Arnold Schwarzenegger
Governor

NATURAL GAS VARIABILITY IN CALIFORNIA: ENVIRONMENTAL IMPACTS AND DEVICE PERFORMANCE

EXPERIMENTAL EVALUATION OF POLLUTANT EMISSIONS FROM RESIDENTIAL APPLIANCES

APPENDIX J. SUMMARY REPORTS FOR TANKLESS 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 Tankless Water Heater TW01

1.1. Experimental information for TW01

This tankless water heater was purchased by LBNL in 2001 and used for approximately 6-months in a re-locatable classroom while building energy use was being monitored for a study of energy efficiency potential. The unit was stored until installation in the laboratory for baseline emission measurements in July 2007. It was stored again until it was re-installed and evaluated for fuel interchangeability in the experiments described here. The water delivery temperature was not changed from the factory setting. A sheet metal adapter and 2-foot long section of 6” duct were mounted over the exhaust port to provide a well-mixed exhaust stream in which a single sampling point could be used for varying levels of burner firing. Experiments were conducted on a single day with PG&E line gas (WN = 1320), fuel mix 1C (WN = 1390), fuel 3C (WN = 1419), then a replicate experiment with PG&E line gas. Each experiment included three burns with water flow rates of 1, 2, and 4 gallons per minute. The aerosol inlet heater was set to automatically follow the measured temperature in the flue. The gas volume and flow electronic counter malfunctioned during this experiment; gas flow data were measured at one point during each water draw using a stop watch and the gas meter dial.

Table 1. Appliance and burner information.

Burner ID	TW01
Burner category	Tankless water heater
Technology	Induced draft, ribbon burner, direct vent (external mount)
Appliance manufacturer	Rinnai
Model	Continuum 2424 (REU2424W-US)
Serial number	01. 04-140043
Manifold P	5.3 in. H_20
Recovery rating	174 gallons per hour
Capacity	0.6-6.5 gallons per hour at 50 F temperature rise
Burner rating	19-180 kBtu/h
Age	Purchased in 2001
Test location	On-site at residence
Notes	Used for approximately 6 months in study of re-locatable classroom energy use.

Table 2. Interchangeability experiments for tankless water heater TW01.

Exp.	Fuel	Date	Burner operation
L082	PG&E	4/1/2008	Each experiment included water draws at 1, 2 and 4 gallons per minute. Each water draw was 8 min and followed a 10 min period of non-operation to cool burner. Purge burn with each fuel change.[1]
L083	1C	4/1/2008	
L084	3C	4/1/2008	
L085	PG&E	4/1/2008	

[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 tankless water heater TW01.

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
L082	PG&E	L082	95.2	2.23	0.18	0.07	1.51	0.81	1008	1320
L083	1C	Cylinder	92.0%	8.00%	-	-	-	-	1071	1390
L084	3C	Cylinder	86.4%	12.0%	1.60%	-	-	-	1125	1419
L085	PG&E	L082	95.2	2.23	0.18	0.07	1.51	0.81	1008	1320

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

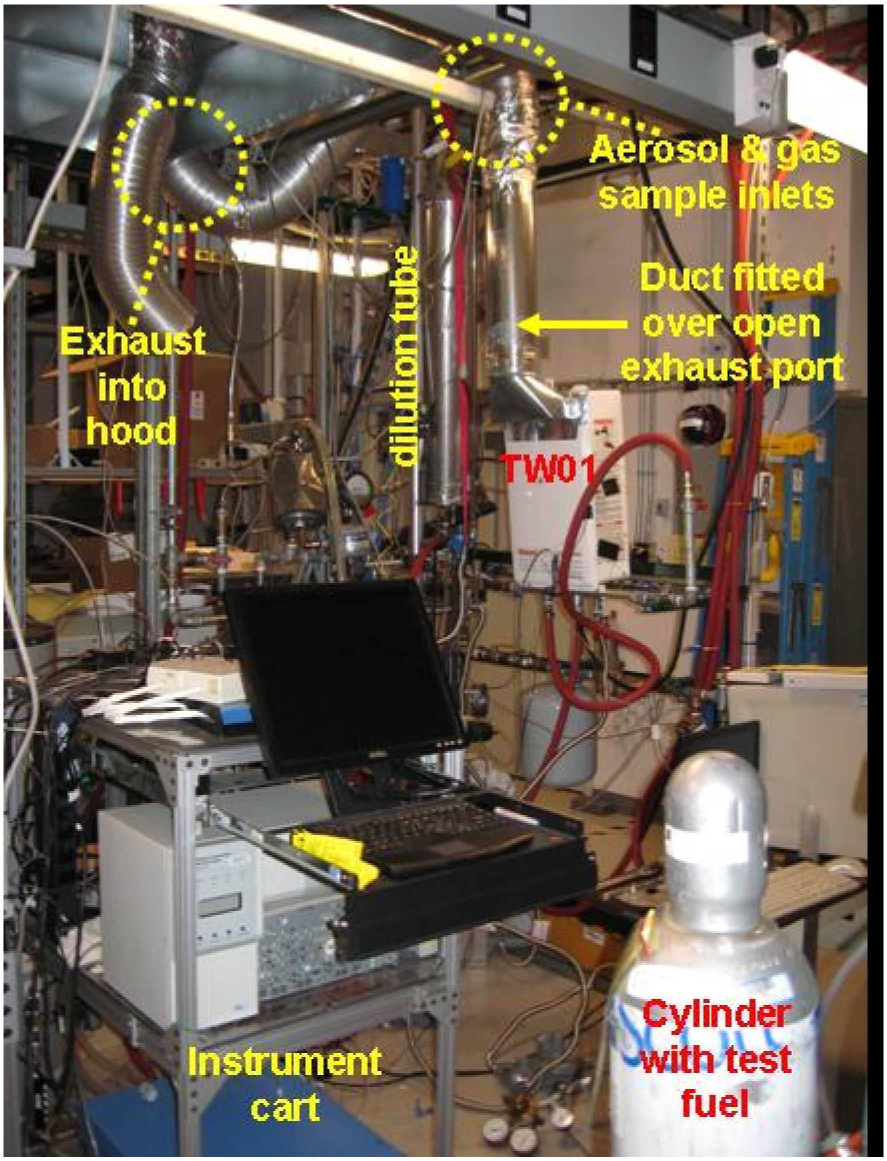

Figure 1. Experimental apparatus installed for tankless water heater TW01.

Flue installed for purpose of achieving well-mixed exhaust sample. Exhaust concentrations vary horizontally across exhaust outlet of appliance owing to orientation and proximity of burners to exhaust port.

Figure 2. Back view of TW01 showing placement of duct connections and sample inlets.

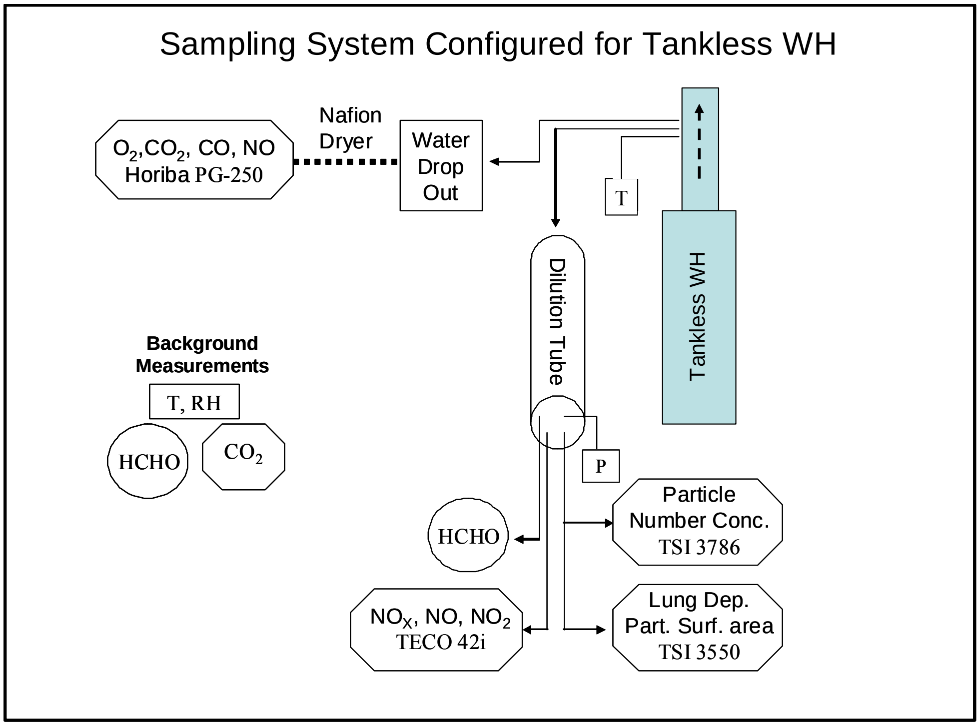

Figure 3. Pollutant sampling configuration for tankless water heater TW01.

Table 4. Analyte ranges and calibration levels for experiments with tankless water heater TW01.

Analyte	Sample location[1]	Equipment[2]	Range	Calibration levels
Carbon dioxide (CO_2)	3" below top of attached flue	Horiba PG-250	0-5%	0, 10%
Oxygen (O_2)	3" below top of attached flue	Horiba PG-250	0-25%	0, 20.95%
Carbon monoxide (CO)	3" below top of attached flue	Horiba PG-250	0-200 ppm	0, 350 ppm
Nitrogen oxides (NO_X)	3" below top of attached flue	Horiba PG-250	0-25 ppm	0, 50 ppm[3]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-25 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, 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. Aerosol instrumentation used for tankless water heater TW01.

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 6. Other measurements for experiments with tankless water heater TW01.

Measured Quantity	Location(s)	Device(s)[1]
Fuel pressure	Inlet to 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	Near air inlet	Precision NTC thermistor (APT)
Relative humidity	Near air inlet	Thermostet polymer based capacitance RH sensor (APT)
Temperature, exhaust	At exhaust sampling location	Thermocouple (K), probe, Omega KQSS-18E-12

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

1.2. Results for TW01

Full burn emission rates were approximately 20-90 ng/J for CO, 23-28 ng/J for NO_X, 0.9-1.7 ng/J for HCHO, and 0.1-7 x 10^4 J^{-1} for PN. Replicate experiments with line gas produced similar results for CO, NO_X and formaldehyde; however particle number (PN) concentrations and emissions were much substantially higher during the first experiment. In each experiment the highest CO occurred during the second burn with water flow at 2 gpm. Air-free concentrations and full-burn emissions for CO and full-cycle emissions of formaldehyde were 1-2 orders of magnitude higher than observed for storage water heaters. NO2 accounted for approximately 35% of total NO_X across all experiments. CO emissions decreased by about 20% and formaldehyde decreased by about 45% when switching from line gas to fuel 3C (WN = 1419). At 2 and 4 gpm, NO_X emissions increased slightly with increasing fuel WN, on the order of 10% when going from line gas to fuel 3C.

Table 7. Burner operating parameters for experiments with tankless water heater TW01.

Exp.	Burn	Start time	End time	Fuel flow[1] (ft^3 h^{-1})	Firing rate[1] (kbtu/h)	Firing rate[3] (kbtu/h)	Supply pressure (in. H_2O)	Appliance manifold P (in. H_2O)
L082	1 gpm	12:13	12:20	30	30	31	7.5	NA
	2 gpm	12:31	12:38	64	65	65	6.9	NA
	4 gpm	12:48	12:56	82	82	NA[2]	6.4	NA
L083	1 gpm	13:26	13:33	30	32	NA[2]	7.8	NA
	2 gpm	13:43	13:51	60	64	NA[2]	7.5	NA
	4 gpm	14:01	14:09	75	80	NA[2]	7.3	NA
L084	1 gpm	14:29	14:37	28	32	NA[2]	7.8	NA
	2 gpm	14:47	14:55	60	68	75	7.6	NA
	4 gpm	15:05	15:13	75	84	107	7.3	NA
L085	1 gpm	15:37	15:45	29	29	NA[2]	7.5	NA
	2 gpm	15:55	16:03	64	65	NA[2]	6.9	NA
	4 gpm	16:13	16:21	90	91	NA[2]	6.2	NA

[1] Fuel flow rate as determined by stopwatch timing of fuel gas meter dial; firing rate calculated from calculated fuel flow rate and higher heating value from fuel composition.
[2] Pulse counter on gas meter malfunctioned. Data from stopwatch timing of gas flow data not yet analyzed.
[3] Firing rate calculated from fuel use measured for each burn (by pulse counter) divided by time of burn.

Table 8. Combustion air conditions[1] for experiments with tankless water heater TW01.

Exp.	Fuel	T (°C)	RH (%)
L082	PG&E	20.7 ± 0.2	42 ± 1
L083	1C	21.2 ± 0.2	41 ± 1
L084	3C	21.0 ± 0.2	42 ± 1
L085	PG&E	21.5 ± 0.4	41 ± 1

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

Table 9. Sampling system conditions for experiments tankless water heater TW01.

Exp.	Sample Location T (°C)[1]			Dilution Ratio[2]		
	1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm
L082	63 ± 2	94 ± 1	103 ± 2	19	19	21
L083	62 ± 1	92 ± 1	102 ± 2	18	19	21
L084	63 ± 1	91 ± 1	101 ± 2	19	19	22
L085	64 ± 1	95 ± 1	112 ± 2	19	20	21

[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 10. Formaldehyde samples for experiments with tankless water heater TW01.

Exp(s)	Location	Sample start/end time		Air vol. (L)	Extract conc. (ng/μL)	Air conc.[1] (μg/m³)
ALL	Bkg air	12:10	16:22	295	2.080	14.1
L082	Dilution Tube	12:10	12:57	50	1.186	47.6
L083		13:14	14:10	60	0.905	29.9
L084		14:28	15:14	50	0.723	28.7
L085		15:35	16:22	51	1.188	47.0

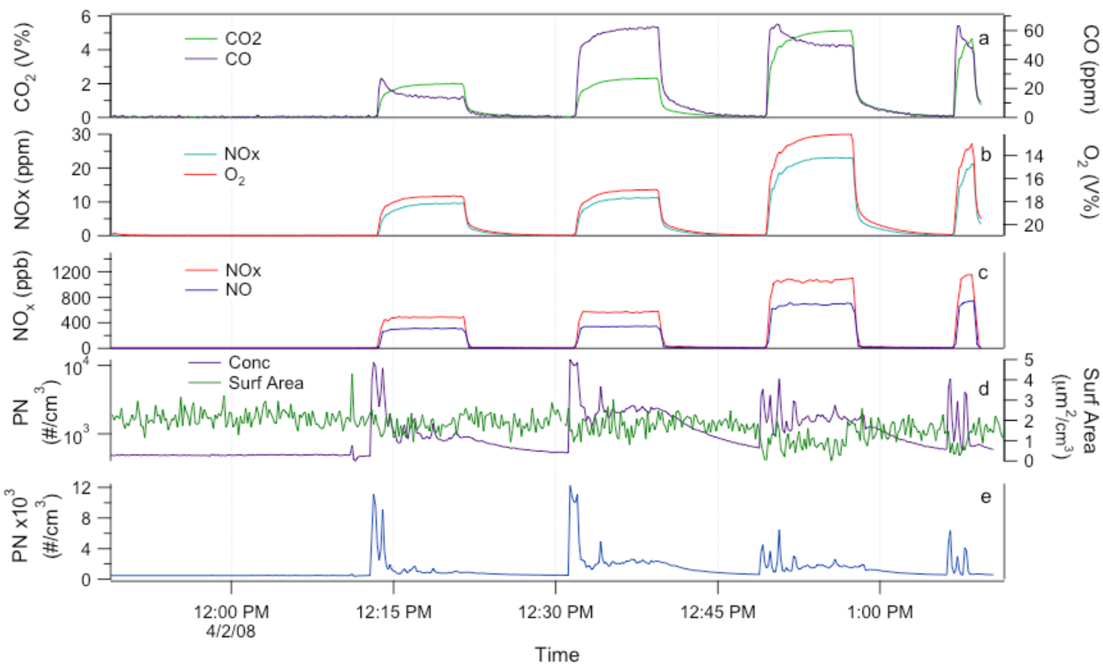

Figure 3. Measured analyte concentrations for tankless water heater TW01 with PG&E line gas (L082). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area. Last peak is a purge burn.

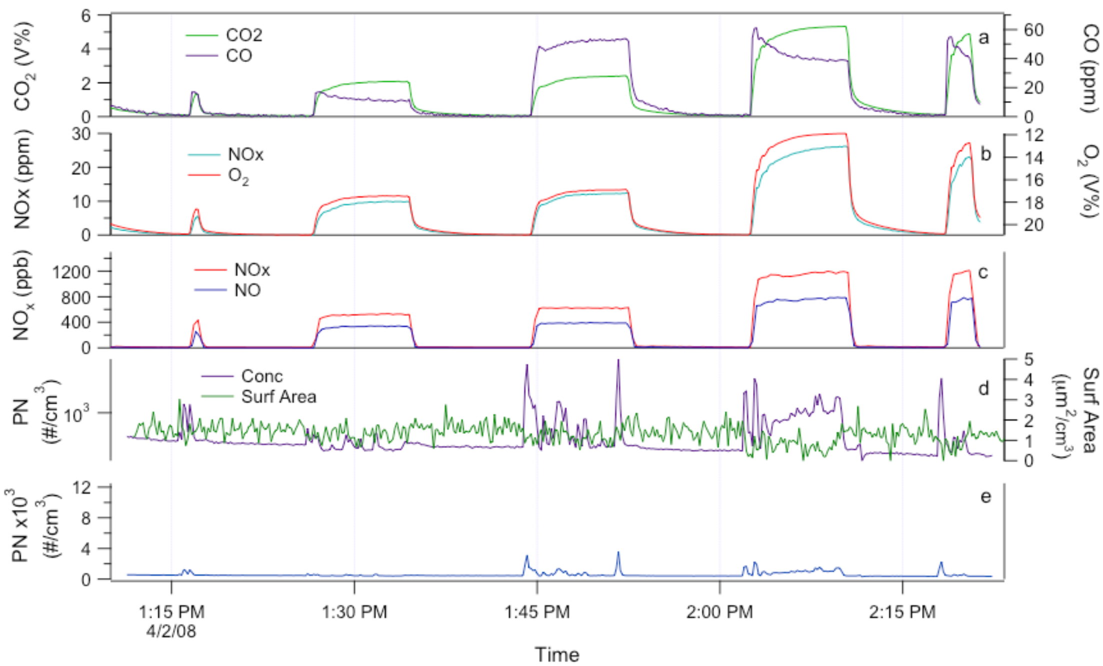

Figure 4. Measured analyte concentrations for tankless water heater TW01 with fuel 1C (L083). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area. First, last peaks are purge burns.

