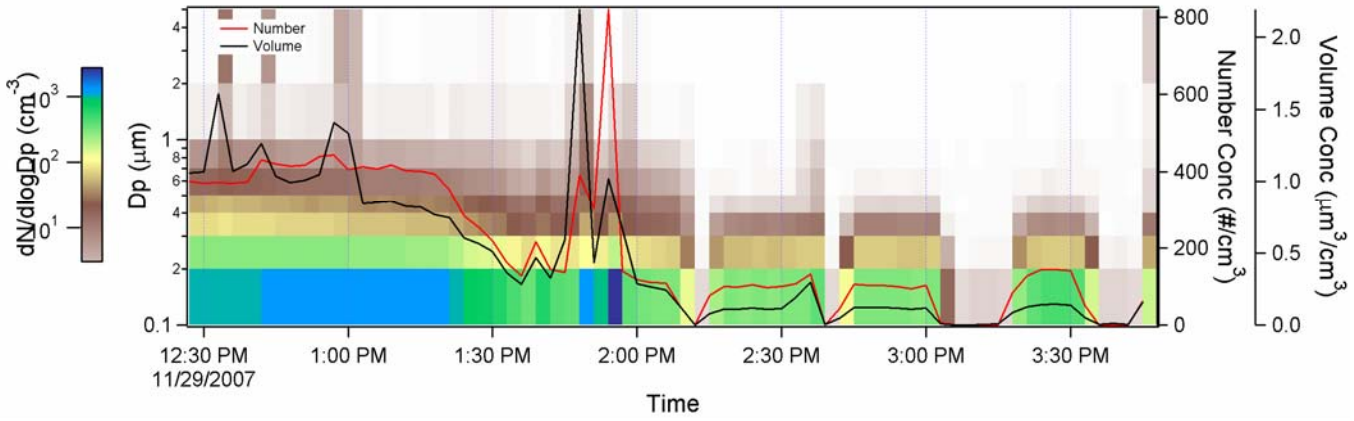

Figure 15. Size-resolved number concentrations of particles larger than 0.1 µm for experiment F022 (Lasair data). This plot includes particle suspension experiments conducted before F022 burns were begun. The data starting at about 2:00 pm show that the number concentrations of particles >0.1 mm in diameter decrease with each burner firing (purge burn at 2:35 pm; burn 1 at 3:00 pm, etc.).

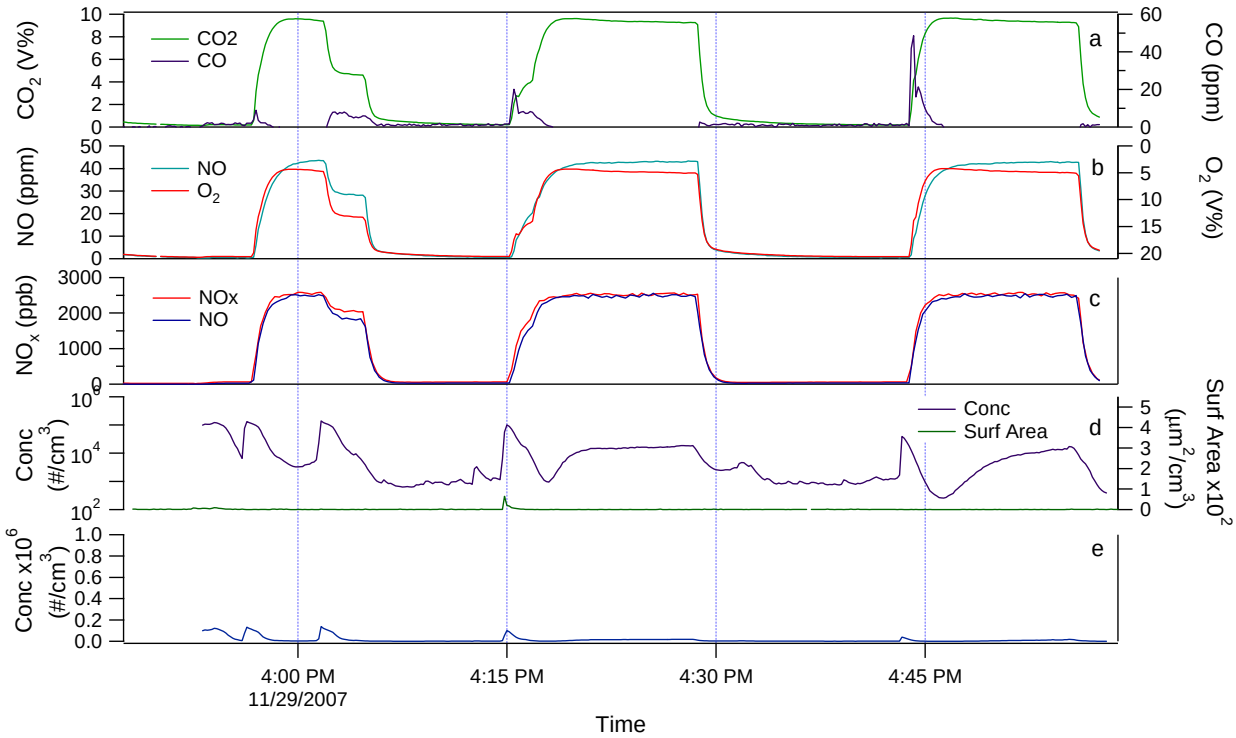

Figure 16. Measured analyte concentrations for storage water heater WH03 with fuel 3C (F023). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

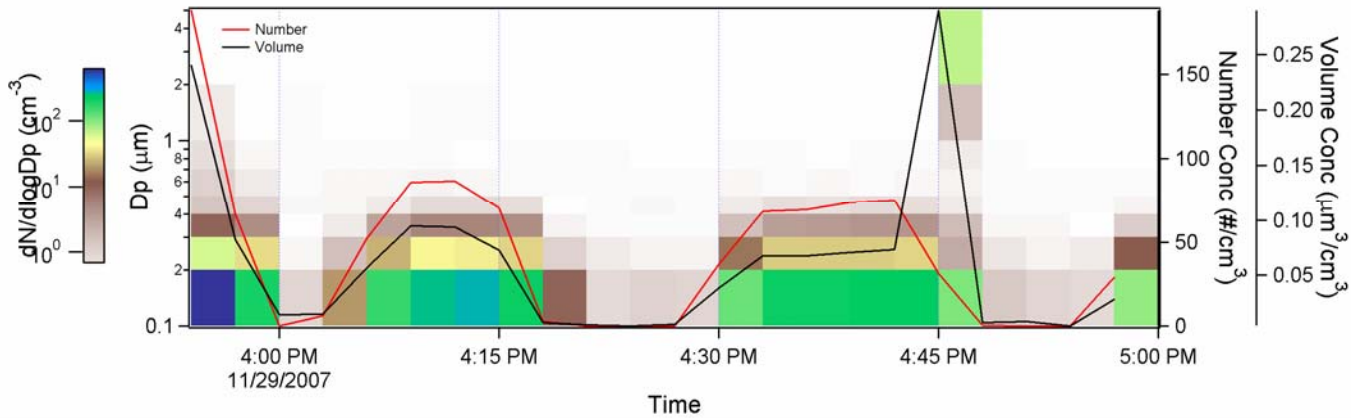

Figure 17. Size-resolved number concentrations of particles larger than 0.1 µm for experiment F023 (Lasair data).

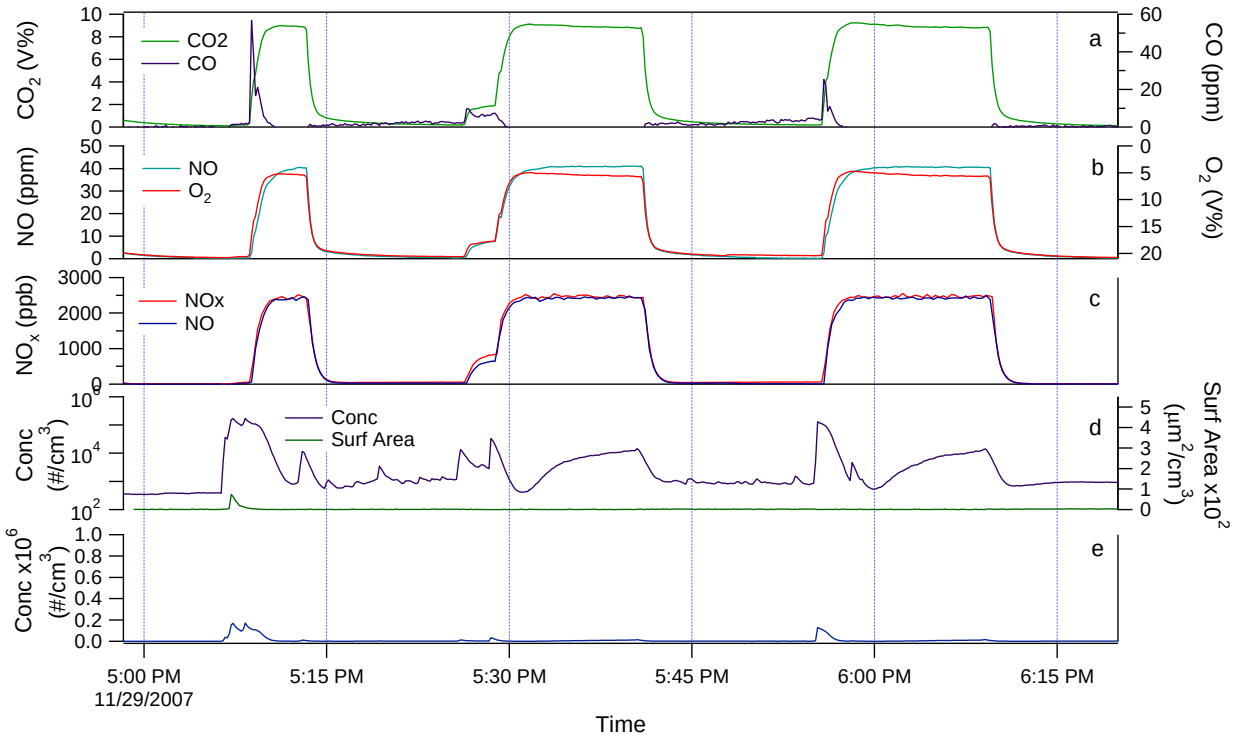

Figure 18. **Measured analyte concentrations for storage water heater WH03 with fuel 1C (F024).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

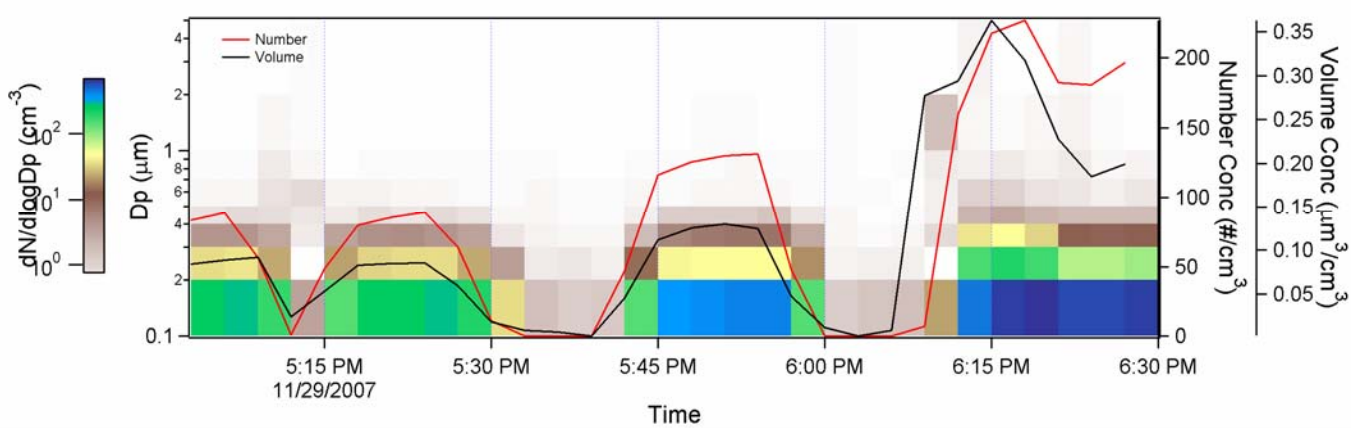

Figure 19. Size-resolved number concentrations of particles larger than 0.1 µm for experiment F024 (Lasair data).

Table 35. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, water heater WH03.

Exp	Fuel	Wobbe	CO (ppm)		NO_X (ppm)		NO (ppm)		NO_2 (ppm)		PN (10^5 cm^{-3})	
			B1	B2	B1	B2	B1	B2	B1	B2	B1	B2
F022	PG&E	1333	-5	-5	59	57	58	56	0.9	0.7	0	0.4
F023	3C	1390	-5	-4	56	56	56	55	0.7	1.0	3.2	1.8
F024	1C	1419	-5	-5	56	56	55	55	0.7	0.9	1.7	1.5

Table 36. Calculated emission rates over entirety of each burn, water heater WH03.

Exp	Fuel ID	Wobbe	CO ($\mu g\ KJ^{-1}$)		NO_X ($\mu g\ KJ^{-1}$)		NO ($\mu g\ KJ^{-1}$)		NO_2 ($\mu g\ KJ^{-1}$)		PN ($10^7\ KJ^{-1}$)	
			B1	B2	B1	B2	B1	B2	B1	B2	B1	B2
F022	PG&E	1333	-1	-1	24[1]	24	24[1]	23	0.2[1]	0.6	8.9	3.0
F023	3C	1390	0	0	25	24	24	23	0.9	0.7	8.2	3.1
F024	1C	1419	-1	-1	24	24	24	23	0.5	0.6	2.8	6.3

[1] Dilution NO_X data unavailable for first part of burn 1; emission rate calculated for period of data availability. See Figure 3..