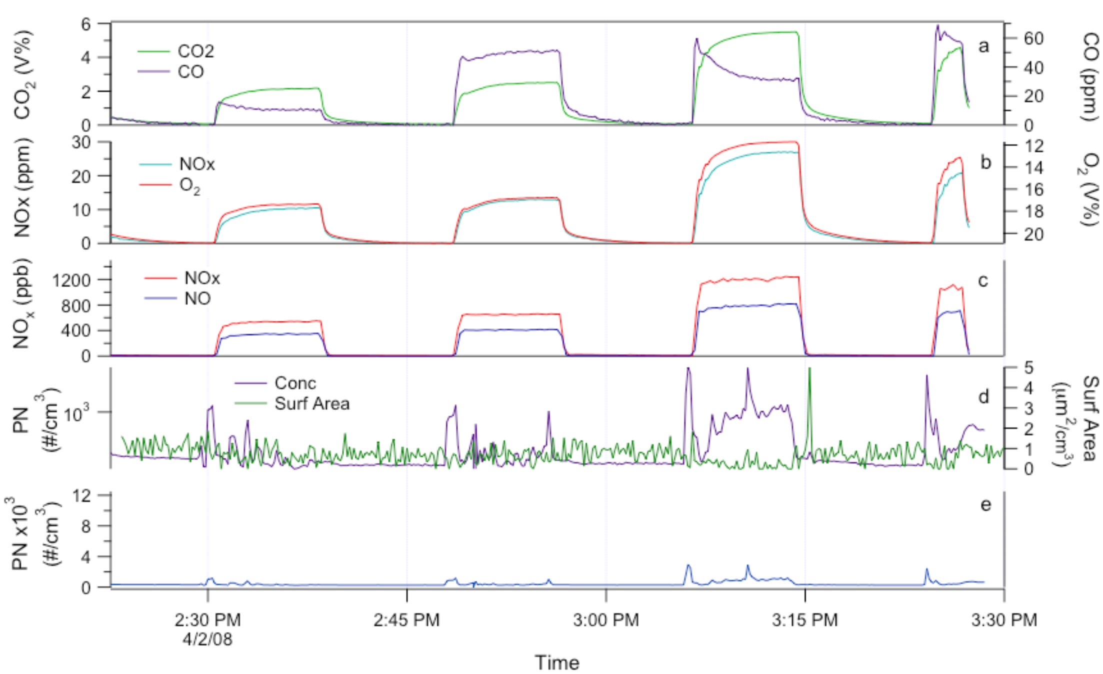

Figure 5. Measured analyte concentrations for tankless water heater TW01 with fuel 3C (L084). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area. Last peak is a purge burn.

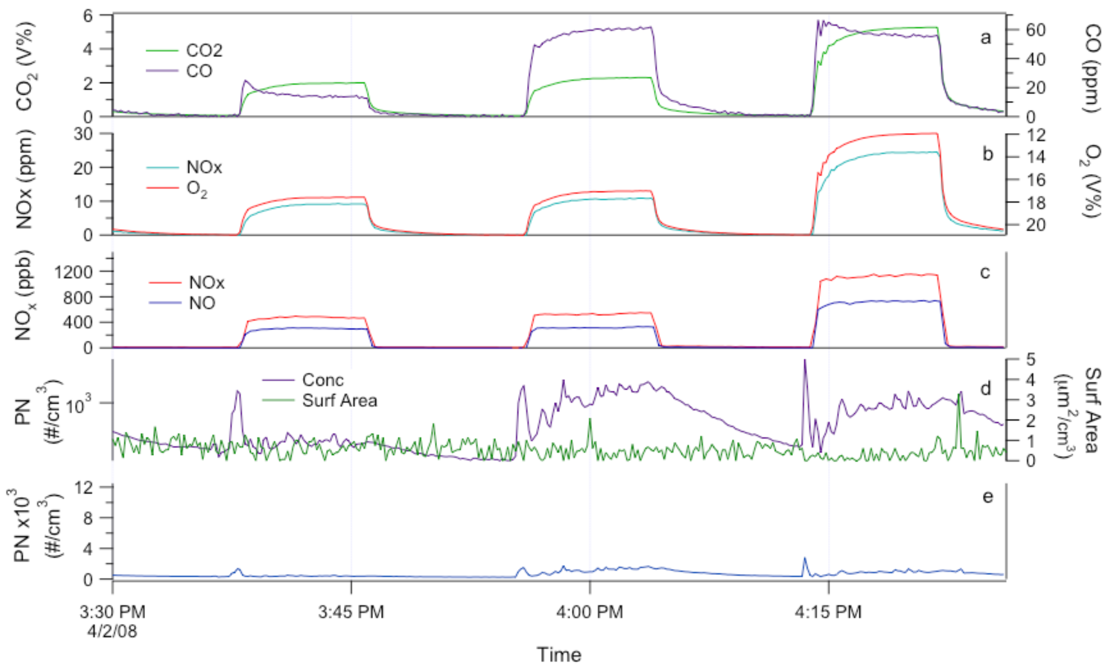

Figure 6. Measured analyte concentrations for tankless water heater TW01 with PG&E line gas (L085). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

Table 11. A. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, tankless water heater TW01.

Exp	Fuel	Wobbe	CO (ppm)			PG250 NO_X (ppm)			PN (10^5 cm^{-3})		
			1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm
L082	PG&E	1320	89	328	122	58	59	54	0.5	1.8	0.6
L083	1C	1390	68	270	93	58	62	58	0	0.2	0.3
L084	3C	1419	62	252	75	58	64	59	0.1	0.1	0.4
L085	PG&E	1320	90	322	132	56	57	55	0.2	1	0.3

Table 12. B. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, tankless water heater TW01.

Exp	Fuel	Wobbe	NO_X (ppm)			NO (ppm)			NO_2 (ppm)		
			1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm
L082	PG&E	1320	58	59	54	37	36	35	21	23	19
L083	1C	1390	58	62	58	38	39	38	20	23	20
L084	3C	1419	58	64	59	38	40	39	21	23	20
L085	PG&E	1320	56	57	55	36	34	36	20	23	20

Table 13. A. Calculated emission rates over entirety of each burn, tankless water heater TW01.

Exp	Fuel	CO (μg KJ^{-1})			PG250 NO_X (μg KJ^{-1})			PN (10^7 KJ^{-1})			HCHO (μg KJ^{-1})
		1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm	
L082	PG&E	28	88	35	25	25	23	3.8	6.5	1.7	1.71
L083	1C	21	75	29	25	27	25	0.1	0.9	0.7	1.21
L084	3C	19	70	24	25	28	25	0.3	0.3	0.8	0.94
L085	PG&E	27	86	37	24	24	24	0.5	2.2	0.8	1.65

Table 14. B. Calculated emission rates over entirety of each burn, tankless water heater TW01.

Exp	Fuel	Wobbe	NO_X (μg KJ^{-1})			NO (μg KJ^{-1})			NO_2 (μg KJ^{-1})		
			1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm
L082	PG&E	1320	25	25	23	15.7	15.4	14.8	8.9	10.0	8.1
L083	1C	1390	25	27	25	16.3	17.1	16.4	8.8	10.3	8.7
L084	3C	1419	25	28	26	16.2	17.6	16.8	9.1	10.3	8.9
L085	PG&E	1320	24	24	24	15.3	14.7	15.3	8.5	9.7	8.3

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2.0 Tankless Water Heater TW02

2.1. Experimental information for TW02

This was the first tankless water heater tested with simulated LNG blends to evaluate interchangeability at a residence. The unit is mounted externally with a ducted flue. Experiments were conducted on the same day with PG&E line gas (WN = 1330), fuel mix 1C (WN = 1389) and fuel 3C (WN = 1416). The aerosol inlet heater was set to automatically follow the measured temperature in the flue. Each experiment included four burns, including burns at 1, 2, 2, and 4 gallons per minute (gpm). During the first 2 gpm burn of F030 (fuel 3C), the NO_X concentration in the direct exhaust went above the range setting for the PG250 analyzer. The range was reset during the experiment. For this burn, NO_X air-free concentrations and emission rates are calculated using the NO_X measurements from the dilution system and the dilution ratio that was measured during the preceding burn at 1 gpm.

Table 15. Appliance and burner information.

Burner ID	TW02
Burner category	Tankless water heater
Technology	Induced draft, ribbon burner; direct vent (external mount); certified to meet 40 ng/J standard (SCAQMD 1146.2)
Appliance manufacturer	Takagi
Model	Flash TK-2
Serial number	15000335
Efficiency	85% [1]
Energy Factor	0.83 [1]
Capacity	0.75 – 6.9 gallons per hour at 50 F temperature rise [1]
DOE gph	228 gallons per hour [1]
Burner rating	20-185 kBtu/h
Age	6 years; installed 2002
Test location	On-side at residence
Notes	Temperature controlled by RE-02 remote; set to 122 F. Unit installed by current homeowner. Used by 2 adults

[1] From manufacturer literature.

Table 16. Interchangeability experiments for tankless water heater TW02.

Exp.	Fuel	Date	Burner operation
F028	PG&E	3/3/08	Initiate burner operation by using hot water at laundry sink; set flow rates using digital display of remote temperature controller. Each experiment included water draws at 1, 2, 2, and 4 gallons per minute. Each water draw was 8 min and followed a 10 min period of non-operation to cool burner. Fuel purge for F029 was done by venting gas just before appliance. Purge for F030 was accomplished using burner.
F029	1C	3/3/08	
F030	3C	3/3/08	

[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 17. Fuel analysis for interchangeability experiments with tankless water heater TW02.

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
F028	Line	F028	96.1	1.92	0.20	0.02	0.94	0.78	1011	1330
F029	1C	1C[2]	92.0	8.00	-	-	-	-	1071	1390
F030	3C	3C[2]	86.4	12.0	1.6	-	-	-	1125	1419

[1] Calculated using the American Gas Association interchangeability program.
[2] Cylinder certified concentrations, verified through sampling.

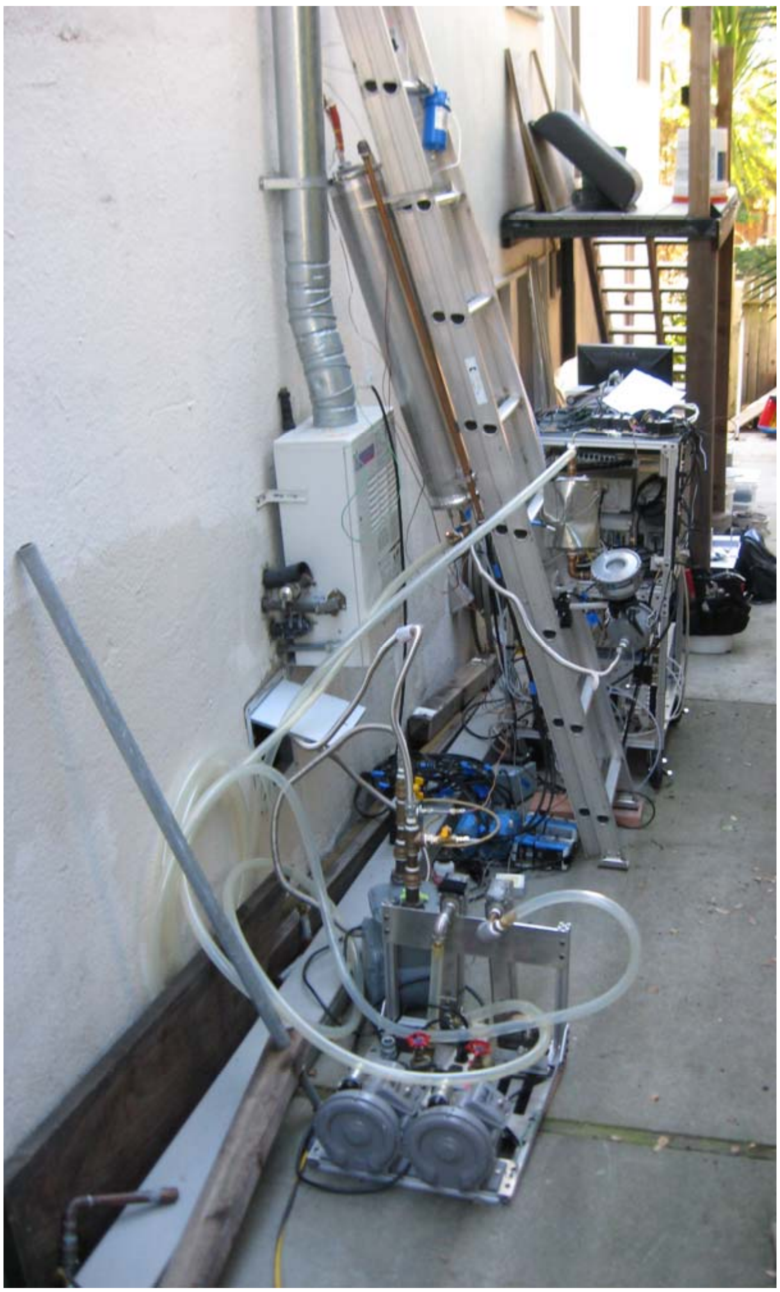

Figure 7. Experimental apparatus installed for tankless water heater TW02.
Visible equipment includes the following: blowers for aerosol dilution system (bottom of picture), gas meter (behind blower unit), peristaltic pumps for aldehyde sampling (behind gas meter), aerosol dilution sampler mounted on underside of ladder, dilution system air supply filter and sorbent assembly (mounted between 3rd and 4th rung of ladder), instrumentation cart (behind ladder).

Figure 8. Sampling lines installed for tankless water heater TW02.
From top: gas sampling line (to water trap and nafion tubing), thermocouple for flue gas temperature (T), aerosol dilution sampler inlet and thermocouple probe for inlet heater (heater matches T measured at inlet to dilution tube with flue T).

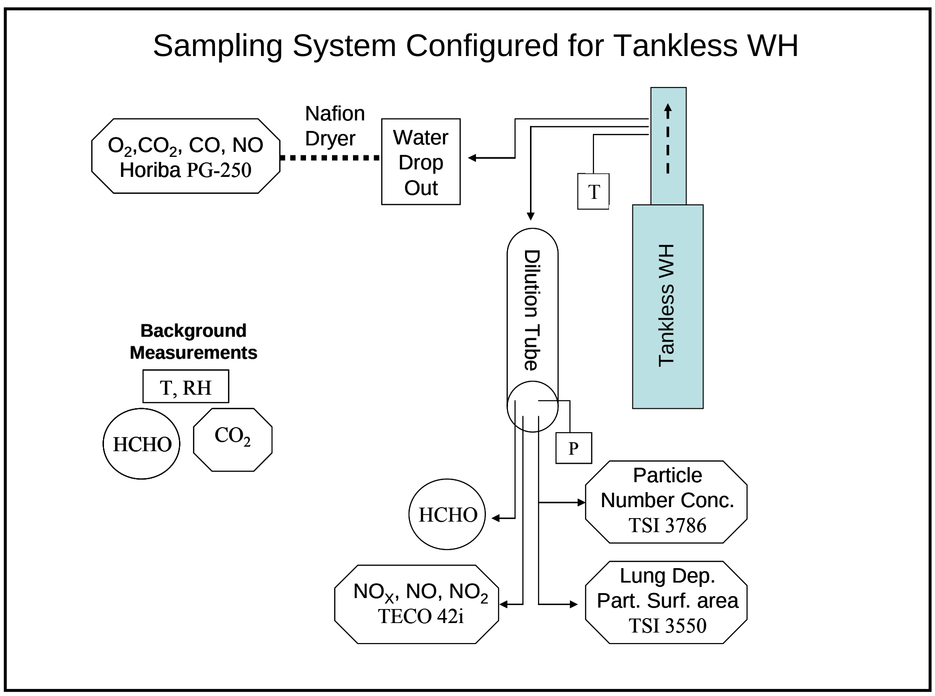

Figure 3. Pollutant sampling configuration for tankless water heater TW02.

Table 18. Analyte ranges and calibration levels for experiments with tankless water heater TW02.

Analyte	Sample location[1]	Equipment[2]	Range	Calibration levels
Carbon dioxide (CO_2)	ducted flue	Horiba PG-250	0-5%	0, 10%
Oxygen (O_2)	ducted flue	Horiba PG-250	0-25%	0, 20.95%
Carbon monoxide (CO)	ducted flue	Horiba PG-250	0-500 ppm	0, 350 ppm
Nitrogen oxides (NO_X)	ducted flue	Horiba PG-250	0-25 ppm 0-50 ppm[3]	0, 20 ppm[4]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-5 ppm	0, 2.0 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] Range changed during experiment F030 when exhaust concentrations exceeded 25 ppm. [4]Calibrated from mixture of NO in N_2.

Table 19. Aerosol instrumentation used for tankless water heater TW02.

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 20. Other measurements for experiments with tankless water heater TW02.

Measured Quantity	Location(s)	Device(s)[1]
Fuel pressure	Inlet to 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	Near air inlet	Precision NTC thermistor (APT)
Relative humidity	Near air inlet	Thermostet polymer based capacitance RH sensor (APT)
Temperature, exhaust	At exhaust sampling location	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 TW02

Full burn emission rates were 33-129 ng/J for CO, 12-36 ng/J for NO_X, 0.55-0.77 ng/J for HCHO and <1 $x10^4$ J^{-1} for PN. CO and NO_X both varied with water flow rate and increased substantially with fuel WN. Full-burn CO emissions (ng/J) were 33-39 with PG&E line gas, 51-94 with fuel 1C (WN=1390) and 85-121 with fuel 3C (WN=1420). Full-burn NO_X emissions were 12-19 with PG&E, 18-26 with 1C and 21-36 with fuel 3C. NO comprised 30-70% of total NO_X as NO_2 varied much less than NO and total NO_X across experiments. For all fuels the fraction of NO_X comprised by NO was lower at 2 gallons per minute (gpm) and higher at 1 and 4 gpm. HCHO emissions (ng/J) decreased by about 30% between line gas and fuel 3C (WN = 1319).

Table 21. Burner operating parameters for experiments with tankless water heater TW02.

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)
F028	1 gpm	11:41	11:49	36	36	7.4	NA
	2 gpm	11:59	12:07	74	74	7.0	NA
	2 gpm	12:17	12:25	71	71	7.1	NA
	4 gpm	12:35	12:43	139	140	5.8	NA
F029	1 gpm	13:02	13:10	36	39	8.4	NA
	2 gpm	13:20	13:28	66	71	8.0	NA
	2 gpm	13:38	13:46	71	75	8.2	NA
	4 gpm	13:56	14:04	134	144	7.2	NA
F030	1 gpm	14:30	14:38	34	38	8.3	NA
	2 gpm	14:48	14:56	60	67	8.2	NA
	2 gpm	15:06	15:14	62	69	8.1	NA
	4 gpm	15:24	15:32	126	140	7.2	NA

[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 22. Combustion air conditions[1] for experiments with tankless water heater TW02.

Exp.	Fuel	T (°C)	RH (%)
F028	PG&E	18.2 ± 0.6	49 ± 2
F029	1C	20.0 ± 0.6	46 ± 2
F030	3C	22.5 ± 0.7	40 ± 2

[1] Mean ± standard deviation of ambient air conditions measured over period of all experimental burns.

Table 23. Sampling system conditions for experiments tankless water heater TW02.

Exp.	Sample Location T (°C)[1]				Dilution Ratio[2]			
	1 gpm	2 gpm	2 gpm	4 gpm	1 gpm	2 gpm	2 gpm	4 gpm
F028	71 ± 0	87 ± 0	87 ± 0	153 ± 3	10	9	9	11
F029	73 ± 0	89 ± 3	87 ± 0	154 ± 0	10	10	10	13
F030	68 ± 0	79 ± 0	80 ± 0	151 ± 1	10	10	10	14

[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 24. Formaldehyde samples for experiments with tankless water heater TW03.