4.0 Water Heater WH04

4.1. Experimental information for WH04

This water heater was purchased new and instrumented for energy efficiency testing under CEC contract 500-06-036. It was installed in one of the two test bays that are being used for LNG interchangeability experiments. It was operated for several weeks of energy efficiency testing prior to evaluation for fuel interchangeability. Several parameters that are normally monitored in the interchangeability study were already being monitored with the data system for energy efficiency testing; these data have not yet been incorporated into our data record. The heater on the aerosol dilution sampler inlet was set to automatic mode. The SMPS was used to collect size-resolved particle number concentrations for these experiments. During a single day, experiments were conducted using PG&E line gas (WN = 1319), fuel 1C (WN = 1390) and fuel 3C (WN = 1420). The latter two fuels were supplied from premixed cylinders used in field study sites.

Table 37. Appliance and burner information.

Burner ID	WH04
Burner category	Storage water heater
Technology	Induced draft, direct vent, FVIR, spark ignition (no pilot burner)
Appliance manufacturer	American
Model	PowerFlex Direct (Model PDVG6240T42NV)
Serial number	0731100252
Capacity	40 gal
Recovery rating	35.6 gal per h
Energy factor rating	0.62
Design manifold P	5 in. H_2O
Burner rating	42,000 Btu/h
Age	New (see history)
Test location	Laboratory
History notes	Purchased in 2007 for study of CEC-funded study on WH energy efficiency modifications; operated intermittently over several weeks before interchangeability experiments

FVIR = Flammable vapor ignition resistant.

Table 38. Interchangeability experiments for storage water heater WH04.

Exp.	Fuel	Date	Burner operation
L077	PG&E	02/25/2008	Each experiment included a purge burn[1] plus 2 sample burns of 15 min each, with 15-min cooling between burns. In all cases, burner operation was preceded by water draw to establish temperature differential with thermostat. Burner control set to “off” during water draw, set to “on” for defined burn period, then back to “off”. Water draws varied from 5-15 gal.
L078	1C	02/25/2008	
L079	3C	02/25/2008	

[1] The “purge” is used to flush the system and ensure that the first experimental burn uses the test fuel.

Table 39. Fuel analysis for interchangeability experiments with storage water heater WH04.

Expt. ID	Fuel ID	Sample ID	C_1 (%)	C_2 (%)	C_3 (%)	C_{4+} (%)	N_2 (%)	CO_2 (%)	HHV[1] (Btu/scf)	Wobbe number
L077	Line	B2	95.5	1.72	0.29	0.14	1.34	1.04	1007	1318
L078	1C	L078-1	92.0	8.04	-	-	-	-	1071	1390
L078	1C	L078-2	92.1	7.86	-	-	-	-	1070	1389
L079	3C	Cylinder	86.4	12.0	1.60	-	-	-	1125	1419

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

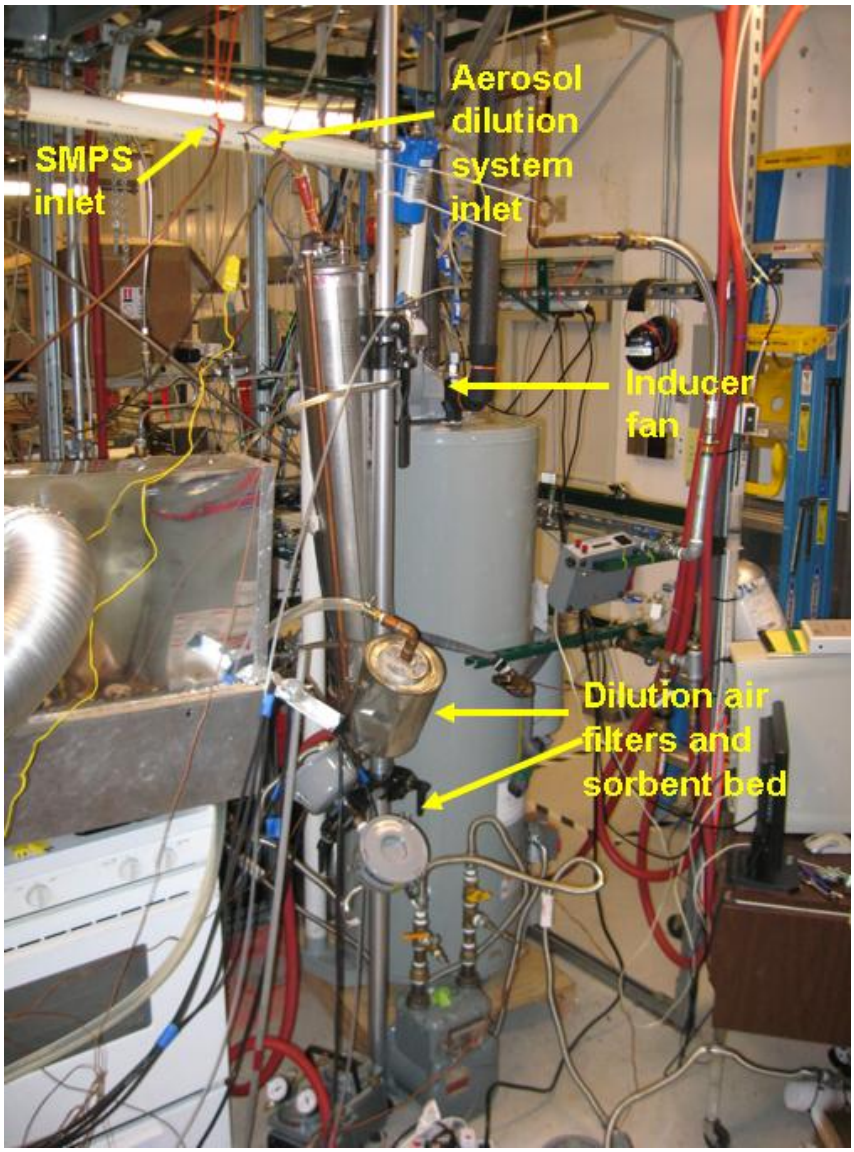

Figure 20. Experimental apparatus installed for storage water heater WH04.