Exp(s)	Location	Sample start/end time		Air vol. (L)	Extract conc. (ng/μL)	Air conc.[1] (μg/m³)
ALL	Bkg air	11:40	15:34	226	0.22	1.98
F028	Dilution Tube	11:40	12:45	60	1.57	52.1
F029		13:01	14:06	61	1.32	43.5
F030		14:22	15:34	68	1.21	35.5

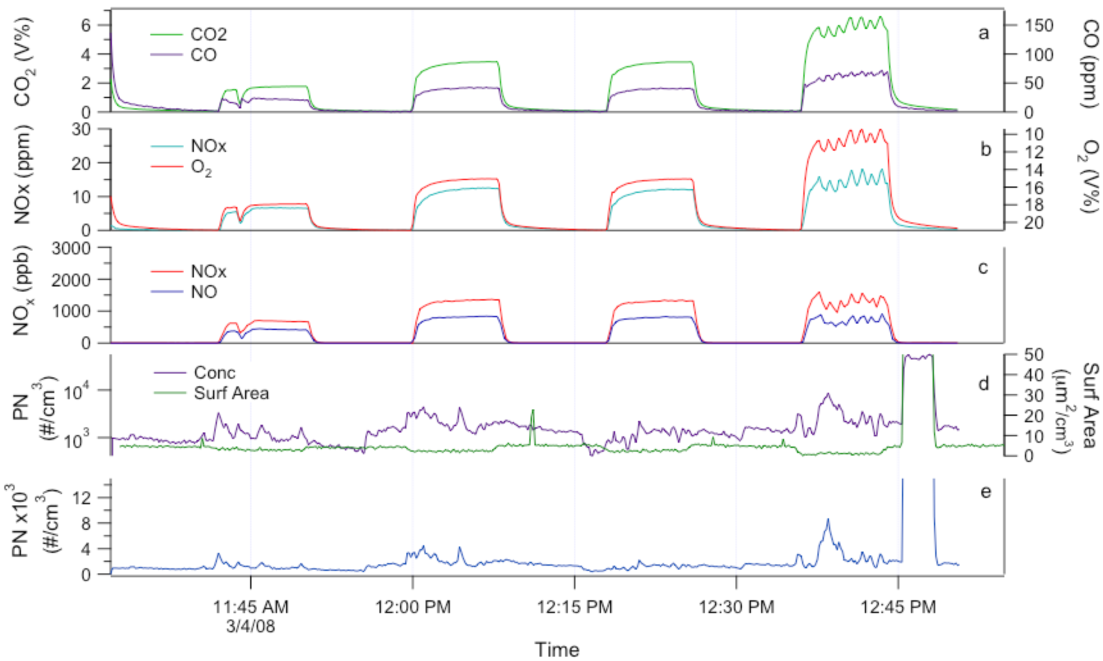

Figure 9. Measured analyte concentrations for tankless water heater TW02 with PG&E line gas (F028). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area. Following Burn 4 the aerosol instruments sampled undiluted ambient air.

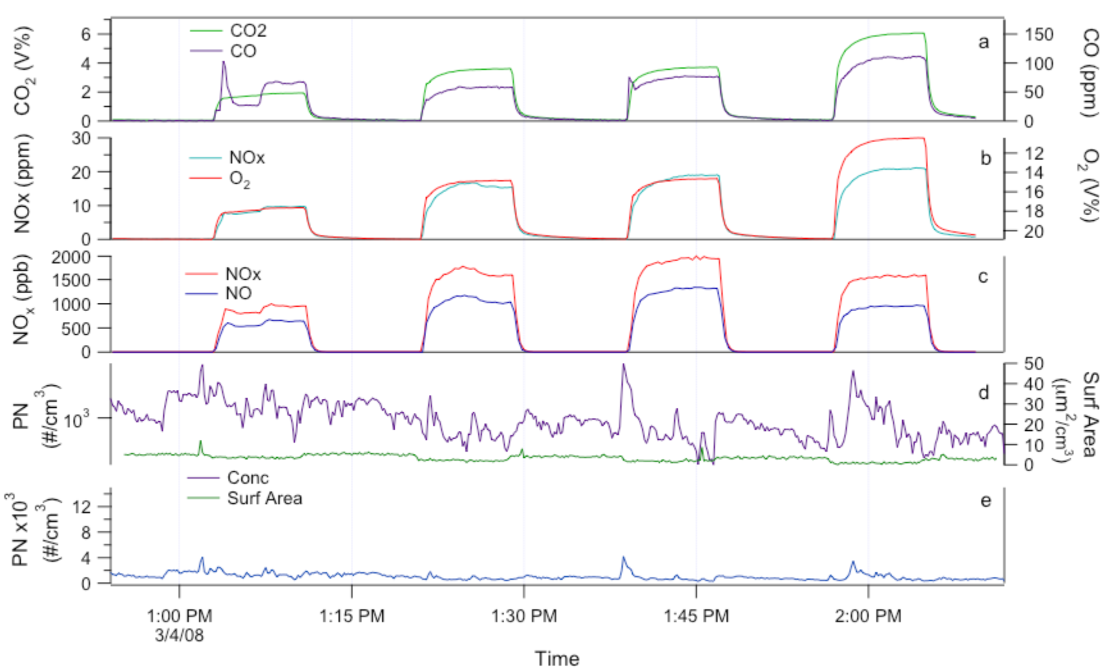

Figure 10. Measured analyte concentrations for tankless water heater TW02 with fuel 1C (F029). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

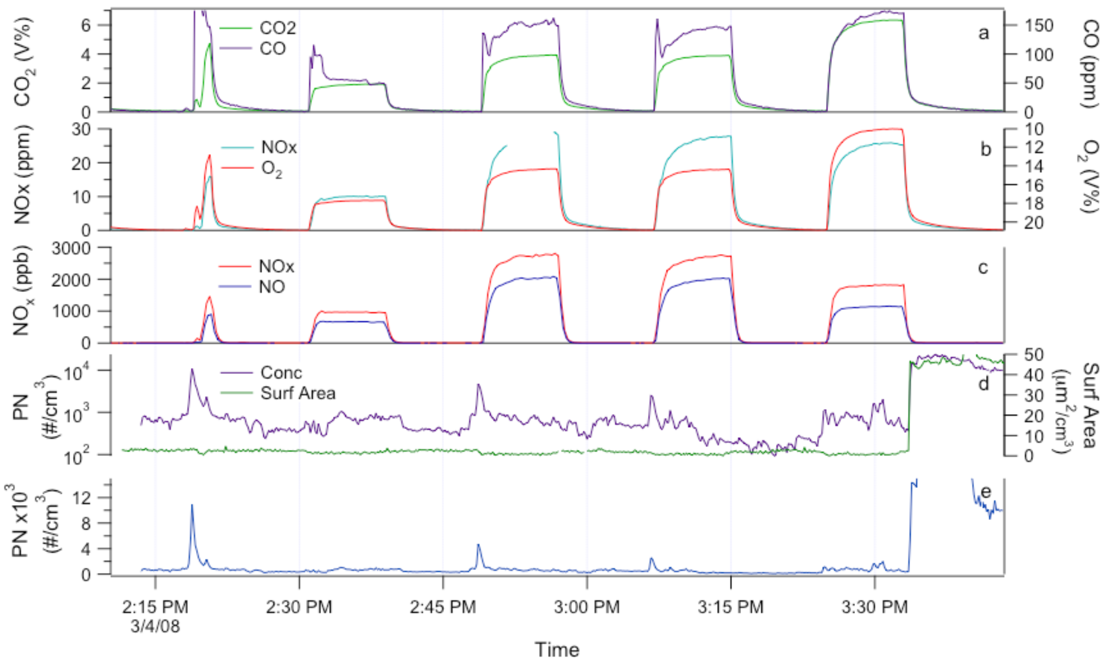

Figure 11. Measured analyte concentrations for tankless water heater TW02 with fuel 3C (F030). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area. The peak prior to Burn 1 is a purge burn. Following Burn 4 the aerosol instruments sampled undiluted ambient air

Table 25. A. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, tankless water heater TW02.

Exp	Fuel	Wobbe	CO (ppm)				PG250 NO_X (ppm)				PN (10^5 cm^{-3})			
			1 gpm	2 gpm	2 gpm	4 gpm	1 gpm	2 gpm	2 gpm	4 gpm	1 gpm	2 gpm	2 gpm	4 gpm
F028	PG&E	1330	144	142	138	127	45	43	42	30	-0.4	0.1	-0.1	0.1
F029	1C	1390	411	192	246	216	60	53	61	41	0.2	-0.1	-0.1	0
F030	3C	1416	330	474	451	326	64	NA[1]	85	49	0.2	0	-0.1	0.1

[1] Concentration went over-range; adjustment was made but data loss affects mean value over period of calculation.

Table 26. B. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, tankless water heater TW02.

Exp	Fuel	Wobbe	NO_X (ppm)				NO (ppm)				NO_2 (ppm)			
			1 gpm	2 gpm	2 gpm	4 gpm	1 gpm	2 gpm	2 gpm	4 gpm	1 gpm	2 gpm	2 gpm	4 gpm
F028	PG&E	1330	45	43	42	30	28	27	26	17	17.1	16.5	16.2	13.5
F029	1C	1390	61	53	61	41	41	35	42	25	19.6	18.3	19.5	16.3
F030	3C	1419	64	90[1]	86	49	44	67[1]	63	31	19.4	23.2[1]	22.3	17.9

[1] Calculated based on dilution ratio from 1 gpm burn.

Table 27. A. Calculated emission rates over entirety of each burn, tankless water heater TW02.

Exp	Fuel ID	Wobbe	CO (μg KJ^{-1})				PG250 NO_X (μg KJ^{-1})				PN (10^7 KJ^{-1})				HCHO (μg KJ^{-1})
			1 gpm	2 gpm	2 gpm	4 gpm	1 gpm	2 gpm	2 gpm	4 gpm	1 gpm	2 gpm	2 gpm	4 gpm	B1-B4
F028	PG&E	1330	39	37	36	33	18.8	17.7	17.3	12.3	-0.5	0.6	-0.3	0.8	0.77
F029	1C	1390	94	51	67	57	25	23	26	17.7	0.7	-0.3	-0.1	0	0.70
F030	3C	1419	109	129	121	85	28	NA[1]	36	21	0.3	0.3	0	0.2	0.55

[1] Concentration went over-range; adjustment was made but data loss affects mean value over period of calculation.

Table 28. B. Calculated emission rates over entirety of each burn, tankless water heater TW02.

Exp	Fuel ID	Wobbe	NO_X (μg KJ^{-1})				NO (μg KJ^{-1})				NO_2 (μg KJ^{-1})			
			1 gpm	2 gpm	2 gpm	4 gpm	1 gpm	2 gpm	2 gpm	4 gpm	1 gpm	2 gpm	2 gpm	4 gpm
F028	PG&E	1330	19.1	17.9	17.5	12.4	11.8	10.9	10.8	6.8	7.3	7.0	6.7	5.6
F029	1C	1390	26	23	26	17.8	17.3	15.2	17.5	10.7	8.4	7.9	8.6	7.1
F030	3C	1419	28	27[1]	36	21	19.2	20[1]	26	13.1	8.6	7.3[1]	9.5	7.6

[1] Calculated based on dilution ratio from 1 gpm burn.

3.0 Tankless Water Heater TW03

3.1. Experimental information for TW03

This was the second tankless water heater tested with simulated LNG blends to evaluate interchangeability at a residence. The unit is mounted in the crawl space with a short duct through the cripple wall. Experiments were conducted on the same day with PG&E line gas (WN = 1329), fuel mix 1C (WN = 1390), fuel 3C (WN = 1419), then a replicate experiment with PG&E line gas. The aerosol inlet heater was set to automatically follow the measured temperature in the flue. Each experiment included three burns with water flow rates of 1, 2, and 3 gallons per minute. The maximum flow rate was limited by the low-flow faucets installed throughout the house.

Table 29. Appliance and burner information.

Burner ID	TW03
Burner category	Tankless water heater
Technology	Induced draft, ribbon burner, direct vent (mount in crawl space); certified to meet 40 ng/J standard
Appliance manufacturer	Controlled Energy Corp (Bosch)
Model	Aquastar 240-FX (Same as Takagi TK-1[1])
Serial number	17017334
Efficiency	82%
Energy Factor	0.81
Capacity	0.75 – 5.3 gallons per hour at 50 F temperature rise
DOE gph	216 gallons per hour
Burner rating	37–165 kBtu/h
Age	Installed in 2005
Test location	On-site at residence
Notes	Installed by current homeowner; used by 1 adult. Water temperature set to 120 F (factory setting).

[1]http://www.boschhotwater.com/HelpfulResources/TechnicalSupport/BoschModels/240FXTK1TechSupport/Specifications/tabid/575/Default.aspx

Table 30. Interchangeability experiments for tankless water heater TW03.

Exp.	Fuel	Date	Burner operation
F031	PG&E	3/7/2008	Initiate burner operation by using hot water at bathtub; measure flow rates using commercial meter. Each experiment included water draws at 1, 2 and 3 gallons per minute. Each water draw was 8 min and followed a 10 min period of non-operation to cool burner. F032 and F033 started with purge burn using 2 ft_3 of fuel.
F032	1C	3/7/2008	
F033	3C	3/7/2008	
F034	PG&E	3/7/2008	

[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 31. Fuel analysis for interchangeability experiments with tankless water heater TW03.

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
F031	PG&E	F031	96.0	2.03	0.14	0.04	0.90	0.86	1011	1329
F032	1C	F032	91.9	8.11	0.00	0.00	0.00	0.00	1072	1390
F033	3C	F033	86.4	11.99	1.58	0.00	0.00	0.00	1125	1419
F034	PG&E	F031	96.0	2.03	0.14	0.04	0.90	0.86	1011	1329

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

Figure 12. Experimental apparatus installed for tankless water heater TW03.
Appliance is mounted in crawl space, just inside of access door. Flue is partially obscured by door, just to right of dilution sampler tube mounted on ladder. Flue rain cover has been removed. Picture taken just prior to experiment F031 (PG&E line gas). Inlet to gas meter connected to compressed gas cylinders for experiments F032-F033.

Figure 13. Sampling lines installed for tankless water heater TW03.
Sampling lines and thermocouples tied together with copper wire to ensure uniform sampling location. Sample probes include gas sampling going to top left of picture, thermocouple for flue gas temperature (T) going to yellow connector at left of picture, aerosol dilution sampler inlet (wrapped in insulation) and thermocouple probe for inlet heater (heater matches T measured at inlet to dilution tube with flue T).

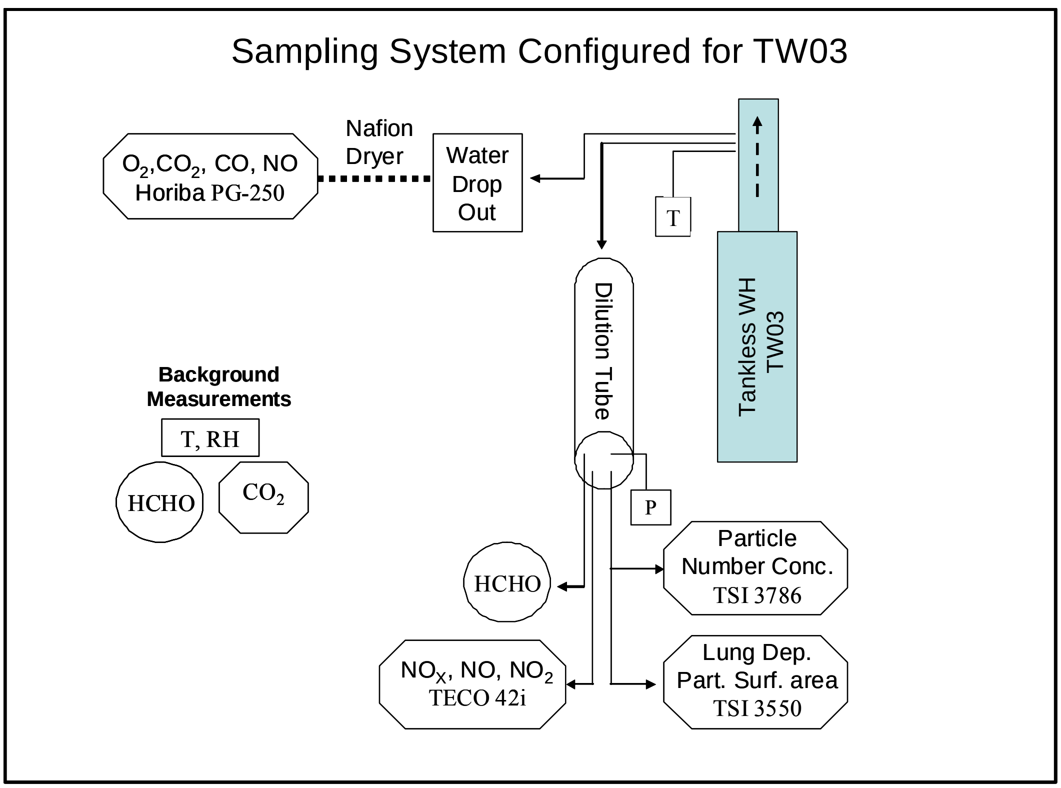

Figure 3. Pollutant sampling configuration for tankless water heater TW03.

Table 32. Analyte ranges and calibration levels for experiments with tankless water heater TW03.

Analyte	Sample location[1]	Equipment[2]	Range	Calibration levels
Carbon dioxide (CO_2)	Inside flue outlet	Horiba PG-250	0-10%	0, 10%
Oxygen (O_2)	Inside flue outlet	Horiba PG-250	0-25%	0, 20.95% check 8%[3]
Carbon monoxide (CO)	Inside flue outlet	Horiba PG-250	0-500 ppm	0, 350 ppm
Nitrogen oxides (NO_X)	Inside flue outlet	Horiba PG-250	0-50 ppm	0, 50 ppm[4]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-5 ppm	0, 2.0 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 8.0% for mixture with 8% O_2 following calibration at 20.95%. [4] Calibrated from mixture of NO in N_2.

Table 33. Aerosol instrumentation used for tankless water heater TW03.

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 34. Other measurements for experiments with tankless water heater TW03.

Measured Quantity	Location(s)	Device(s)[1]
Fuel pressure	Inlet to 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	Near air inlet	Precision NTC thermistor (APT)
Relative humidity	Near air inlet	Thermostet polymer based capacitance RH sensor (APT)
Temperature, exhaust	At exhaust sampling location	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 TW03

Full burn emission rates were approximately 70-110 ng/J for CO, 16-20 ng/J for NO_X, 2.2-2.4 ng/J for HCHO, ≤1 x 10^4 J^{-1} for PN at 1-2 gpm water flow, and 7-14 x 10^4 J^{-1} for PN at 3 gpm water flow. For each fuel, CO emissions were highest at 3 gpm, NO_X emissions were lowest at 3 gpm and PN emissions were substantial only at 3 gpm. NO comprised approximately 65% of total NO_X for all burns. Emissions rates were generally consistent in the two experiments with PG&E line gas. Full-burn NO_X emission rates were slightly higher and HCHO emissions slightly lower with the higher WN fuels relative to line gas. Relative to PG&E line gas, NO_X emissions (ng/J on 2 and 3 gpm water draws) were 3-9% higher for fuel 1C and 7-13% higher for fuel 3C. HCHO emission rates (ng/J) were within 3% for the replicate experiments with PG&E line gas; emission rates with fuels 1C and 3C were about 8-9% lower. These HCHO emission rates are the highest observed for any burner tested to date.

Table 35. Burner operating parameters for experiments with tankless water heater TW03.

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)
F031	1 gpm	11:54	12:02	46	46	7.4	NA
	2 gpm	12:12	12:20	88	89	7.0	NA
	3 gpm	12:30	12:38	147	148	6.6	NA
F032	1 gpm	12:57	13:05	41	43	7.9	NA
	2 gpm	13:15	13:23	84	90	7.6	NA
	3 gpm	13:33	13:41	140	150	6.9	NA
F033	1 gpm	14:01	14:09	37	42	8.1	NA
	2 gpm	14:19	14:27	82	91	7.7	NA
	3 gpm	14:37	14:45	134	149	6.9	NA
F034	1 gpm	15:02	15:10	46	46	6.7	NA
	2 gpm	15:20	15:28	86	87	6.5	NA
	3 gpm	15:38	15:46	146	147	6.4	NA

[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 36. Combustion air conditions[1] for experiments with tankless water heater TW03.

Exp.	Fuel	T (°C)	RH (%)
F031	PG&E	22.6 ± 1.7	46 ± 4
F032	1C	26.7 ± 2.2	38 ± 3
F033	3C	25.2 ± 1.2	38 ± 2
F034	PG&E	21.6 ± 0.8	40 ± 2

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

Table 37. Sampling system conditions for experiments tankless water heater TW03.