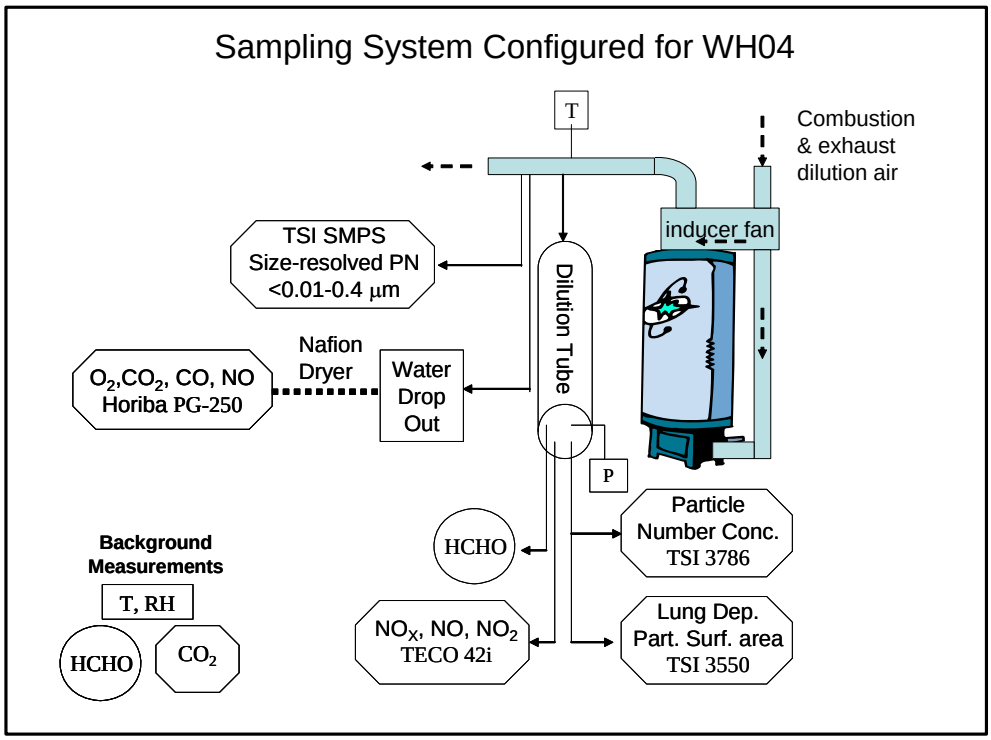

Figure 3. Pollutant sampling configuration for storage water heater WH04.

Table 40. Analyte ranges and calibration levels for experiments with storage water heater WH04.

Analyte	Sample location[1]	Equipment[2]	Range	Calibration levels
Carbon dioxide (CO_2)	As shown in Fig. 1	Horiba PG-250	0-5%	0, 3%
Oxygen (O_2)	As shown in Fig. 1	Horiba PG-250	0-25%	0, 20.95%
Carbon monoxide (CO)	As shown in Fig. 1	Horiba PG-250	0-200 ppm	0, 40 ppm
Nitrogen oxide (NO)	As shown in Fig. 1	Horiba PG-250	0-25 ppm	0, 10 ppm[3]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-25 ppm	0, 2.0 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] Calibrated from mixture of NO in N_2.

Table 41. Aerosol instrumentation used for storage water heater WH04.

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}
TSI SMPS[5]: 3071A classifier, 3025A ultrafine CPC	PN resolved by size (aerodynamic diameter)	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. 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 42. Other measurements for experiments with storage water heater WH04.

Measured Quantity	Location(s)	Device(s)[1]
Fuel pressure	Inlet to appliance regulator Outlet of appliance regulator	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, air	Air inlet underneath WH	Precision NTC thermistor (APT)
Relative humidity	Air inlet underneath WH	Thermostet polymer based capacitance RH sensor (APT)
Temperature, exhaust	At exhaust sampling location, 3” below top of WH central flue	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 WH04

CO emissions were extremely low and comprised only a small peak at ignition. Flue CO concentrations during warmed burner operation were indistinguishable from the noise level of

the instrument, and thus below detection limits. NO_X emissions were approximately 30 μg KJ^{-1} across all burns and experiments without a strong trend by fuel Wobbe number. The vast majority of NOX formed was in the form of NO. PN emissions very low relative to cooking appliance burners but higher than for the other new water heater tested (WH01). PN emissions were roughly consistent for all burns and indistinguishable between fuels. HCHO emissions were low relative to cooking appliance burners, but higher than WH01. Full burn emission rates were <3 ng/J for CO, 29-31 ng/J for NO_X, 5-14 x 10^4 J^{-1} for PN and 0.04-0.05 ng/J for HCHO.

Table 43. Burner operating parameters for experiments with storage water heater WH04.

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)
L077	B1	14:35	14:50	38	38	5.2	4.7
	B2	15:05	15:20	38	38	5.1	4.6
L078	B1	15:48	16:03	38	41	5.2	4.6
	B2	16:18	16:33	37	40	5.1	4.2
L079	B1	17:02	17:17	36	40	5.1	4.5
	B2	17:32	17:47	36	40	5	4.4

[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 44. Combustion air conditions[1] for experiments with water heater WH04.

Exp.	Fuel	T (°C)	RH (%)
L077	PG&E	20.6 ± 0.1	50 ± 1
L078	1C	20.8 ± 0.0	49 ± 1
L079	3C	20.6 ± 0.1	49 ± 1

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

Table 45. Sampling system conditions for experiments with water heater WH04.

Exp.	Sample Location T (°C)[1]		Dilution Ratio[2]	
	Burn 1	Burn 2	Burn 1	Burn 2
L077	81 ± 8	82 ± 8	16	16
L078	83 ± 9	84 ± 8	16	16
L079	84 ± 8	85 ± 8	16	16

[1] Mean ± standard deviation measured during each burn.
[2] Calculated by comparing NO measured in gas manifold (PG-250) and dilution sampler (Thermo 42i) for each burn.

Table 46. Formaldehyde samples for experiments with storage water heater WH04.

Exp(s)	Location	Date	Sample start/end time		Sample start/end time		Air vol. (L)	Extract conc. (ng/μL)	Air conc.[1] (μg/m^3)
L077	Dilution Tube	2/25/2008	14:35	14:50	15:05	15:20	27	0.024	1.75
L078			15:48	16:03	16:18	16:33	27	0.020	1.43
L079			17:01	17:17	17:31	17:51	33	0.020	1.23

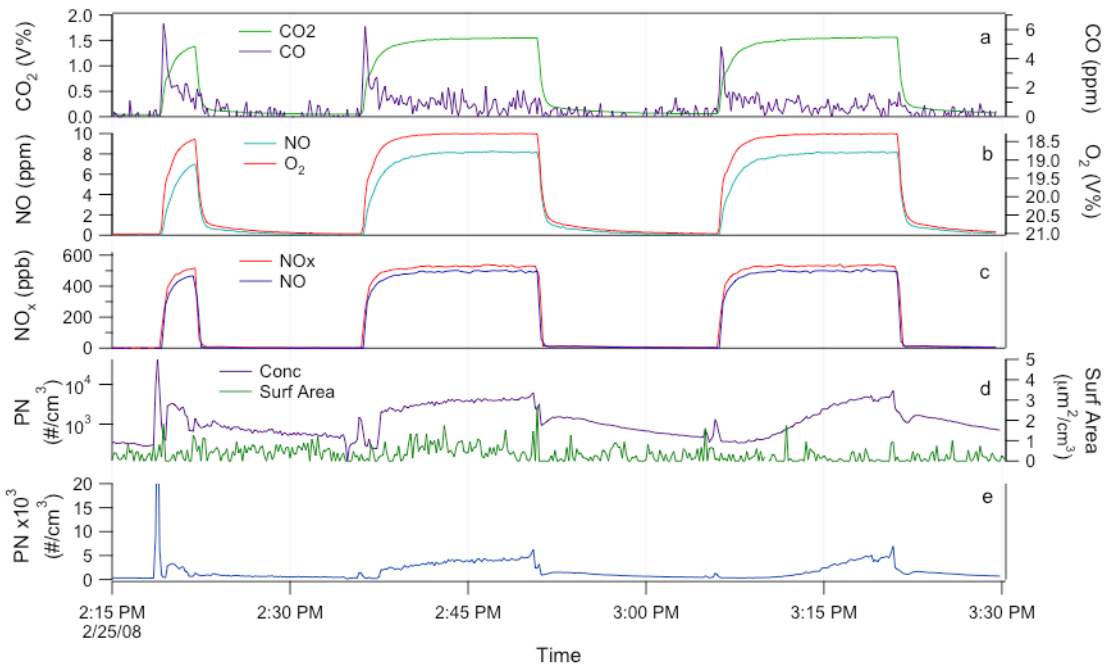

Figure 21. **Measured analyte concentrations for storage water heater WH04 with PG&E line gas (L077).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area. Peak prior to Burn 1 is the purge burn.

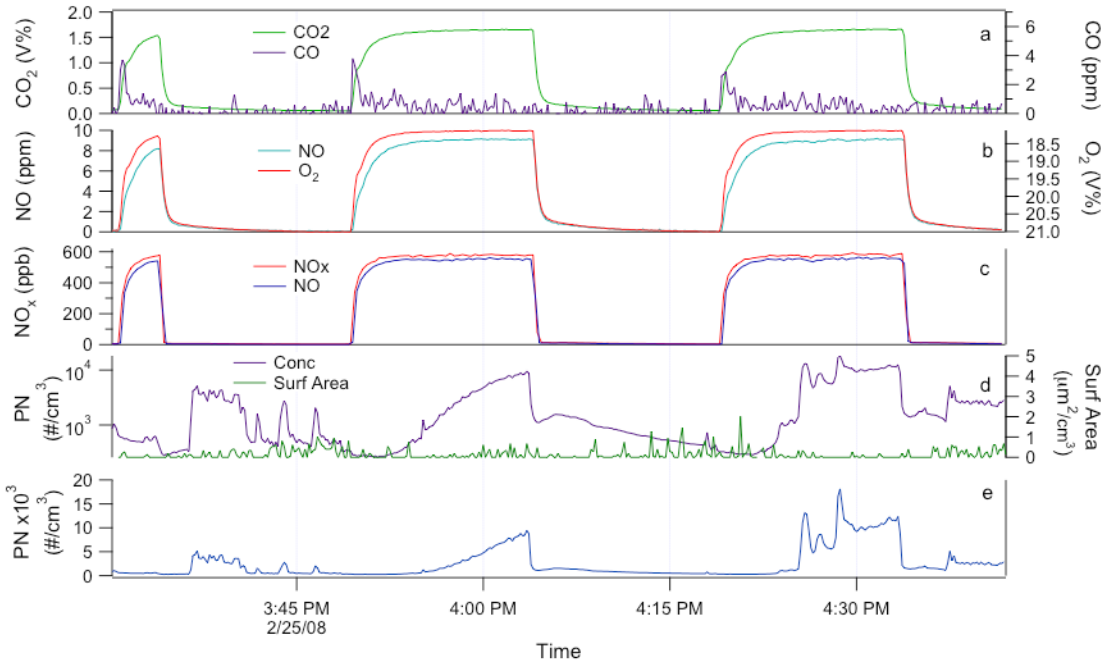

Figure 22. Measured analyte concentrations for storage water heater WH04 with fuel 1C (L078). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area. Peak prior to Burn 1 is the purge burn. PN instruments sampled from ambient air following Burn 2.

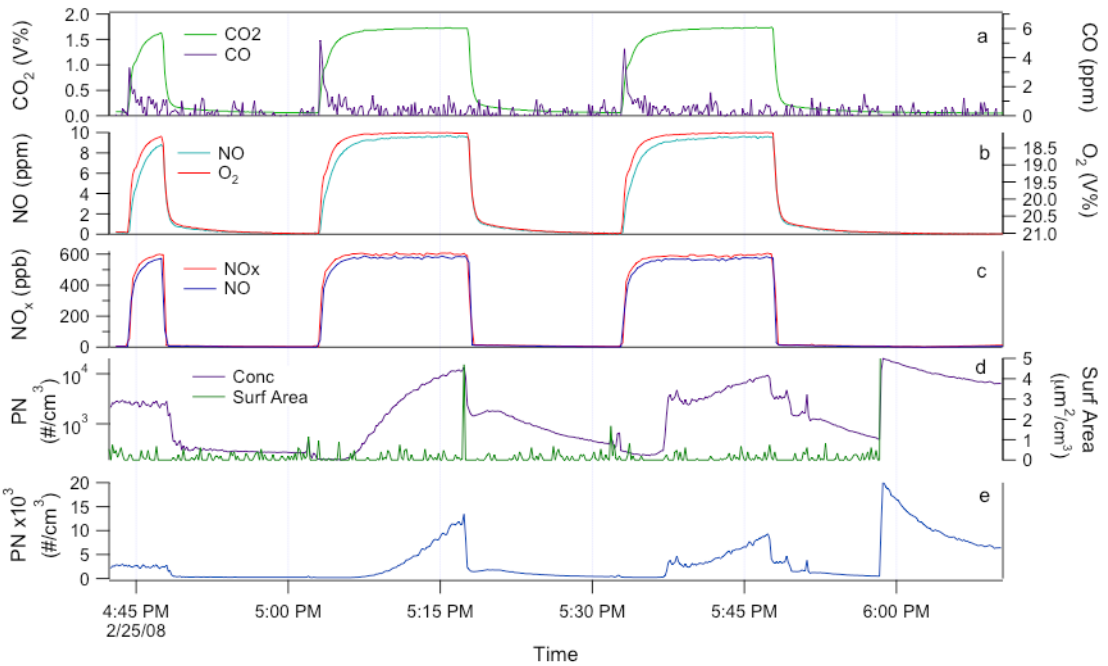

Figure 23. **Measured analyte concentrations for storage water heater WH04 with fuel 3C (L079).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area. Peak prior to Burn 1 is the purge burn. Particle instruments sampled from ambient air following Burn 2.

Table 47. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, water heater WH04.

Exp	Fuel	Wobbe	CO (ppm)		NO_X (ppm)		NO (ppm)		NO_2 (ppm)		PN (10^5 cm^{-3})	
			B1	B2	B1	B2	B1	B2	B1	B2	B1	B2
L077	PG&E	1319	7	2	68	68	64	64	3.7	4.3	5	4.8
L078	1C	1390	1	2	70	69	67	67	3	2.1	9	13
L079	3C	1419	0	1	71	70	69	68	1.9	2.4	13	9.1

Table 48. Calculated emission rates over entirety of each burn, water heater WH04.