Exp.	Sample Location Temperature (°C)[1]			Dilution Ratio[2]		
	1 gpm	2 gpm	3 gpm	1 gpm	2 gpm	3 gpm
F031	88 ± 4	139 ± 0	197 ± 0	13	14	14
F032	86 ± 0	140 ± 0	200 ± 0	12	14	15
F033	85 ± 0	125 ± 0	200 ± 0	13	13	15
F034	88 ± 0	140 ± 0	198 ± 0	13	14	14

[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 38. Formaldehyde samples for experiments with tankless water heater TW03.

Exp(s)	Location	Sample start/end time		Air vol. (L)	Extract conc. (ng/μL)	Air conc.[1] (μg/m^3)
ALL	Bkg air	11:50	15:48	244	0.347	2.85
F031	Dilution Tube	11:52	12:41	49	2.609	107
F032		12:56	13:43	45	2.226	98
F033		14:00	14:47	46	2.125	93
F034		15:01	15:48	45	2.457	110

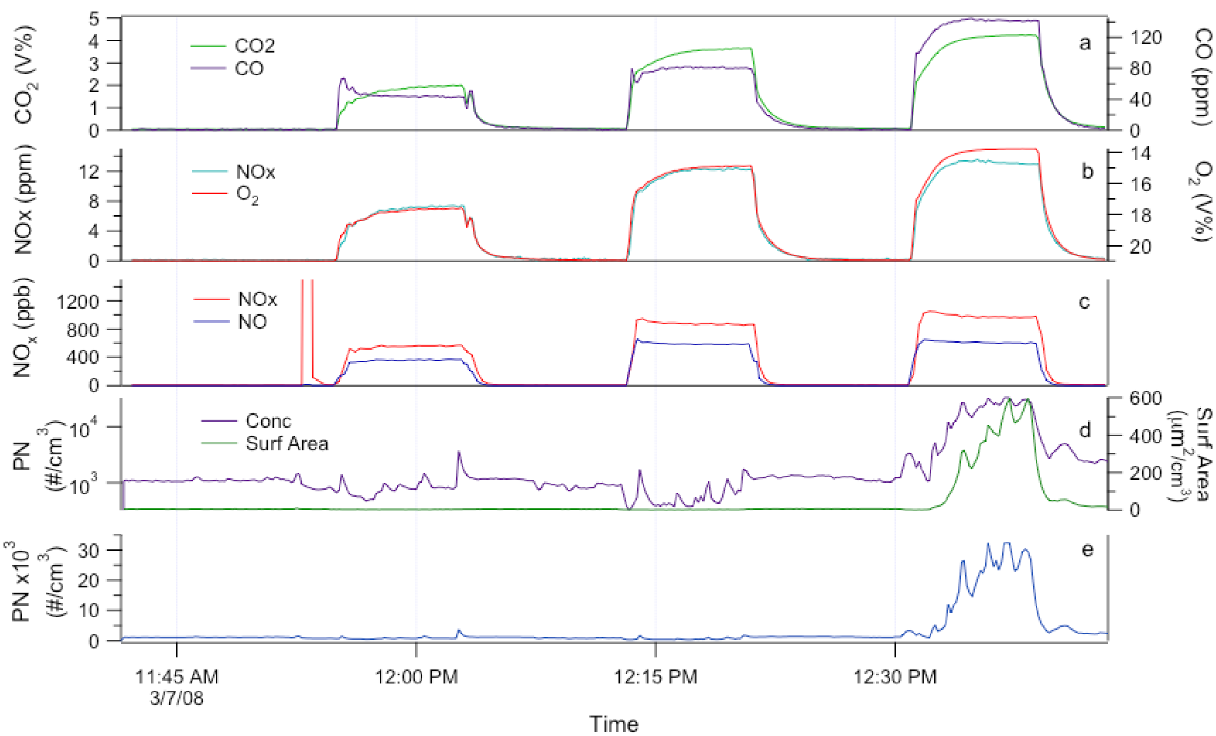

Figure 14. Measured analyte concentrations for tankless water heater TW03 with PG&E line gas (F031). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

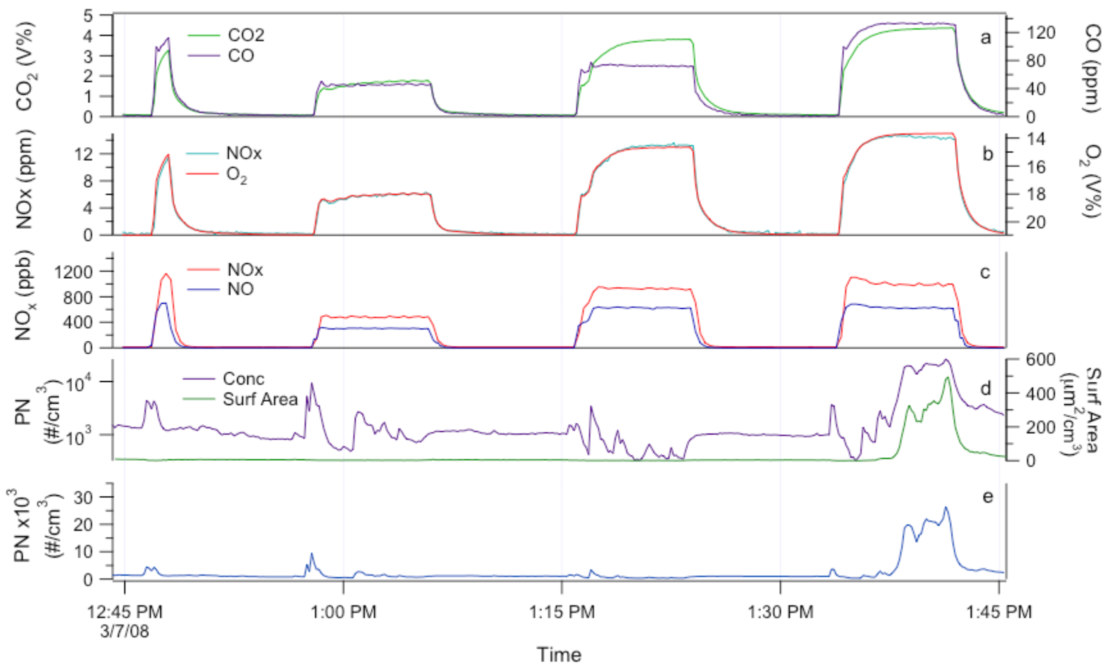

Figure 15. Measured analyte concentrations for tankless water heater TW03 with fuel 1C (F032). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area. The peak prior to Burn 1 is a purge burn.

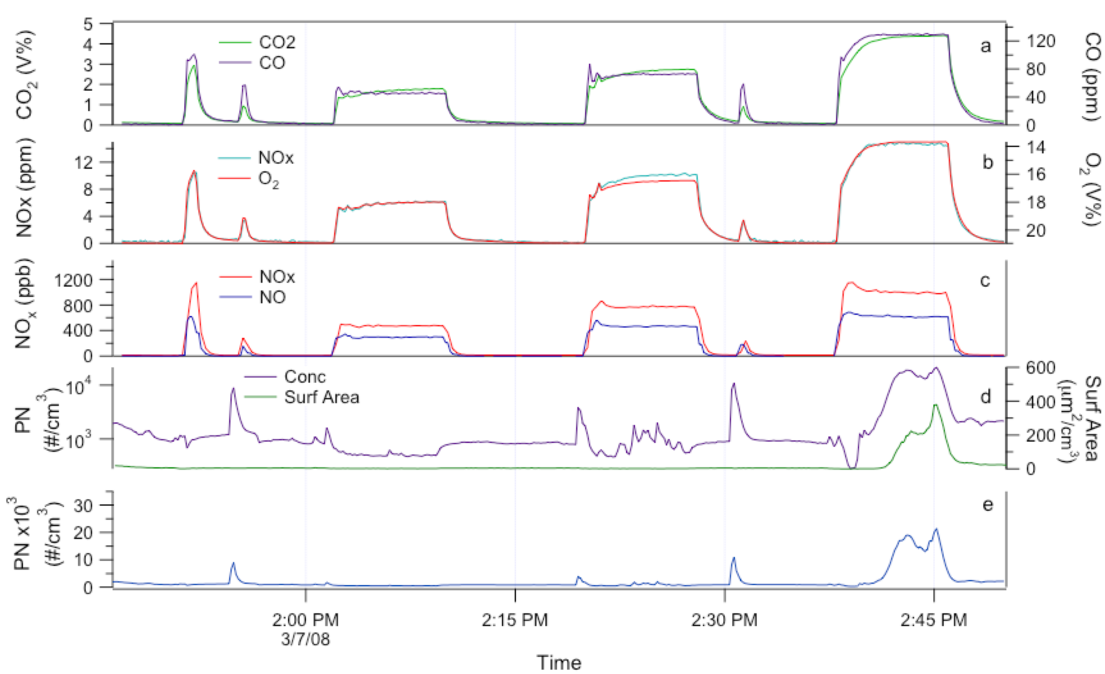

Figure 16. Measured analyte concentrations for tankless water heater TW03 with fuel 3C (F033). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area. The peak prior to Burn 1 is a purge burn.

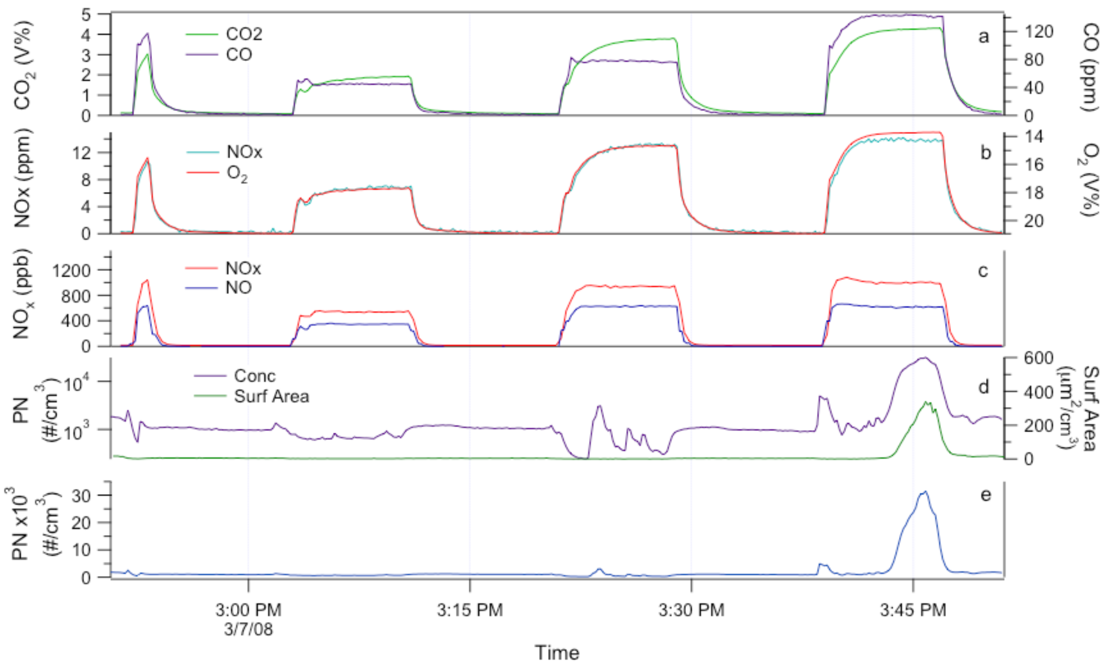

Figure 17. **Measured analyte concentrations for tankless water heater TW03 with PG&E line gas (F034).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area. The peak prior to Burn 1 is a purge burn.

Table 39. A. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, tankless water heater TW03.

Exp	Fuel	Wobbe	CO (ppm)			PG250 NO_X (ppm)			PN (10^5 cm^{-3})		
			1 gpm	2 gpm	3 gpm	1 gpm	2 gpm	3 gpm	1 gpm	2 gpm	3 gpm
F031	PG&E	1329	264	264	399	45	40	37	0	-0.1	9.8
F032	1C	1390	312	226	365	41	42	40	0	-0.3	6.6
F033	3C	1419	312	322	356	42	45	41	-0.3	0.1	6.3
F034	PG&E	1329	281	245	398	43	41	38	-0.3	-0.2	6.4

Table 40. B. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, tankless water heater TW03.

Exp	Fuel	Wobbe	NO_X (ppm)			NO (ppm)			NO_2 (10^5 cm^{-3})		
			1 gpm	2 gpm	3 gpm	1 gpm	2 gpm	3 gpm	1 gpm	2 gpm	3 gpm
F031	PG&E	1329	45	40	37	30	27	23	15.2	13.2	13.8
F032	1C	1390	41	42	40	26	28	25	14.5	13.2	14.4
F033	3C	1419	42	45	41	27	28	25	14.8	17.4	15.1
F034	PG&E	1329	43	41	38	28	28	24	14.4	13.3	14.3

Table 41. A. Calculated emission rates over entirety of each burn, tankless water heater TW03.

Exp	Fuel	Wobbe	CO ($\mu g\ KJ^{-1}$)			PN ($10^7\ KJ^{-1}$)			HCHO ($\mu g\ KJ^{-1}$)
			1 gpm	2 gpm	3 gpm	1 gpm	2 gpm	3 gpm	
F031	PG&E	1329	84	73	109	0	-0.2	14	2.42
F032	1C	1390	90	68	101	1.0	-0.4	8.3	2.19
F033	3C	1419	91	91	99	-0.6	0.2	7.4	2.27
F034	PG&E	1329	81	70	108	-0.6	-0.3	7.9	2.34

Table 42. B. Calculated emission rates over entirety of each burn, tankless water heater TW03.

Exp	Fuel	Wobbe	NO_X ($\mu g\ KJ^{-1}$)			NO ($\mu g\ KJ^{-1}$)			NO_2 ($\mu g\ KJ^{-1}$)		
			1 gpm	2 gpm	3 gpm	1 gpm	2 gpm	3 gpm	1 gpm	2 gpm	3 gpm
F031	PG&E	1329	19.3	17.5	16.4	12.7	11.8	10.3	6.8	5.8	6.0
F032	1C	1390	18.2	18.4	17.7	11.8	12.5	11.3	6.4	5.9	6.5
F033	3C	1419	18.6	19.8	18.0	12.2	12.5	11.4	6.5	7.4	6.7
F034	PG&E	1329	18.4	17.7	16.7	12.1	12.0	10.7	6.3	5.8	6.2

4.0 Tankless Water Heater TW04

4.1. Experimental information for TW04

This was the third tankless water heater tested with simulated LNG blends to evaluate interchangeability at a residence. The unit is mounted outside with direct (non-ducted) exhaust. The water delivery temperature was set by the homeowner at 108ºF to avoid scalding of the young children living in the home. The exhaust port is rusted on one side, presumably resulting from the predominant mode of operation in which only some fraction of the burner set is firing. A sheet metal adapter and 2-foot long section of 6” duct were mounted over the exhaust port to provide a well-mixed exhaust stream in which a single sampling point could be used for varying levels of burner firing. Experiments were conducted on the same day with PG&E line gas (WN = 1330), fuel mix 1C (WN = 1390), fuel 3C (WN = 1420), then a replicate experiment with PG&E line gas. Each experiment included three burns with water flow rates of 1, 2, and 4 gallons per minute. The aerosol inlet heater was set to automatically follow the measured temperature in the flue.

Table 43. Appliance and burner information.

Burner ID	TW04
Burner category	Tankless water heater
Technology	Induced draft, ribbon burner, direct vent (external mount); certified to meet 40 ng/J standard
Appliance manufacturer	Rinnai
Model	Continuum 2532
Serial number	Not recorded
Efficiency	84%
Energy Factor	0.82
Capacity	Max 6.5 gal/min (gpm) at 50 F temperature rise; min. 0.6 gal/min.
Burner rating	15 - 199 kBtu/h
Manifold pressure	0.56 - 3.4 in. H_2O
Age	Installed in 2005
Test location	On-site at residence
Notes	Installed by current homeowner; water temperature set to 108 F to avoid scalding of small children. Used by 3 adults and 2 children.

Table 44. Interchangeability experiments for tankless water heater TW04.

Exp.	Fuel	Date	Burner operation
F035	PG&E	3/11/2008	Initiate burner operation with hot water valve just below unit; measure flow rates using commercial meter. Each experiment included water draws at 1, 2 and 4 gallons per minute. Each water draw was 8 min and followed a 10 min period of non-operation to cool burner. Purge burn with each fuel change.
F036	1C	3/11/2008	
F037	3C	3/11/2008	
F038	PG&E	3/11/2008	

[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 45. Fuel analysis for interchangeability experiments with tankless water heater TW04.

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
F035	PG&	F035	95.6	2.15	0.25	0.13	1.05 [2]	0.81	1014	1330 [2]
F036	1C	F036	91.8	8.17	0.00	0.00	0.00	0.00	1072	1390
F037	3C	F037	86.2	12.13	1.61	0.04	0.00	0.00	1127	1420
F038	PG&	F038	95.6	2.09	0.19	0.06	1.30 [2]	0.80	1009	1324 [2]

[1] Calculated using the American Gas Association interchangeability program.
[2] Differences shown between F035 and F038 may result from analysis method imprecision or actual changes in fuel.

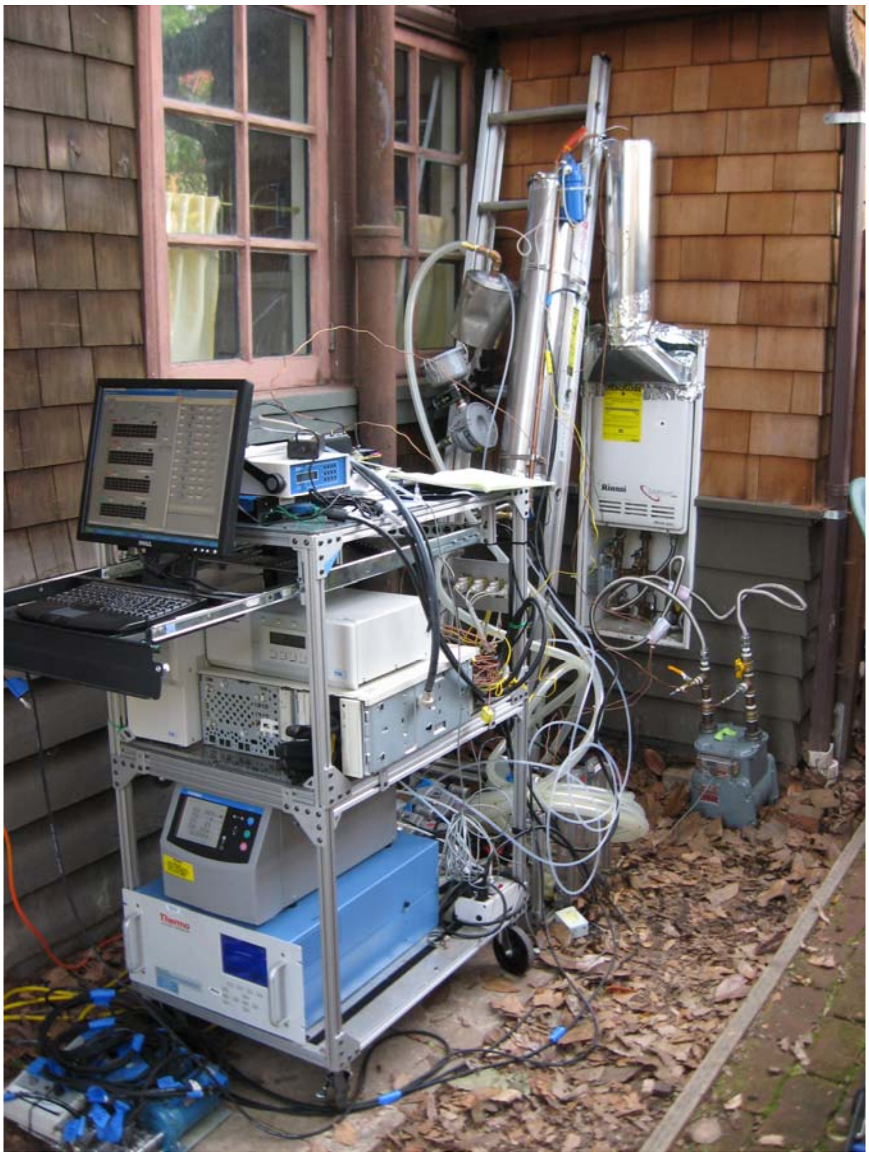

Figure 18. Experimental apparatus installed for tankless water heater TW04.
Flue installed for purpose of achieving well-mixed exhaust sample. Exhaust concentrations vary horizontally across exhaust outlet of appliance owing to orientation and proximity of burners to exhaust port.

Figure 19. Top view of sampling probes installed for tankless water heater TW04.
Sample probes for combustion gas analyzer, thermocouple for flue gas temperature (T), aerosol dilution sampler inlet (wrapped in insulation) and thermocouple probe for inlet heater (heater matches T measured at inlet to dilution tube with flue T). Sampling probes installed 3-4" down into vent.

Figure 20. TW04 mounted outside of residence.
Wear pattern on exhaust port likely results from more frequent firing of burners on right side of unit during low flow water draws.

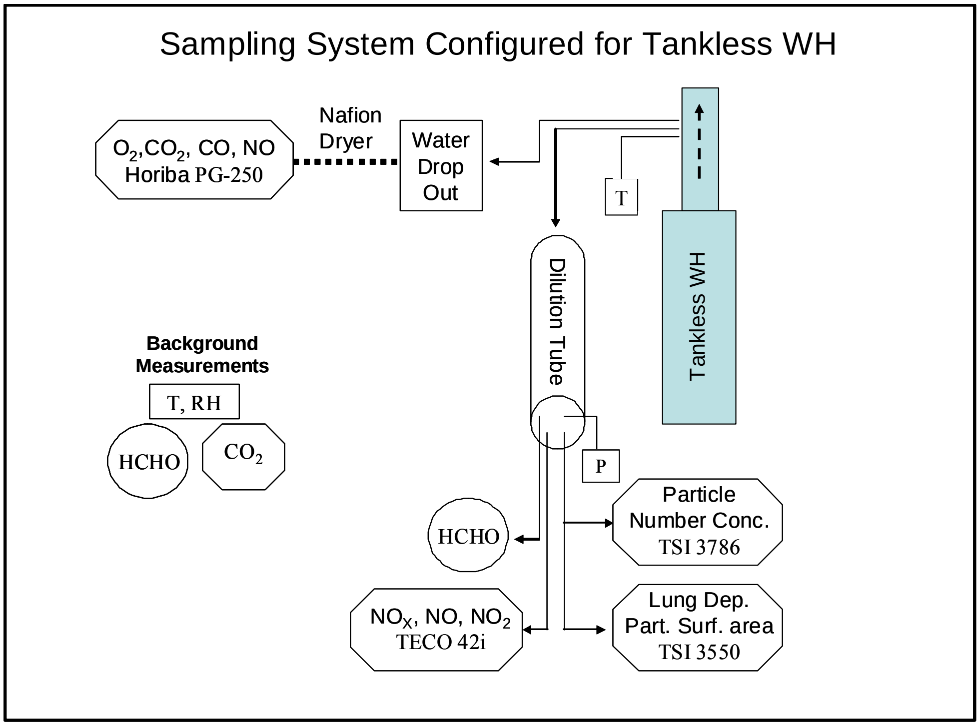

Figure 3. Pollutant sampling configuration for tankless water heater TW04.

Table 46. Analyte ranges and calibration levels for experiments with tankless water heater TW04.

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

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

Table 47. Aerosol instrumentation used for tankless water heater TW04.

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 48. Other measurements for experiments with tankless water heater TW04.

Measured Quantity	Location(s)	Device(s)[1]
Fuel pressure	Inlet to 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	Near air inlet	Precision NTC thermistor (APT)
Relative humidity	Near air inlet	Thermostet polymer based capacitance RH sensor (APT)
Temperature, exhaust	At exhaust sampling location	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 TW04

Full burn emission rates were 17-33 ng/J for CO, 6-18 ng/J for NO_X, 0.22-0.26 ng/J for HCHO, and <1 to 15 x 10^4 J^{-1} for PN. CO, NO_X and PN all varied substantially with fuel WN and water flow rate with NO_X and PN varying more on a relative scale. For each fuel, NO_X concentrations and emissions were generally similar for 1 gpm and 2 gpm water flows (even though firing rate increased substantially) while NO_X emissions at 4 gpm water flow were much lower. Full-burn NO_X emissions (ng/J) at the three water flow rates (1, 2 and 4 gpm) were approximately 10, 10.5

and 6.5) with PG&E line gas (mean of two experiments), (14, 15 and 9) with fuel 1C and (15, 18 and 10) with fuel 3C. For each fuel, PN emissions were generally similar between 2 and 4 gpm flows (despite firing rate increase) and higher at these flows than at 1 gpm. Full-burn PN emissions (10^4 J^{-1}) at 2 and 4 gpm were substantially lower with 3C (1.7-1.9) compared with fuel 1C (3.8-4.7) and PG&E line gas (9.1-9.6 in first experiment, 15-16 in replicate). The NO fraction of total NO_X increased slightly with fuel WN. Emissions rates were generally consistent in the two experiments with PG&E line gas. HCHO emission rates (ng/J) agreed to within 2% for the replicate experiments with PG&E line gas, and were lower by about 15% with fuels 1C and 3C.

Table 49. Burner operating parameters for experiments with tankless water heater TW04.

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)
F035	1 gpm	12:13	12:21	35	35	7.2	NA
	2 gpm	12:31	12:39	63	64	7.0	NA
	4 gpm	12:49	12:57	113	115	6.3	NA
F036	1 gpm	13:16	13:24	32	35	7.6	NA
	2 gpm	13:34	13:42	60	64	7.4	NA
	4 gpm	13:52	14:00	112	120	6.7	NA
F037	1 gpm	14:19	14:27	26	29	7.6	NA
	2 gpm	14:37	14:47	53	60	7.4	NA
	4 gpm	14:58	15:06	103	117	6.9	NA
F038	1 gpm	15:22	15:30	31	31	7.3	NA
	2 gpm	15:40	15:48	56	57	7.0	NA
	4 gpm	15:58	16:06	113	114	6.2	NA

[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 50. Combustion air conditions[1] for experiments with tankless water heater TW04.

Exp.	Fuel	T (°C)	RH (%)
F035	PG&E	17.6 ± 0.4	65 ± 1
F036	1C	18.4 ± 0.3	64 ± 1
F037	3C	16.9 ± 0.3	66 ± 1
F038	PG&E	15.8 ± 0.3	71 ± 1

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

Table 51. Sampling system conditions for experiments tankless water heater TW04.

Exp.	Sample Location T (°C)[1]			Dilution Ratio[2]		
	1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm
F035	55 ± 1	62 ± 1	90 ± 2	12	13	13
F036	55 ± 1	62 ± 1	91 ± 2	12	13	14
F037	53 ± 1	60 ± 0	86 ± 2	12	13	14
F038	54 ± 1	59 ± 1	89 ± 2	12	13	14

[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 52. Formaldehyde samples for experiments with tankless water heater TW04.

Exp(s)	Location	Sample start/end time		Air vol. (L)	Extract conc. (ng/µL)	Air conc.[1] (µg/m³)
ALL	Bkg air	12:11	16:07	233	0.137	1.18
F035	Dilution Tube	12:12	12:58	44	0.358	16.4
F036		13:15	14:02	47	0.337	14.3
F037		14:18	15:07	47	0.330	14.2
F038		15:21	16:07	45	0.376	16.8

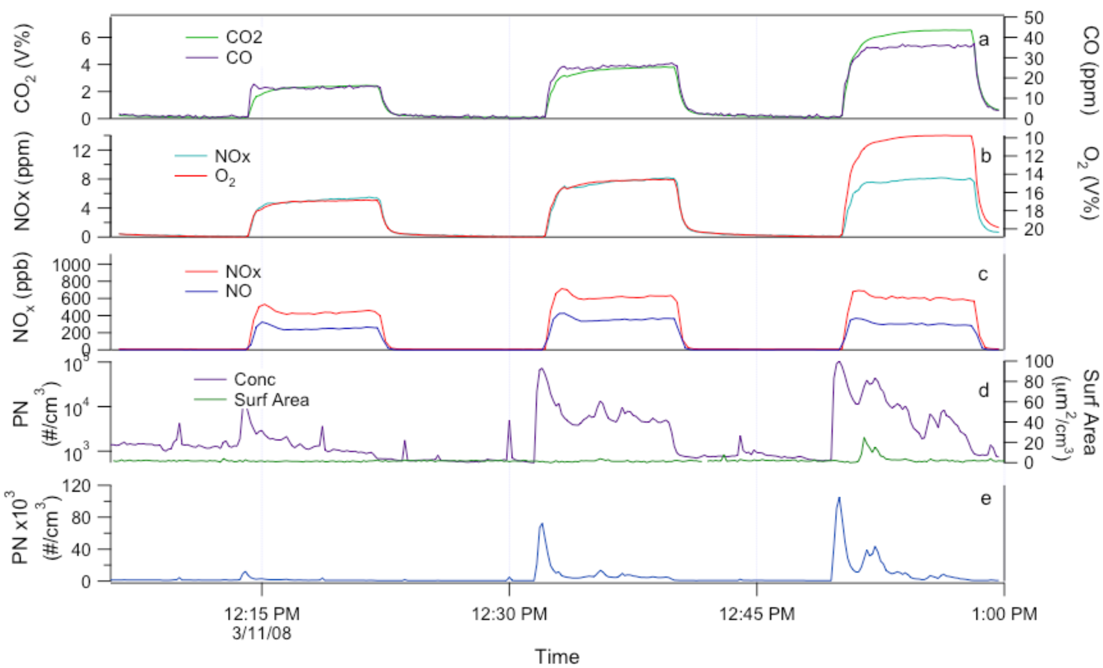

Figure 21. **Measured analyte concentrations for tankless water heater TW04 with PG&E line gas (F035).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area.

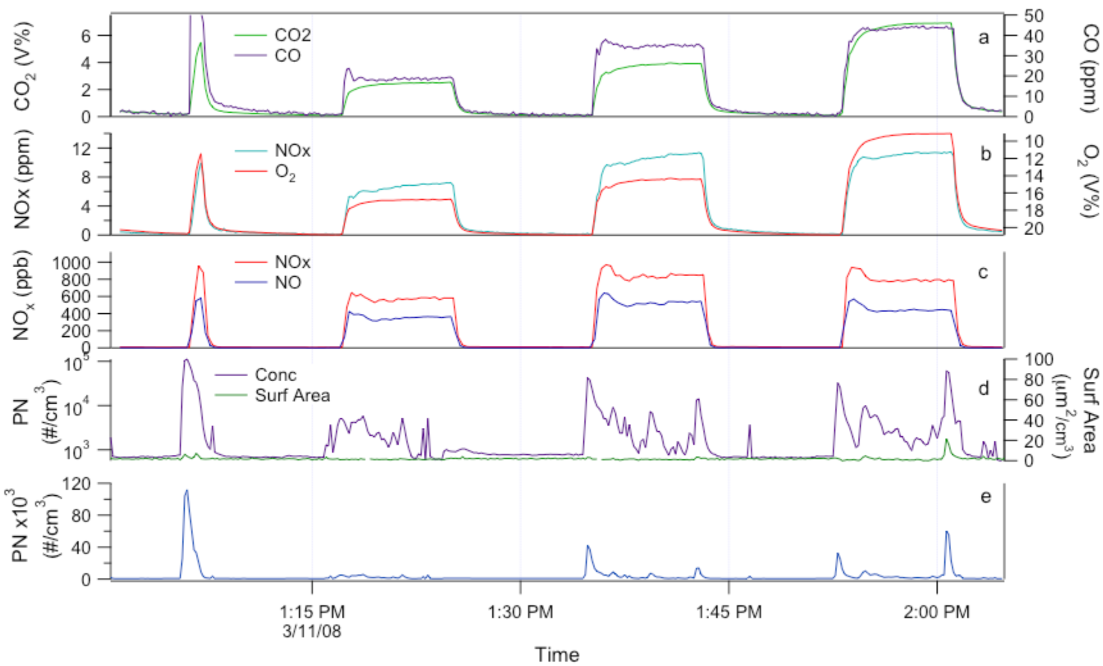

Figure 22. Measured analyte concentrations for tankless water heater TW04 with fuel 1C (F036). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area. The peak prior to Burn 1 is a purge burn.

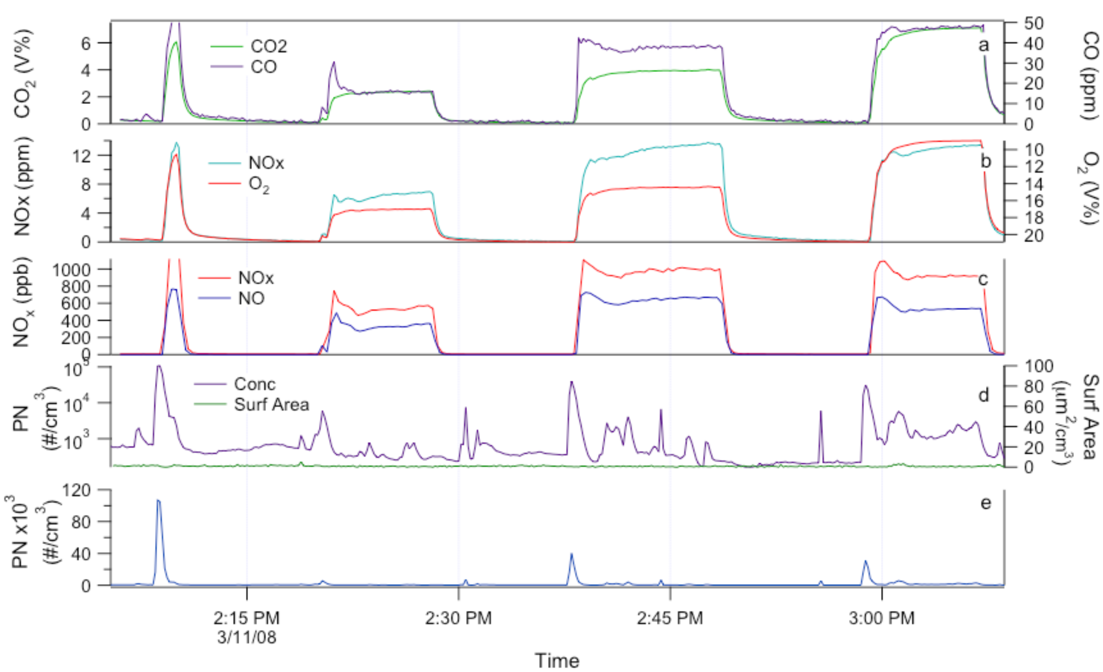

Figure 23. Measured analyte concentrations for tankless water heater TW04 with fuel 3C (F037). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area. The first peak is a purge burn.

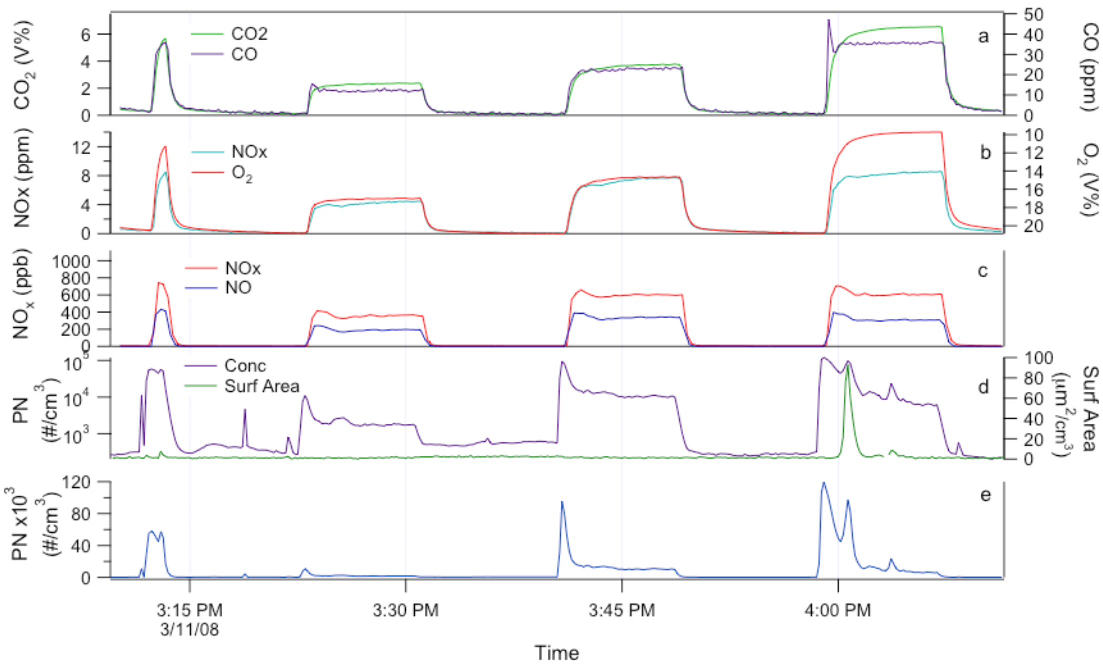

Figure 24. **Measured analyte concentrations for tankless water heater TW04 with PG&E line gas (F038).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. Panel (d) presents surface area of particles that would deposit on human lung alveoli, not total particle surface area. The first peak is a purge burn.

Table 53. A. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, tankless water heater TW04.

Exp	Fuel	Wobbe	CO (ppm)			PG250 NO_X (ppm)			PN (10^5 cm^{-3})		
			1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm
F035	PG&E	1330	75	81	65	26	25	15	0.1	1.9	0.9
F036	1C	1390	87	105	75	33	33	19	0.5	0.6	0.3
F037	3C	1420	79	115	81	34	41	22	0	0	0.3
F038	PG&E	1324	60	72	64	22	24	15	0.7	3.9	2.2

Table 54. B. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, tankless water heater TW04.

Exp	Fuel	Wobbe	NO_X (ppm)			NO (ppm)			NO_2 (10^5 cm^{-3})		
			1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm
F035	PG&E	1330	26	25	15	15	14	7	10.9	10.4	7.2
F036	1C	1390	33	33	19	21	21	11	12.3	12.2	8.5
F037	3C	1420	34	41	22	21	27	13	12.6	13.7	9.3
F038	PG&E	1324	22	24	15	12	14	8	9.9	10.4	7.4

Table 55. A. Calculated emission rates over entirety of each burn, tankless water heater TW04.

Exp	Fuel	Wobbe	CO (μg KJ^{-1})			PN (10^7 KJ^{-1})			HCHO (μg KJ^{-1})
			1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm	
F035	PG&E	1330	21	22	18	1.4	9.1	9.6	0.26
F036	1C	1390	25	30	21	2.1	4.7	3.8	0.23
F037	3C	1420	24	33	23	0.4	1.9	1.7	0.22
F038	PG&E	1324	17	20	18	2.5	15	16	0.26

Table 56. B. Calculated emission rates over entirety of each burn, tankless water heater TW04.

Exp	Fuel	Wobbe	NO_X (μg KJ^{-1})			NO (μg KJ^{-1})			NO_2 (μg KJ^{-1})		
			1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm
F035	PG&E	1330	11.1	10.6	6.3	6.4	6.2	3.2	4.7	4.4	3.1
F036	1C	1390	14.3	14.6	8.6	8.9	9.2	4.9	5.4	5.4	3.7
F037	3C	1420	14.7	17.5	9.9	9.2	11.6	5.8	5.5	5.9	4.1
F038	PG&E	1324	9.1	10.2	6.6	5.0	5.8	3.4	4.1	4.3	3.2

5.0 Tankless Water Heater TW05

5.1. Experimental information for TW05

This unit was purchase new from a local supplier and installed in our laboratory for the purpose of fuel interchangeability evaluation. A section of 4” flexible duct was attached to the top exhaust port of the tankless water heater with the exhaust directed to an overhead hood (as show in Figure 1). The unit was operated with the factory setting for water temperature, and was used on a very limited basis prior to the execution of these experiments. Experiments were conducted on the same day with PG&E line gas (WN = 1322), fuel mix 1C (WN = 1390), fuel 3C (WN = 1419), then a replicate experiment with PG&E line gas. Each experiment included three burns with water flow rates of 1, 2, and 4 gallons per minute. The aerosol inlet heater was set to automatically follow the measured temperature in the flue.