Exp	Fuel ID	Wobbe	CO (µg KJ^{-1})		NO_X (µg KJ^{-1})		NO (µg KJ^{-1})		NO_2 (µg KJ^{-1})		PN (10^7 KJ^{-1})		HCHO (µg KJ^{-1})
			B1	B2	B1	B2	B1	B2	B1	B2	B1	B2	
L077	PG&E	1319	2	2	29	29	27	27	2.2	2.2	8.2	4.7	0.05
L078	1C	1390	1	1	31	30	29	29	1.6	1.4	6.2	14	0.04
L079	3C	1419	1	1	31	31	30	29	1.3	1.3	9.4	9.2	0.04

5.0 Water Heater WH05

5.1. Experimental information for WH05

This unit was selected as being representative of the many aging legacy water heaters that are still in service well past their projected lifetime. It is located alongside CF04, which was evaluated just prior to WH05. Experiments were conducted on a single day with (in order) PG&E line gas (WN = 1326), fuel 1C (WN = 1390), fuel 3C (WN = 1419), and a replicate with line gas. The aerosol inlet heater was set to track the temperature at the sampling point in the flue. Pollutants were sampled from the 4" flue approximately 1.5 feet downstream of the flue collar at the top of the water heater (i.e. following secondary dilution); this arrangement differs from that used for other water heater experiments.

Table 49. Appliance and burner information.

Burner ID	WH05
Burner category	Storage water heater
Technology	Conventional stamped sheet metal burner; pre-FVIR (open combustion chamber); natural draft w/pilot
Appliance manufacturer	American
Model	GV2F90-433T
Serial number	9124303149
Capacity	40 gal.
Recovery rating	Not available
Energy factor rating	Not available
Design manifold P	3.5 in. H_2O
Burner ratings (Btu/h)	34,000
Age	17 years at time of testing (installed 1991)
Test location	As installed in basement / crawl space of residence
History notes	Unit installed by current homeowner; used by family of 2 adults and 2 pre-teen / teenage children for approximately 10 y, then 2 adults.

FVIR = Flammable vapor ignition resistant.

Table 50. Interchangeability experiments for storage water heater WH05.

Exp.	Fuel	Date	Burner operation
F047	PG&E	3/20/08	Each experiment included a purge burn[1] plus 2 sample burns of 15 min each, with 15-min cooling between burns. In all cases, burner operation was preceded by water draw of 5-10 gal to create temperature differential with thermostat. Burner control set to "pilot" between burns, then to "on" for defined burn period.
F048	1C		
F049	3C		
F050	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 51. Fuel analysis for interchangeability experiments with storage water heater WH05.

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
F047	PG&E	F047	95.5	2.19	0.21	0.07	1.32	0.73	1011	1326
F048	1C	F048	91.9	8.10	0.00	0.00	0.00	0.00	1072	1390
F049	3C	F049	86.2	12.17	1.60	0.00	0.00	0.00	1127	1420
F050	PG&E	F050	95.6	1.73	0.30	0.15	0.98	1.23	1009	1320

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

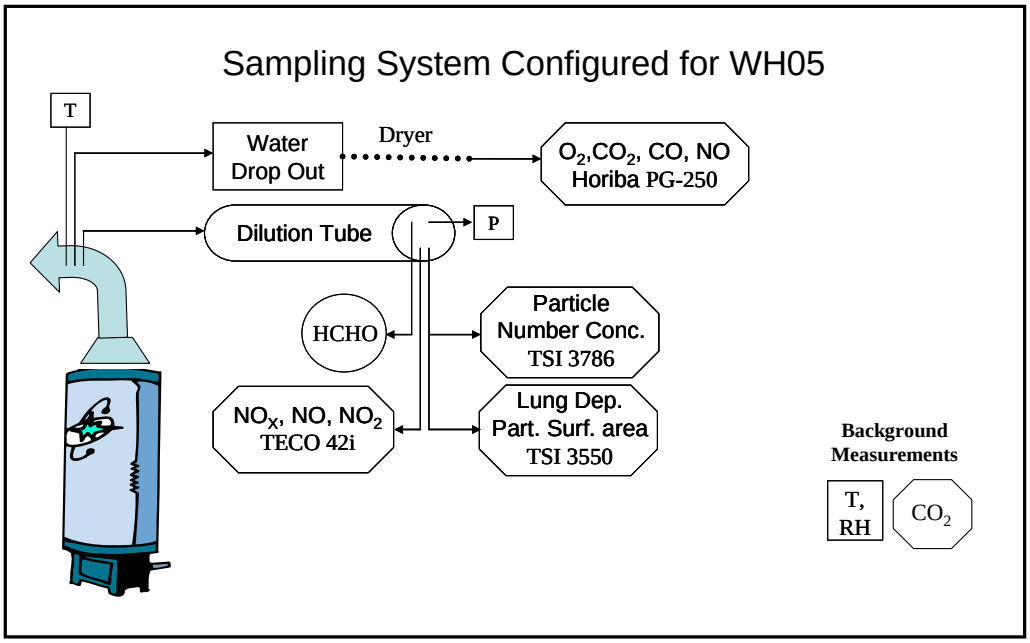

Figure 24. Pollutant sampling configuration for storage water heater WH05.

Figure 25. **Sample probes installed in flue for WH05.**
Probes enter flue in upper left quadrant of photograph. Probes include dilution sampler inlet (wrapped in orange heater and orange insulation), inlet for combustion gas analyzer (going to blue water trap, partially visible at top left of photo), thermocouple for lead temperature for inlet heater, and thermocouple to record flue temperature.

Table 52. Analyte ranges and calibration levels for experiments with storage water heater WH05.

Analyte	Sample location[1]	Equipment[2]	Range	Calibration levels
Carbon dioxide (CO_2)	3" below top of central flue	Horiba PG-250	0-10%	0, 10%
Oxygen (O_2)	3" below top of central flue	Horiba PG-250	0-25%	0, 20.95% check 8%[3]
Carbon monoxide (CO)	3" below top of central flue	Horiba PG-250	0-200 ppm	0, 40 ppm
Nitrogen oxide (NO_x)	3" below top of central flue	Horiba PG-250	0-50 ppm	0, 50 ppm[4] check 20 ppm[5]
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 7.9% for mixture with 8% O_2 following calibration at 20.95%. [4] Calibrated from mixture of NO in N_2. [5] Instrument read 21.9 ppm for mixture of 20 ppm NO in N_2.

Table 53. Aerosol instrumentation used for storage water heater WH05.

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 54. Other measurements for experiments with storage water heater WH05.

Measured Quantity	Location(s)	Device(s) [1]
Fuel pressure	Inlet to appliance regulator Outlet of appliance regulator	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, air	Air inlet underneath WH	Precision NTC thermistor (APT)
Relative humidity	Air inlet underneath WH	Thermostet polymer based capacitance RH sensor (APT)
Temperature, exhaust	At exhaust sampling location, 3” below top of WH central flue	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 WH05

Similar to the other storage water heaters evaluated in this study, emissions of both CO and formaldehyde were extremely low. Particle number emissions were concentrated at the beginning of each burn with very low concentrations observed during end of burn periods. NO_X end of burn concentrations and full-burn emissions did not vary with fuel and NO comprised the vast majority of NO_X in all experiments. CO and NO_2 (NO_X-NO) increased with fuel Wobbe number. Despite large relative changes, the absolute magnitude of the increase was small in both cases given the very low baseline emission rates for these pollutants from this burner. Full burn

emission rates were <1 to 6 ng/J for CO, 28-29 ng/J for NO_X, 1.5-2.5 ng/J for NO_2, 10-50 x 10^4 J^{-1} for PN and <0.1 ng/J for formaldehyde.

Table 55. Burner operating parameters for experiments with central furnace WH05.

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)
F047	B1	11:03	11:18	32	32	3.3	6.3
	B2	11:33	11:48	31	31	3.3	6.2
F048	B1	12:25	12:40	31	33	7.5	3.5
	B2	12:55	13:10	179	192	7.5	3.6
F049	B1	13:39	13:54	29	33	7.5	3.5
	B2	14:09	14:24	30	34	7.5	3.5
F050	B1	14:53	15:08	30	31	6.2	3.4
	B2	15:23	15:38	30	31	6.2	3.4

[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 56. Combustion air conditions[1] for experiments with central furnace WH05.

Exp.	Fuel	T (°C)	RH (%)
F047	PG&E	15.5 ± 0.2	50 ± 2
F048	1C	16.7 ± 0.3	50 ± 2
F049	3C	17.8 ± 0.2	52 ± 4
F050	PG&E	18.7 ± 0.3	50 ± 4

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

Table 57. Sampling system conditions for experiments central furnace WH05.

Exp.	Sample Location T (°C)[1]		Dilution Ratio[2]	
	Burn 1	Burn 2	Burn 1	Burn 2
F047	107 ± 2	107 ± 2	20	20
F048	107 ± 2	108 ± 2	21	21
F049	110 ± 2	107 ± 2	21	21
F050	108 ± 4	105 ± 2	22	22

[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 58. Formaldehyde samples for experiments with central furnace WH05.

Exp(s)	Location	Sample start/end time		Air vol. (L)	Extract conc. (ng/μL)	Air conc.[1] (μg/m^3)
ALL	Bkg air	10:53	15:39	284	0.179	1.26
F047	Dilution Tube	10:53	11:49	49	0.056	2.30
F048		12:25	13:11	41	0.044	2.13
F049		13:38	14:25	43	0.044	2.05
F050		14:53	15:39	44	0.044	2.02

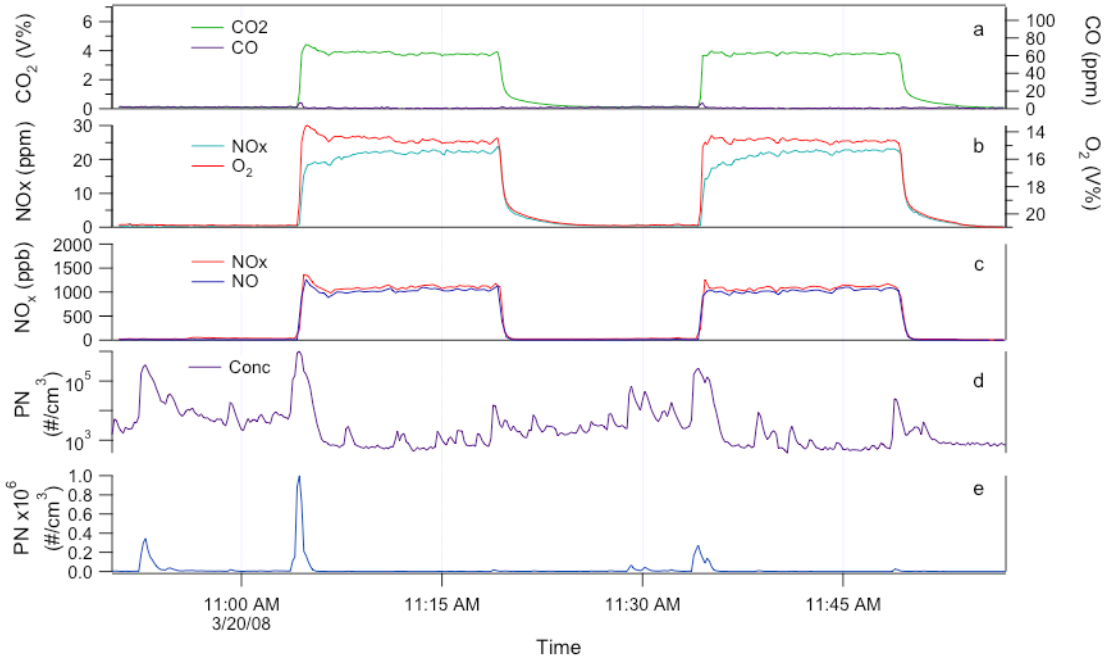

Figure 26. Measured analyte concentrations for storage water heater WH05 with PG&E line gas (F047). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents particle number concentration in a log scale.

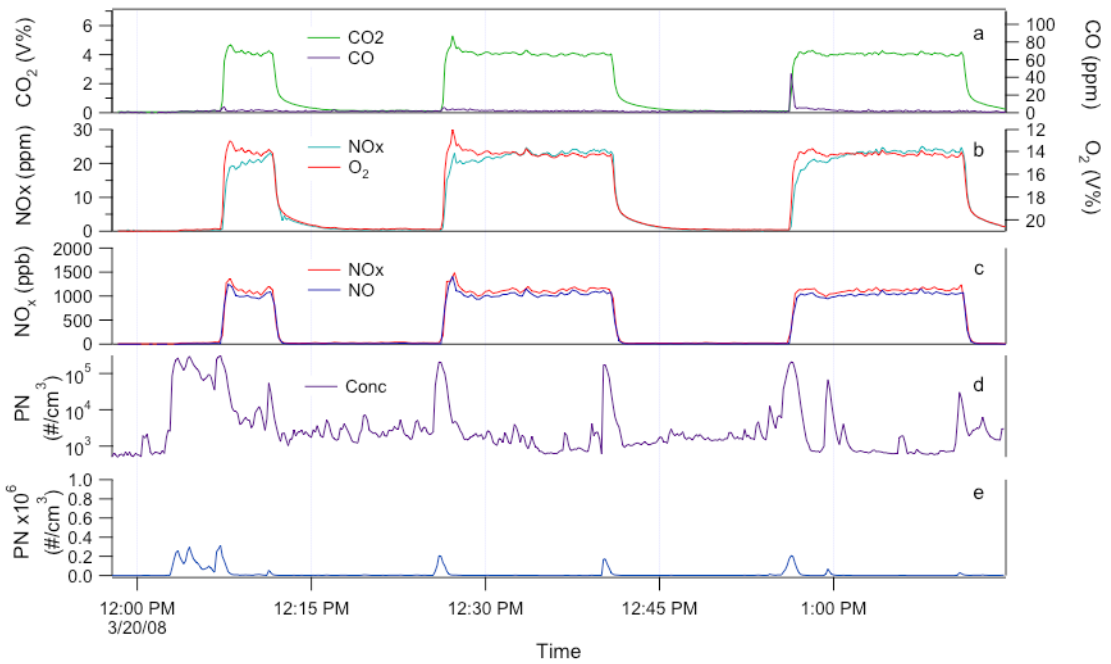

Figure 27. Measured analyte concentrations for storage water heater WH05 with fuel 1C (F048). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents particle number concentration in a log scale. The peak prior to Burn 1 is a purge burn.