Table 57. Appliance and burner information.

Burner ID	TW05
Burner category	Tankless water heater
Technology	Induced draft, ribbon burner, direct vent (external mount); certified to meet 40 ng/J standard
Appliance manufacturer	Rheem
Model	RTG-74PVN-2
Serial number	RHNG1007900955
Energy Factor	0.82
Capacity	Max. flow 6.6 gal/min (gpm) at 50 F temperature rise
Recovery rating	200 gal/h
Burner rating	19-199 kBtu/h
Manifold pressure	2.76 in. H_2O
Age	New
Test location	LBNL
Notes	Purchased at retail price from local plumbing supplier.

Table 58. Interchangeability experiments for tankless water heater TW05.

Exp.	Fuel	Date	Burner operation
L106	PG&E	5/13/2008	Each experiment included water draws at 1, 2 and 4 gallons per minute. Each water draw was 8 min and followed a 10 min period of non-operation to cool burner. A purge burn occurred after each fuel change.[1]
L107	1C		
L108	3C		
L109	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 59. Fuel analysis for interchangeability experiments with tankless water heater TW05.

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
L106	PG&E	L106	96.1%	1.38%	0.33%	0.15%	0.69%	1.32%	1009	1322
L107	1C	Cylinder	92.0%	8.00%	-	-	-	-	1071	1390
L108	3C	Cylinder	86.4%	12.00	1.60%	-	-	-	1125	1419
L109	PG&E	L106	96.1%	1.38%	0.33%	0.15%	0.69%	1.32%	1009	1322

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

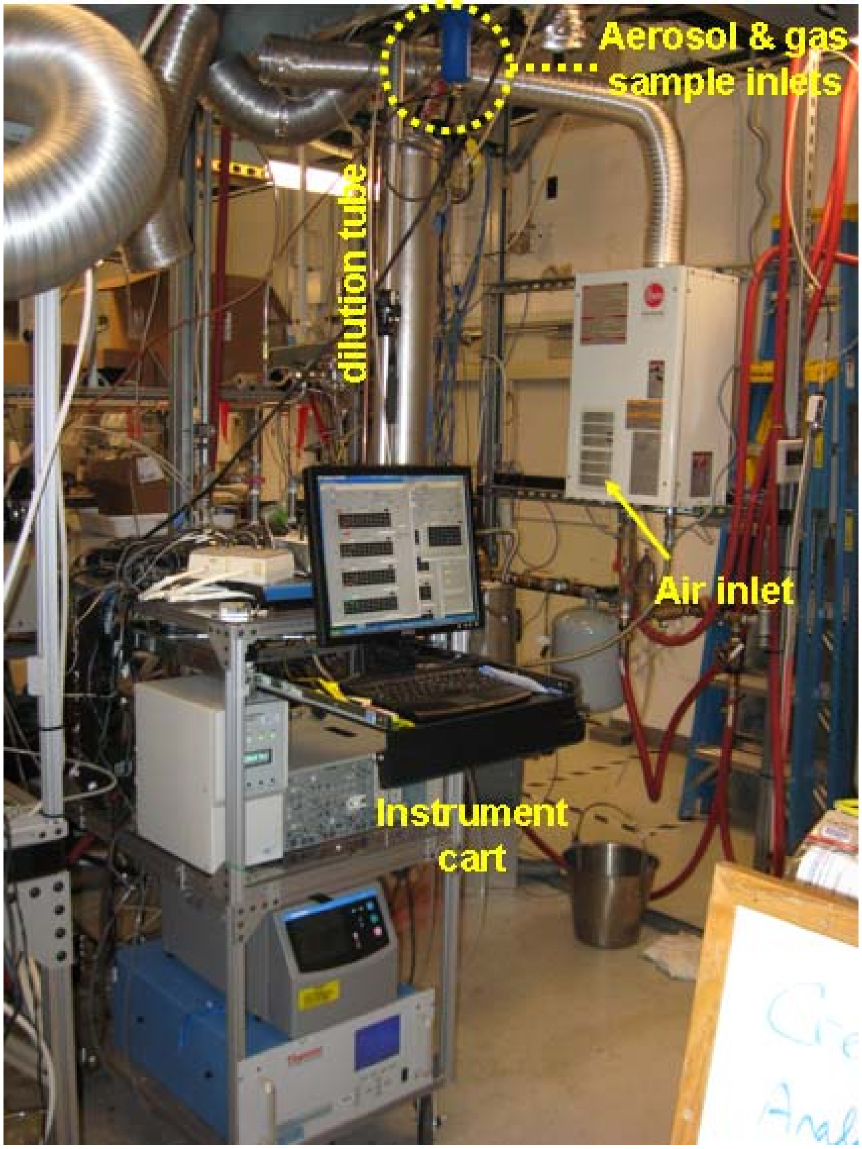

Figure 25. Experimental apparatus installed for tankless water heater TW05.
Flue installed for purpose of achieving well-mixed exhaust sample. Exhaust concentrations vary horizontally across exhaust outlet of appliance owing to orientation and proximity of burners to exhaust port.

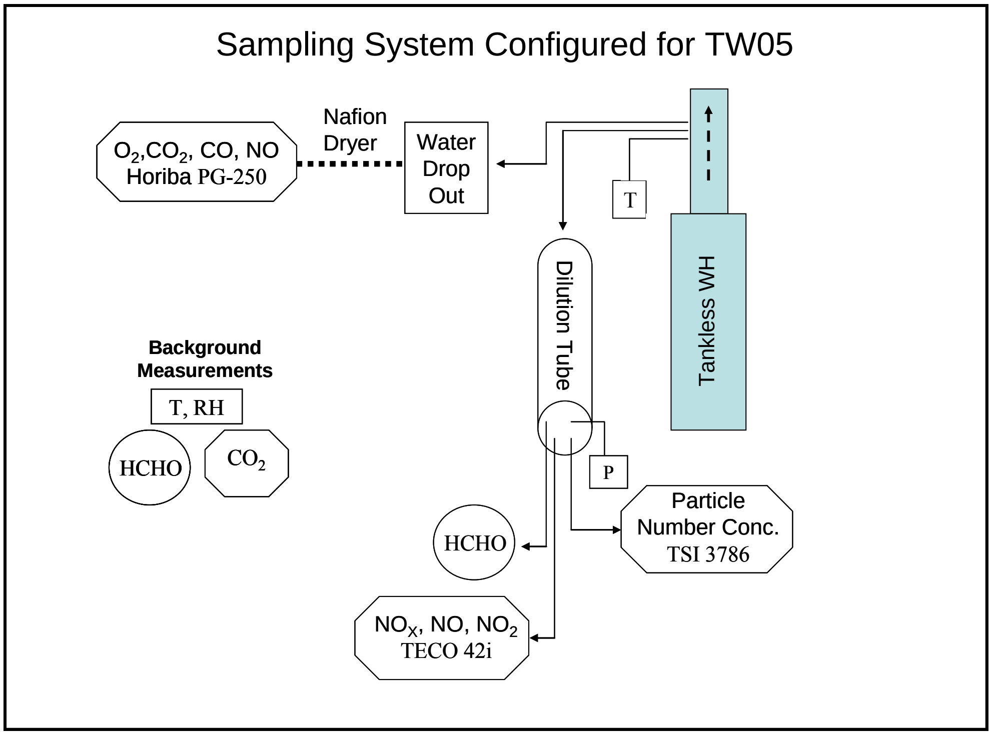

Figure 3. Pollutant sampling configuration for tankless water heater TW05.

Table 60. Analyte ranges and calibration levels for experiments with tankless water heater TW05.

Analyte	Sample location[1]	Equipment[2]	Range	Calibration levels
Carbon dioxide (CO_2)	Exhaust duct	Horiba PG-250	0-20%	0, 10%
Oxygen (O_2)	Exhaust duct	Horiba PG-250	0-25%	0, 20.95%
Carbon monoxide (CO)	Exhaust duct	Horiba PG-250	0-200 ppm	0, 175 ppm
Nitrogen oxides (NO_X)	Exhaust duct	Horiba PG-250	0-100 ppm	0, 50 ppm[3]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-25 ppm	0, 2.4 ppm[3]
Carbon dioxide (CO_2)	ambient air in laboratory	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 61. Aerosol instrumentation used for tankless water heater TW05.

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%

[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.

Table 62. Other measurements for experiments with tankless water heater TW05.

Measured Quantity	Location(s)	Device(s)[1]
Fuel pressure	Upstream 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	Near air inlet	Precision NTC thermistor (APT)
Relative humidity	Near air inlet	Thermostet polymer based capacitance RH sensor (APT)
Temperature, exhaust	At exhaust sampling location	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 TW05

Full burn emission rates were approximately 30-60 ng/J for CO, 20-25 ng/J for NO_X, 2.0-2.4 ng/J for HCHO, and 1-27 x 10^4 J^{-1} for PN. CO emissions were remarkably similar across experiments and fuels and PN variability across fuels was less than the difference between the replicate experiments with line gas. NOX emissions appeared to increase on the order of 10-15% between line gas and fuel 3C (WN=1319). CO emission levels were moderate relative to other tankless water heaters and much higher than the storage water heaters evaluated in this study. NO_2 (NO_X – NO) accounted for a bit less than half of total NO_X.

Table 63. Burner operating parameters for experiments with tankless water heater TW05.

Exp.	Burn	Start time	End time	Fuel flow[1] ($ft^3\ h^{-1}$)	Firing rate[1] (kbtu/h)	Supply Pressure[2] (in. H_2O)	Background Supply P[2] (in. H_2O)
L106	1 gpm	12:31	12:39	32	33	7.5	8.0-8.2
	2 gpm	12:49	12:57	47	48	7.2	
	4 gpm	13:07	13:15	113	114	5.6	
L107	1 gpm	13:37	13:45	21	22	7.8	7.9-8.1
	2 gpm	13:55	14:03	63	67	7.6	
	4 gpm	14:25	14:33	113	121	6.6	
L108	1 gpm	19:35	19:43	23	26	7.8	7.9-8.2
	2 gpm	19:53	20:01	45	51	7.6	
	4 gpm	20:11	20:19	100	112	6.8	
L109	1 gpm	20:35	20:43	23	23	7.6	8.1-8.2
	2 gpm	20:53	21:01	44	45	7.3	
	4 gpm	21:11	21:19	104	105	5.9	

[1] Fuel flow rate ($ft^3\ h^{-1}$) calculated from fuel use measured for each burn (by pulse counter) divided by time of burn; firing rate calculated from calculated fuel flow rate and higher heating value from fuel composition.
[2] Supply pressure when TW05 not operating.

Table 64. Combustion air conditions[1] for experiments with tankless water heater TW05.

Exp.	Fuel	T (°C)	RH (%)
L106	PG&E	22.3 ± 0.2	44 ± 1
L107	1C	22.8 ± 0.2	39 ± 1
L108	3C	22.8 ± 0.2	43 ± 1
L109	PG&E	22.6 ± 0.1	38 ± 1

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

Table 65. Sampling system conditions for experiments tankless water heater TW05.

Exp.	Sample Location T (°C)[1]			Dilution Ratio[2]		
	1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm
L106	52 ± 0	60 ± 0	94 ± 0	17	17	18
L107	52 ± 0	60 ± 0	96 ± 1	16	17	18
L108	53 ± 0	60 ± 0	90 ± 1	17	18	19
L109	52 ± 0	59 ± 0	88 ± 0	16	17	18

[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 66. Formaldehyde samples for experiments with tankless water heater TW05.

Exp(s)	Location	Sample start/end time		Sample start/end time		Air vol. (L)	Extract conc. (ng/μL)	Air conc.[1] (μg/m³)
Bkg	Lab air	12:28	21:25			565	3.68	13.0
L106	Dilution Tube	12:30:10	12:46:30	12:48:30	13:16:30	41.2	1.68	81.4
L107		13:36:30	13:46:30	13:54:30	14:34:30	47.7	2.07	86.9
L108		19:34:40	20:20:30			42.5	1.53	72.2
L109		20:34:30	20:44:30	20:52:30	21:21:00	35.2	1.68	95.5

[1] Average formaldehyde concentration in the air drawn through the dilution system; the effect of gas quality on formaldehyde emissions is indicated in a subsequent table.

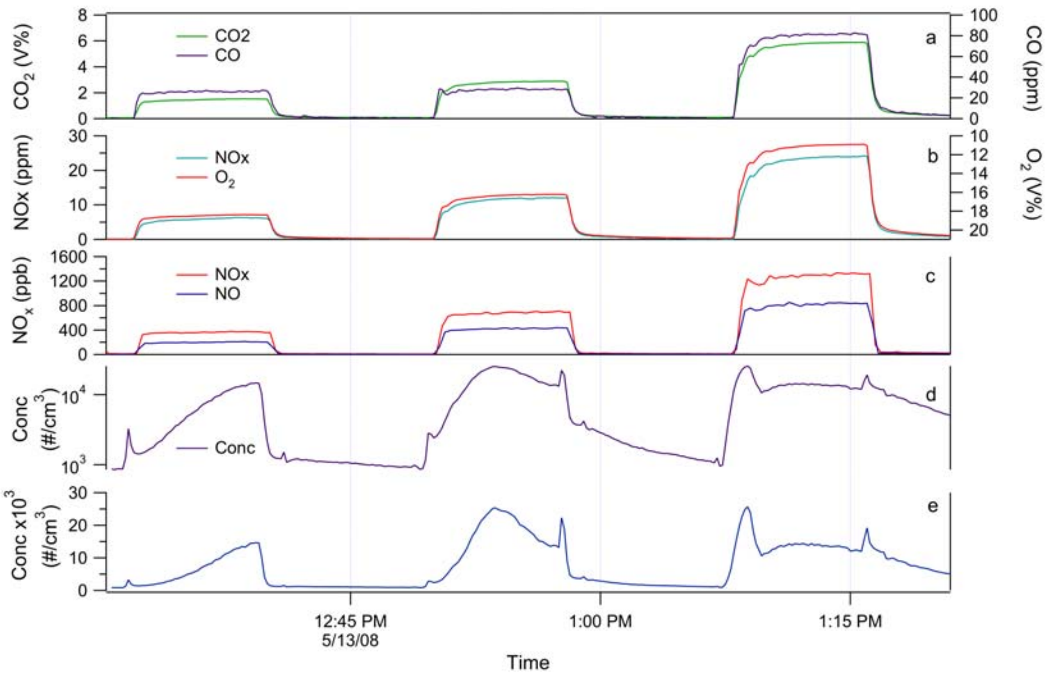

Figure 26. **Measured analyte concentrations for tankless water heater TW05 with PG&E line gas (L106).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

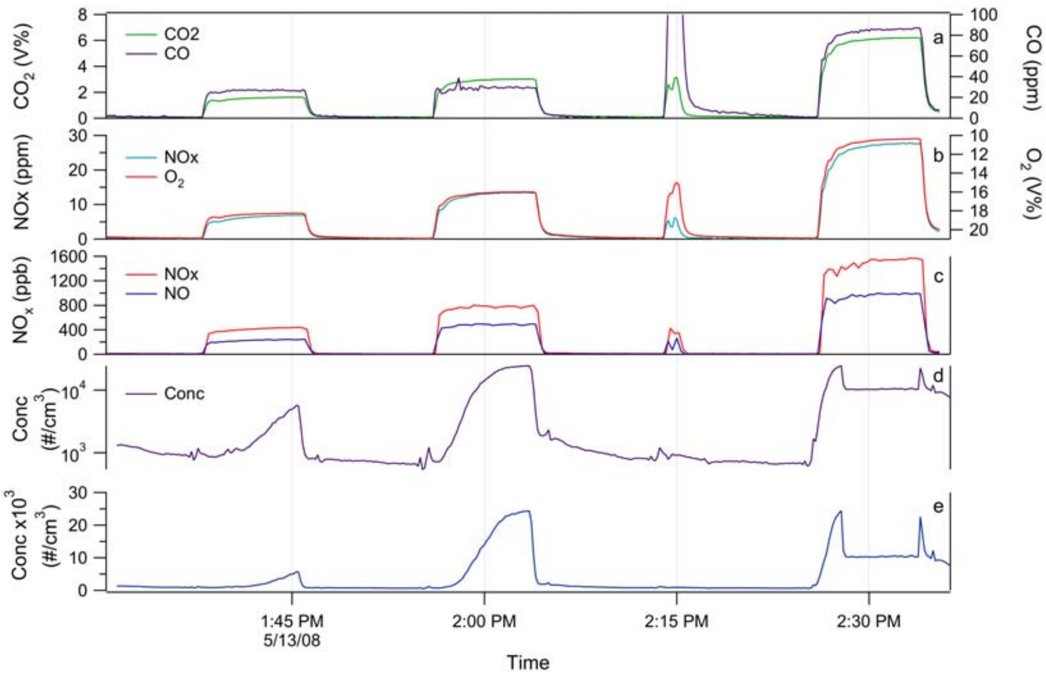

Figure 27. Measured analyte concentrations for tankless water heater TW05 with fuel 1C (L107). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration. 4 pgm burn at 2:15 aborted because cylinder valve not open completely; burn occurred in its entirety after another 10 min cooling period.