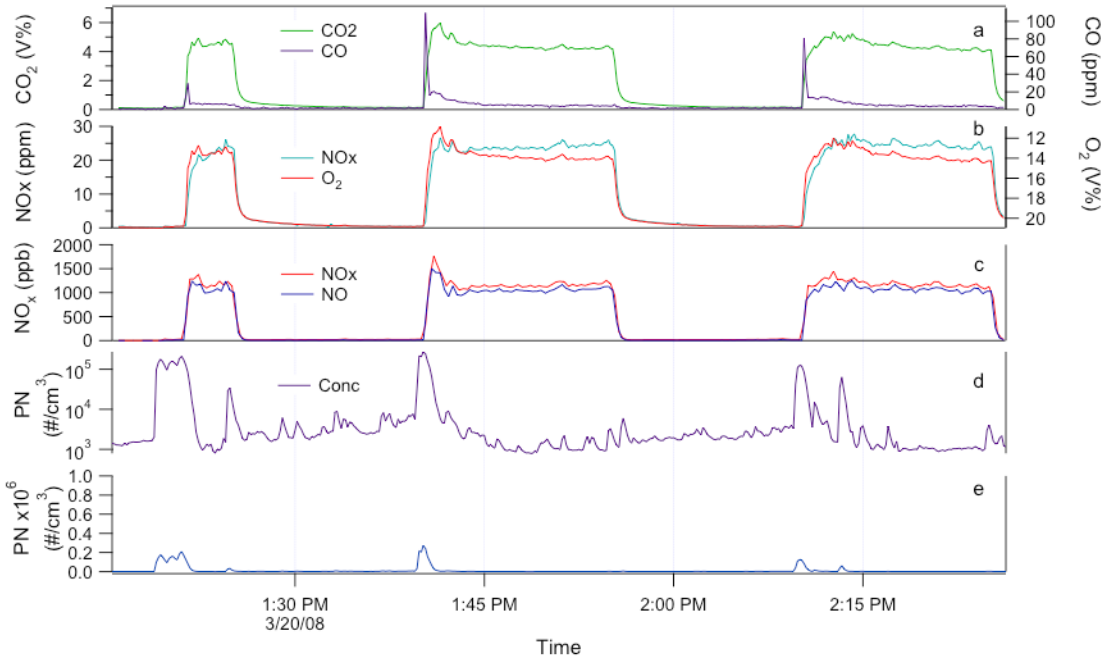

Figure 28. Measured analyte concentrations for storage water heater WH05 with fuel 3C (F049). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents particle number concentration in a log scale. The peak prior to Burn 1 is a purge burn.

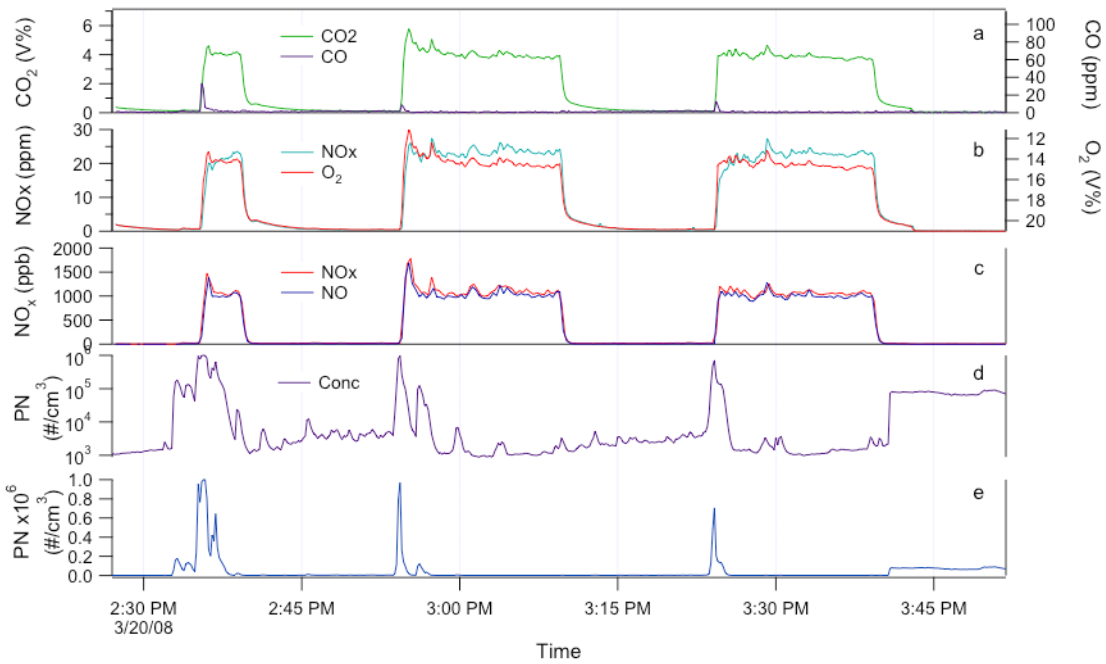

Figure 29. **Measured analyte concentrations for storage water heater WH05 with PG&E line gas (F050).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents particle number concentration in a log scale. The peak prior to Burn 1 is a purge burn.

Table 59. A. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, WH05.

Exp	Fuel	Wobbe	CO (ppm)		PG250 NO_X (ppm)		PN (10^5 cm^{-3})	
			B1	B2	B1	B2	B1	B2
F047	PG&E	1326	0	0	71	71	0.1	-0.1
F048	1C	1390	5	4	70	70	0.2	0
F049	3C	1420	11	10	70	70	0.3	0.2
F050	PG&E	1320	1	0	73	72	0.3	0.4

Table 60. B. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, WH05.

Exp	Fuel	Wobbe	NO (ppm)		NO_X (ppm)		NO_2 (ppm)	
			B1	B2	B1	B2	B1	B2
F047	PG&E	1326	71	71	67	67	3.7	3.5
F048	1C	1390	70	70	65	66	4.6	4.6
F049	3C	1420	70	70	64	65	5.8	5.6
F050	*PG&E*	1320	73	72	69	68	4.0	3.9

Table 61. A. Calculated emission rates over entirety of each burn for storage water heater WH05.

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	
F047	PG&E	1326	0	0	28	29	51	22	0.06
F048	1C	1390	2	2	29	29	22	18	0.05
F049	3C	1420	6	5	28	29	20	11	0.04
F050	PG&E	1320	0	1	29	29	43	33	0.04

Table 62. B. Calculated emission rates over entirety of each burn for storage water heater WH05.

Exp	Fuel	Wobbe	NO ($\mu g\ KJ^{-1}$)		NO_X ($\mu g\ KJ^{-1}$)		NO_2 ($\mu g\ KJ^{-1}$)	
			B1	B2	B1	B2	B1	B2
F047	PG&E	1326	28	29	27	27	1.8	1.6
F048	1C	1390	29	29	27	27	2.0	2.1
F049	3C	1420	28	29	26	26	2.5	2.6
F050	PG&E	1320	29	29	27	28	1.8	1.5