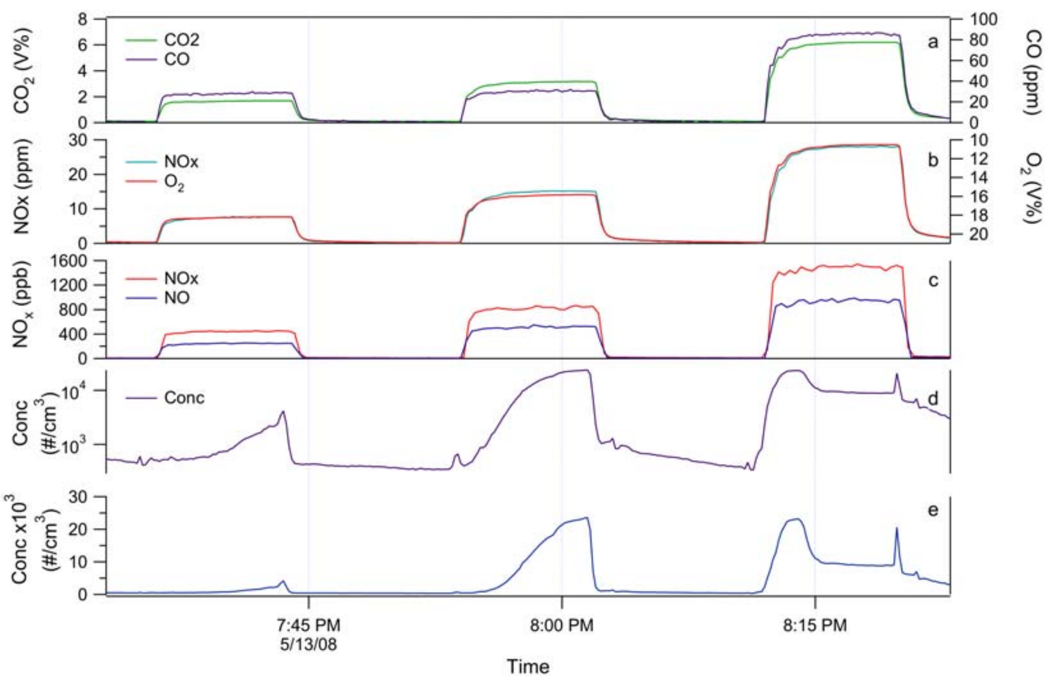

Figure 28. Measured analyte concentrations for tankless water heater TW05 with fuel 3C (L108). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

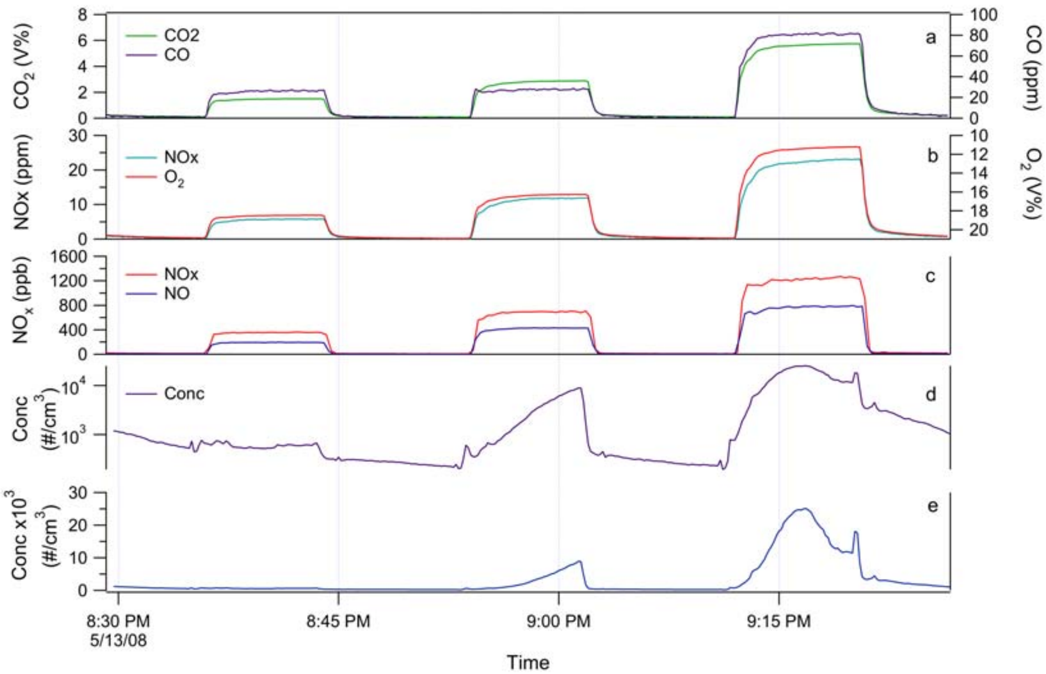

Figure 29. Measured analyte concentrations for tankless water heater TW05 with PG&E line gas (L109). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

Table 67. A. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, tankless water heater TW05.

Exp	Fuel	Wobbe	CO (ppm)			PG250 NO_X (ppm)			PN (10^5 cm^{-3})		
			1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm
L106	PG&E	1322	220	123	168	50	50	49	11	14	5
L107	1C	1390	214	121	168	51	53	53	2.4	11	3.5
L108	3C	1419	213	121	170	56	59	55	1	9.3	4
L109	PG&E	1322	222	120	172	47	50	48	0.3	2.4	7.2

Table 68. B. Calculated air-free concentrations (using CO_2) over last 5 min of each burn, tankless water heater TW05.

Exp	Fuel	Wobbe	NO_X (ppm)			NO (ppm)			NO_2 (10^5 cm^{-3})		
			1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm
L106	PG&E	1322	50	50	49	28	31	31	22.1	18.9	17.6
L107	1C	1390	51	53	53	28	33	34	22.6	20	19
L108	3C	1419	56	59	55	31	37	35	24.7	22	20
L109	PG&E	1322	47	50	48	26	31	30	21.4	18.9	17.6

Table 69. A. Calculated emission rates over entirety of each burn, tankless water heater TW05.

Exp	Fuel	Wobbe	CO (μg KJ^{-1})			PN (10^7 KJ^{-1})			HCHO (μg KJ^{-1})
			1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm	
L106	PG&E	1322	61	34	46	21	27	13	2.17
L107	1C	1390	59	34	46	5.3	19	9.6	2.39
L108	3C	1419	58	33	46	2.4	17	10	1.95
L109	PG&E	1322	60	34	47	0.9	4.8	13	2.15

Table 70. B. Calculated emission rates over entirety of each burn, tankless water heater TW05.

Exp	Fuel	Wobbe	NO_X (μg KJ^{-1})			NO (μg KJ^{-1})			NO_2 (μg KJ^{-1})		
			1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm
L106	PG&E	1322	22	22	21	11.9	13.6	13.5	9.7	8.3	7.6
L107	1C	1390	22	23	23	12.3	14.5	14.9	9.8	8.7	8.2
L108	3C	1419	24	25	24	13.6	15.9	15.1	10.7	9.4	8.7
L109	PG&E	1322	21	22	21	11.2	13.3	12.9	9.4	8.2	7.7

6.0 Tankless Water Heater TW06

6.1. Experimental information for TW06

This unit was purchase new from a local supplier and installed in our laboratory for the purpose of fuel interchangeability evaluation. A section of 4" flexible duct was attached to the top exhaust port of the tankless water heater with the exhaust directed to an overhead hood (as show in Figure 1); the section above the bend was sloped as directed in the installation manual. The unit was operated with the factory setting for water temperature, and was used on a very limited basis prior to the execution of these experiments. Experiments were conducted on the first of two sampling days with PG&E line gas (WN = 1332), fuel mix 1C (WN = 1390), fuel 3C (WN = 1419), then a replicate experiment with PG&E line gas. Each experiment included three burns with water flow rates of 1, 2, and 4 gallons per minute. The aerosol inlet heater was set to automatically follow the measured temperature in the flue. Instrument ranges and calibration levels were determined based on results of a range finding run at 4 gpm water flow. Exhaust concentrations went over range for CO during B1 of the first experiment (L110) and the CO range was reset from 500 to 2000 ppm. Exhaust concentrations exceeded this range during B1 of L112 and the range was changed to 5000 ppm. After the last experiment of the day (L113) – with the instrument range set to 5000 ppm – calibration checks at 4008, 2505, and 1002 ppm yielded readings of 3770, 2440, and 1005 ppm.

A pair of follow-up experiments were conducted on a different day using the same methods; these included PG&E line gas (WN = 1327) and fuel 3C (WN = 1419). For these experiments, the CO range was set to 5000 ppm and the instrument was calibrated at 4509 ppm. Prior to these experiments, the installation was inspected to ensure there were no impediments to exhaust air flow.

Table 71. Appliance and burner information.

Burner ID	TW06
Burner category	Tankless water heater
Technology	Induced draft, ribbon burner, direct vent (mount in crawl space); certified to meet 40 ng/J standard
Appliance manufacturer	Noritz
Model	N0631-S
Serial number	2008. 03 - 008853
Efficiency	82% (calculated as ratio of rated maximum output to maximum input)
Capacity	Max. 5.8 gal/min at 50 F temperature rise; min. flow 0.5 gal/min
Burner rating	25 - 180 kBtu/h
Manifold pressure	0.55 - 2.25 in. H_2O
Age	New
Test location	LBNL
Notes	Purchased at retail price from local plumbing supplier.

Table 72. Interchangeability experiments for tankless water heater TW06.

Exp.	Fuel	Date	Burner operation
L110	PG&E	5/19/2008	Each experiment included water draws at 1, 2 and 4 gallons per minute. Each water draw was 8 min and followed a 10 min period of non-operation to cool burner. A purge burn occurred after each fuel change.[1]
L111	1C	5/19/2008	
L112	3C	5/19/2008	
L113	PG&E	5/19/2008	
L114	PG&E	5/21/2008	
L115	3C	5/21/2008	

[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 73. Fuel analysis for interchangeability experiments with tankless water heater TW06.

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
L110	PG&E	L110	96.6%	1.70%	0.12%	0.03%	0.82%	0.69%	1010	1332
L111	1C	Cylinder	92.0%	8.00%	-	-	-	-	1071	1390
L112	3C	Cylinder	86.4%	12.0%	1.60%	-	-	-	1125	1419
L113	PG&E	L110	96.6%	1.70%	0.12%	0.03%	0.82%	0.69%	1010	1332
L114	PG&E	L114	95.6%	2.11%	0.22%	0.08%	1.25%	0.74%	1011	1327
L115	3C	Cylinder	86.4%	12.0%	1.60%	-	-	-	1125	1419

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

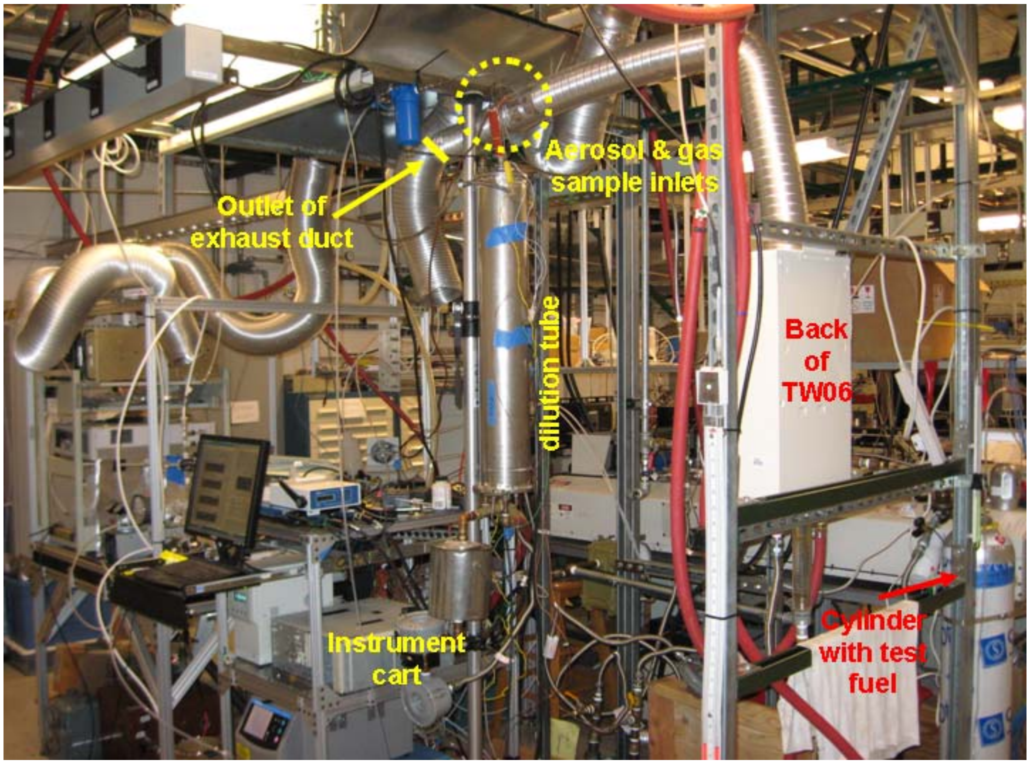

Figure 30. Experimental apparatus installed for tankless water heater TW06.
Appliance is mounted in crawl space, just inside of access door. Flue is partially obscured by door, just to right of dilution sampler tube mounted on ladder. Flue rain cover has been removed. Picture taken just prior to experiment L110 (PG&E line gas). Inlet to gas meter connected to compressed gas cylinders for experiments L111-L112.

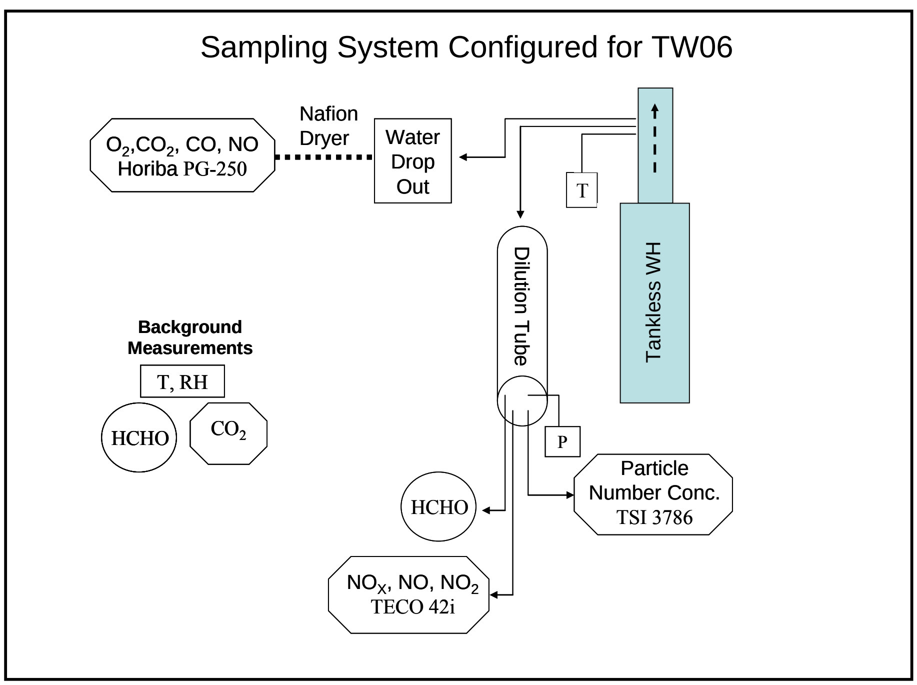

Figure 31. Pollutant sampling configuration for tankless water heater TW06.

Table 74. Analyte ranges and calibration levels for experiments with tankless water heater TW06.

Analyte	Sample location[1]	Equipment[2]	Range	Calibration levels
Carbon dioxide (CO_2)	Ducted exhaust	Horiba PG-250	0-20%	0, 10%
Oxygen (O_2)	Ducted exhaust	Horiba PG-250	0-25%	0, 20.95%
Carbon monoxide (CO), L110-L113	Ducted exhaust	Horiba PG-250	0-500 ppm, 0-2000 ppm 0-5000 ppm[3]	Span: 0, 501 ppm, Check: 1002, 2505, 4008 ppm[3]
Carbon monoxide (CO), L114-L115	Ducted exhaust	Horiba PG-250	0-5000 ppm	0, 4509 ppm
Nitrogen oxides (NO_X), L110-L113	Ducted exhaust	Horiba PG-250	0-100 ppm	0, 100 ppm[4]
Nitrogen oxides (NO_X), L114-L115	Ducted exhaust	Horiba PG-250	0-250 ppm	0, 200 ppm[4]
Nitrogen oxides (NO, NO_X)	dilution sampler	Thermo 42i	0-5 ppm	0, 4.0 ppm4[3]
Carbon dioxide (CO_2)	ambient air in laboratory	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 set to 1000 ppm range for calibration at 501 ppm span then reset to 500 ppm range for start of L110. Range reset to 2000 ppm during B1 of L110 when measured concentrations went over-range. Range reset to 5000 ppm during B1 of L112 when measured concentrations again went over-range. Following L113 – with range set to 5000 ppm – calibration checks at 4008, 2505, and 1002 ppm yielded readings of 3770, 2440, and 1005 ppm.
[4] Calibrated from mixture of NO in N_2.

Table 75. Aerosol instrumentation used for tankless water heater TW06.

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%
PN resolved by size (aerodynamic diameter)	TSI SMPS: 3071A classifier, 3025A ultrafine 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. Ultrafine particles (UFP) are generally defined as having aerodynamic diameters <100 nm. [3] Product 3001788, purchased from TSI.

Table 76. Other measurements for experiments with tankless water heater TW06.

Measured Quantity	Location(s)	Device(s)[1]
Fuel pressure	Inlet to 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	Near air inlet	Precision NTC thermistor (APT)
Relative humidity	Near air inlet	Thermostet polymer based capacitance RH sensor (APT)
Temperature, exhaust	At exhaust sampling location	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).

6.2. Results for TW06

Full burn emission rates were 60-3000 ng/J for CO, 26-46 ng/J for NO_X, <1 TO 15 x 10^4 J^{-1} for PN and consistent at approximately 0.2 for HCHO for all experiments. CO emissions from this device were extremely high, as discussed below. CO varied dramatically by water flow rate and fuel; CO emissions were lowest at 4 gpm and with line gas and increased sharply at lower flow rates and with higher WN fuels. At 4 gpm, full-burn CO emissions increased by several times from 58-86 ng/J in 3 experiments with line gas to 210-490 ng/J in 3 experiments with fuels 1C and 3C. End-of-burn air-free CO concentrations at 4 gpm were on the order of 220-360 ppm with line gas and increased to roughly 1000-2000 ppm with fuels 1C and 3C. At 1 gpm, CO emissions were in the range of 600-1300 ng/J with line gas and 3000 ng/J with fuel 3C. On a relative basis, the effect of fuel WN on CO emissions increased from 1 to 2 to 4 gpm water flow. NO_X emissions increased moderately with fuel WN with larger increases seen at increasing water flow rate. Relative to line gas (mean of 3 experiments), NO_X emissions with fuel 3C (mean of 2 experiments) were approximately 10%, 30%, and 60% higher at 1, 2 and 4 gpm water flow rates. PN emissions were highest during the first experiment each day and decreased with each experiment. PN emissions were higher for the first experiment on the second day (L114) than the last experiment on the first day (L113) even though both used PG&E line gas.

CO emissions for TW06 were much higher than other tankless WHs tested in this study and far in excess of what is expected for a properly functioning new unit. Based on knowledge of unpublished testing, project advisory committee members have affirmed that the CO emissions levels of TW06 are not indicative of the emissions measured from other units produced by the manufacturer. At our request, the manufacturer inspected the unit and determined that the cause of the high emissions was a gas pressure regulator operating outside of manufacturer specifications. This caused an oversupply of fuel that affected the fuel-air mixing ratio and lead to higher CO emissions. The manufacturer communicated that the regulator malfunction is thought to be rare but did not provide estimates of frequency.

Table 77. Burner operating parameters for experiments with tankless water heater TW06.

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)
L110	1 gpm	12:09	12:17	32	32	7.4	NA
	2 gpm	12:27	12:35	58	59	6.9	NA
	4 gpm	12:45	12:53	109	110	5.7	NA
L111	1 gpm	13:10	13:18	27	29	7.7	NA
	2 gpm	13:28	13:36	54	58	7.5	NA
	4 gpm	13:46	13:54	103	110	6.8	NA
L112	1 gpm	14:15	14:23	29	33	7.7	NA
	2 gpm	14:33	14:41	50	57	7.5	NA
	4 gpm	14:51	14:59	100	113	6.8	NA
L113	1 gpm	15:15	15:23	31	31	7.4	NA
	2 gpm	15:33	15:41	58	58	7	NA
	4 gpm	15:51	15:59	113	114	5.7	NA
L114	1 gpm	13:00	13:08	32	33	7.4	NA
	2 gpm	13:18	13:26	58	58	6.9	NA
	4 gpm	13:36	13:44	109	110	5.7	NA
L115	1 gpm	14:00	14:08	29	32	7.7	NA
	2 gpm	14:18	14:26	49	55	7.6	NA
	4 gpm	14:36	14:44	100	112	6.8	NA

[1] Fuel flow rate (ft^3 h^{-1}) calculated from stopwatch timing of ¼-foot or 1-foot dial on gas meter. Digital counter appeared to function properly in only one experiment, L113, and indicated fuel flow rates of 30, 57, and 112 ft^3 h^{-1} at 1, 2, and 4 gpm.

Table 78. Combustion air conditions[1] for experiments with tankless water heater TW06.

Exp.	Fuel	T (°C)	RH (%)
L110	PG&E	22.5 ± 0.1	52 ± 1
L111	1C	22.8 ± 0.1	53 ± 0
L112	3C	23.0 ± 0.1	52 ± 1
L113	PG&E	23.0 ± 0.1	52 ± 1
L114	PG&E	22.3 ± 0.1	42 ± 1
L115	3C	22.5 ± 0.1	42 ± 0

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

Table 79. Sampling system conditions for experiments tankless water heater TW06.

Exp.	Sample Location Temperature (°C)[1]			Dilution Ratio[2]		
	1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm
L110	57 ± 0	72 ± 0	88 ± 0	18	17	19
L111	56 ± 0	69 ± 0	82 ± 0	18	18	21
L112	55 ± 0	67 ± 0	82 ± 0	20	18	20
L113	54 ± 0	69 ± 0	87 ± 0	18	18	19
L114	55 ± 0	69 ± 0	82 ± 1	20	18	19
L115	54 ± 0	66 ± 0	79 ± 0	20	19	21

[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 80. Formaldehyde samples for experiments with tankless water heater TW06.

Exp(s)	Location	Sample start/end time		Air vol. (L)	Extract conc. (ng/µL)	Air conc.[1] (µg/m³)
L110-L113	Bkg air	12:04	16:00	265	0.760	5.7
L110	Dilution Tube	12:08:30	12:54:30	43.6	0.246	11.3
L111		13:09:30	13:55:30	46.6	0.226	9.7
L112		14:14:30	15:00:30	45.9	0.255	11.1
L113		15:14:30	16:00:30	45.6	0.262	11.5
L114-L115	Bkg air	12:59:30	14:45:30	119	0.329	5.5
L114	Dilution Tube	12:59:30	13:45:30	45.9	0.243	10.6
L115		13:59:30	14:45:30	46.4	0.219	9.4

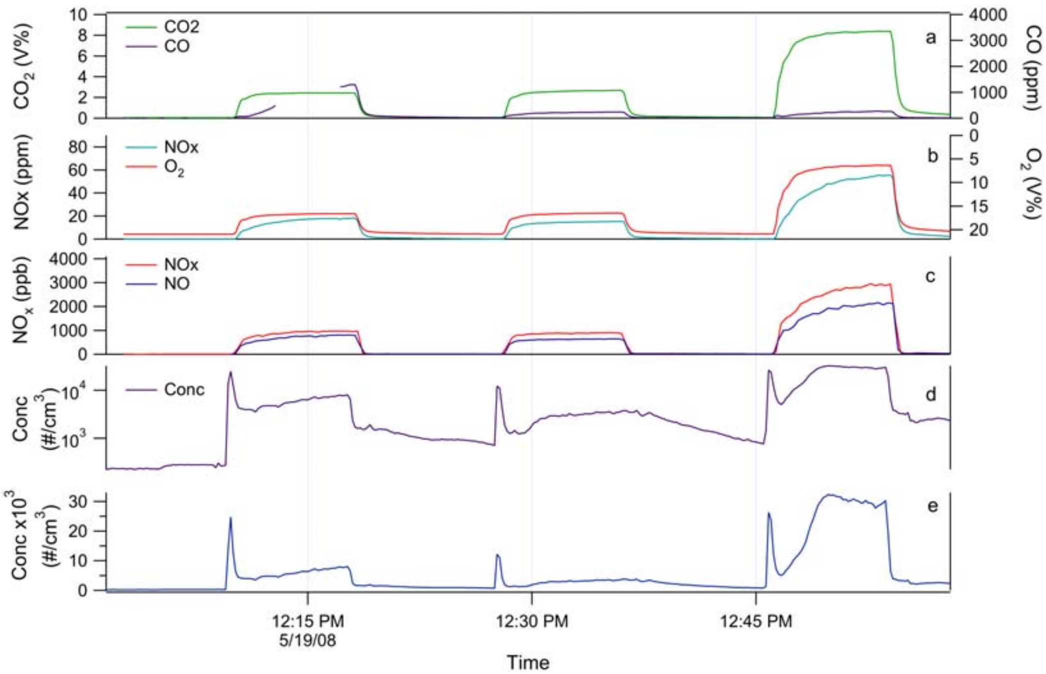

Figure 32. Measured analyte concentrations for tankless water heater TW06 with PG&E line gas (L110). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

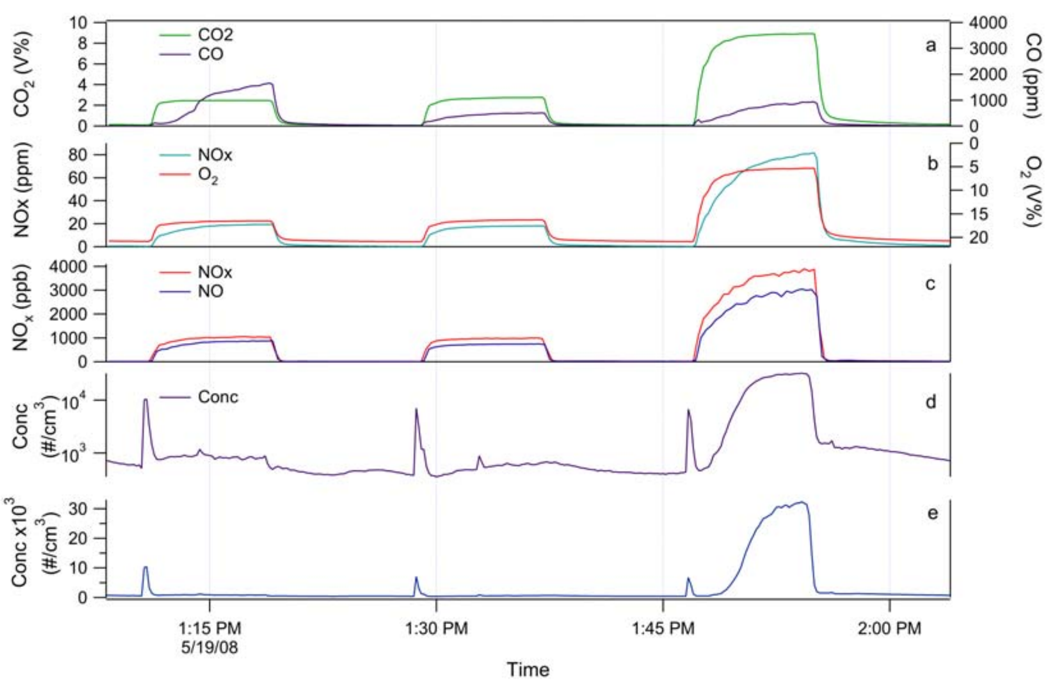

Figure 33. Measured analyte concentrations for tankless water heater TW06 with fuel 1C (L111). Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

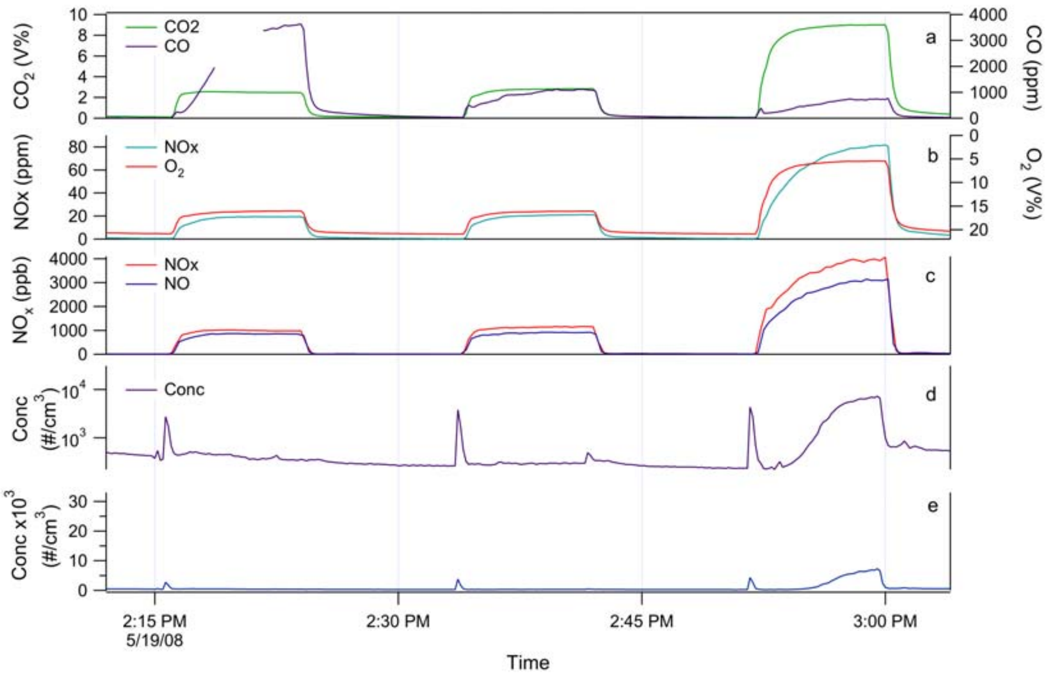

Figure 34. **Measured analyte concentrations for tankless water heater TW06 with fuel 3C (L112).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

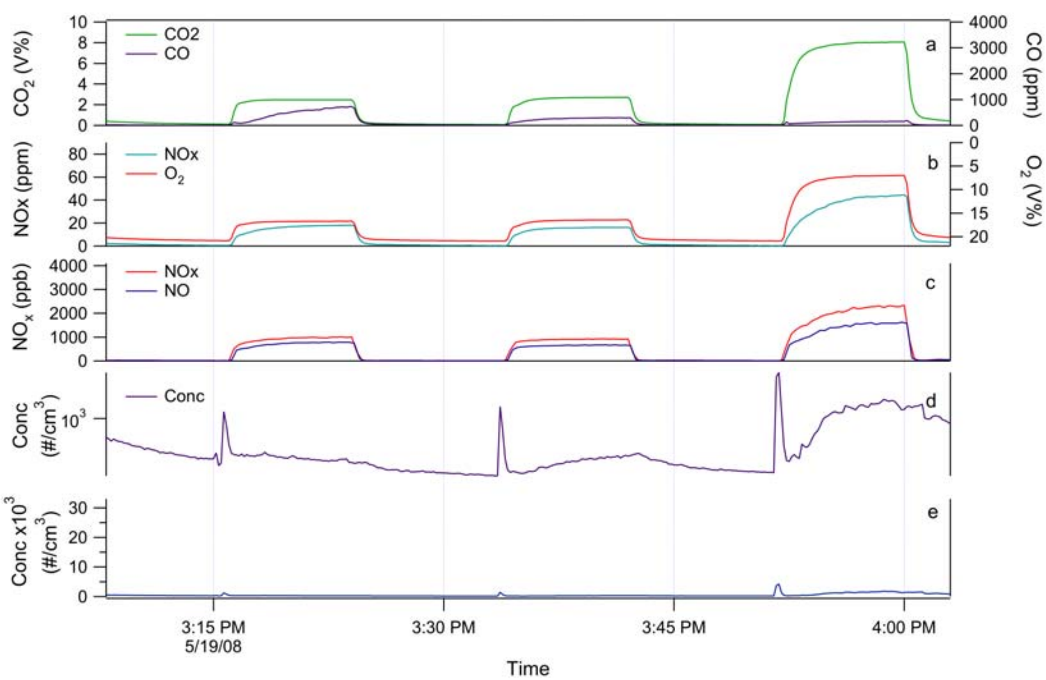

Figure 35. **Measured analyte concentrations for tankless water heater TW06 with PG&E line gas (L113).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

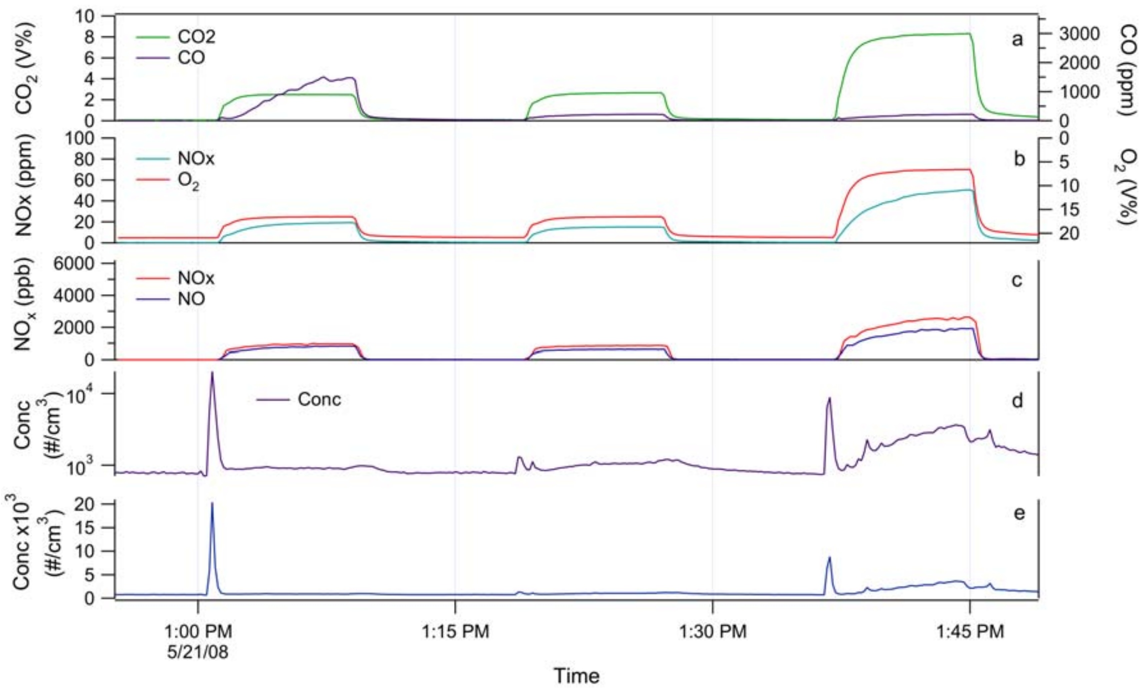

Figure 36. **Measured analyte concentrations for tankless water heater TW06 with PG&E line gas (L114).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

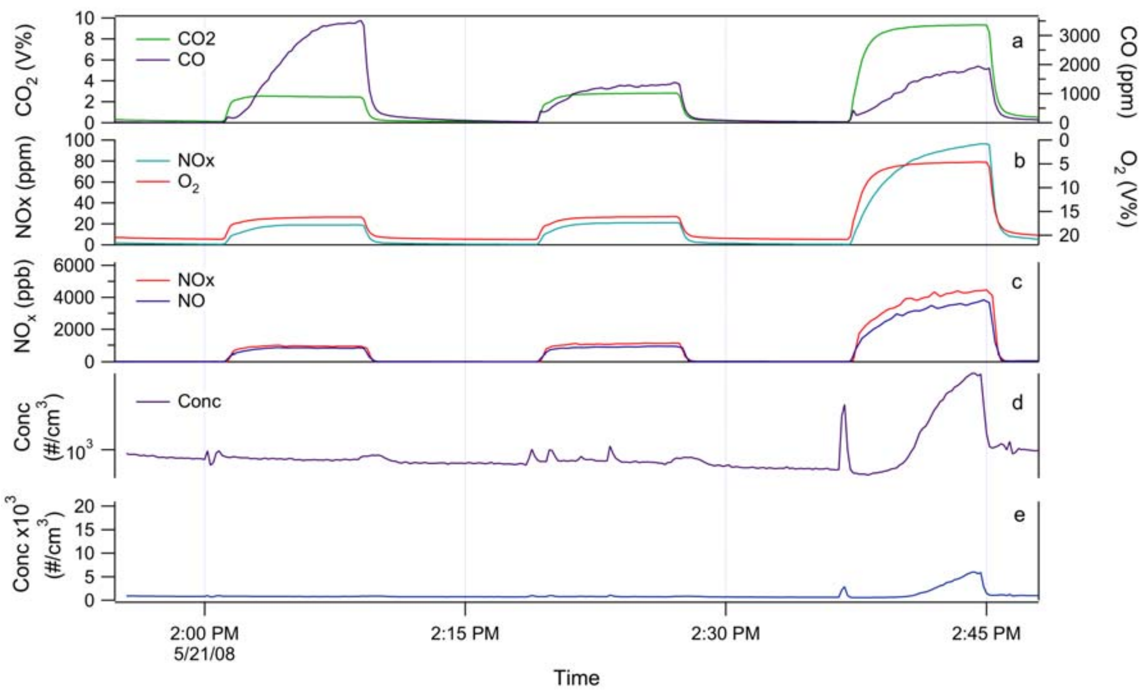

Figure 37. **Measured analyte concentrations for tankless water heater TW06 with fuel 3C (L115).** Panels (a)-(b) present data measured with the Horiba PG-250 analyzer in the gas manifold; panels (c)-(e) present measurements from the dilution system. PN refers to particle number concentration.

Table 81. A. Calculated air-free concentrations (using CO_2)[1] over last 5 min of each burn, tankless water heater TW06.

Exp	Fuel	Wobbe	CO (ppm)			PG250 NO_X (ppm)			PN (10^5 cm^{-3})		
			1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm
L110	PG&E	1332	6100	1050	360	87	68	76	6.1	2.3	8
L111	1C	1390	7100	2200	1150	93	79	104	0.5	0.3	8.1
L112	3C	1419	17000	4700	950	95	90	105	0.1	0	1.3
L113	PG&E	1332	3100	1300	220	86	72	64	0	0	0.4
L114	PG&E	1327	6400	990	300	91	68	69	0.1	0.2	0.6
L115	3C	1419	16000	5600	2300	94	91	119	0	0	0.8

[1] Calculation based on assumption of complete combustion. High CO levels introduce some bias to results. The bias will be addressed in subsequent reporting.

Table 82. B. Calculated air-free concentrations (using CO_2) [1] over last 5 min of each burn, tankless water heater TW06.

Exp	Fuel	Wobbe	NO (ppm)			NO_X (ppm)			NO_2 (10^5 cm^{-3})		
			1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm
L110	PG&E	1332	87	68	76	71	49	55	16.3	19.1	20.7
L111	1C	1390	93	79	104	77	60	81	15.5	19.1	22.8
L112	3C	1419	95	90	105	83	72	82	12.3	18.2	23.2
L113	PG&E	1332	86	72	64	68	52	44	18.1	19.6	19.5
L114	PG&E	1327	91	68	69	76	50	51	14.4	18.2	18.6
L115	3C	1419	94	91	119	83	76	98	10.9	15.6	21.1

[1] Calculation based on assumption of complete combustion. High CO levels introduce some bias to results. The bias will be addressed in subsequent reporting.

Table 83. A. Calculated emission rates over entirety of each burn, tankless water heater TW06.

Exp	Fuel	Wobbe	CO (μg KJ^{-1})			PN (10^7 KJ^{-1})			HCHO (μg KJ^{-1})
			1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm	
L110	PG&E	1332	740	270	86	13	5.5	15	0.25
L111	1C	1390	1350	520	250	2.1	0.9	11	0.21
L112	3C	1419	2900	1100	210	0.5	0.3	1.6	0.24
L113	PG&E	1332	640	320	58	0.1	0	0.7	0.26
L114	PG&E	1327	1250	250	73	1.7	0.5	1.2	0.24
L115	3C	1419	3100	1350	490	0.1	0	1	0.21

Table 84. B. Calculated emission rates over entirety of each burn, tankless water heater TW06.

Exp	Fuel	Wobbe	NO_X (μg KJ^{-1})			NO (μg KJ^{-1})			NO_2 (μg KJ^{-1})		
			1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm	1 gpm	2 gpm	4 gpm
L110	PG&E	1332	35	29	30	27	21	22	7.4	8.3	8.2
L111	1C	1390	37	34	41	30	25	31	6.9	8.5	9.6
L112	3C	1419	39	39	41	33	31	31	5.8	7.9	9.5
L113	PG&E	1332	35	31	26	27	23	18	7.9	8.5	7.9
L114	PG&E	1327	36	30	27	29	21	19	7.0	8.2	7.9
L115	3C	1419	38	39	46	33	32	37	5.2	6.5	9.0

[1] Calculation of air-free concentrations assumes complete combustion. Bias increases with CO emission levels and is approximately X% (on relative basis) for CO concentrations of Y%.