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Effect of Fuel Wobbe Number on Pollutant Emissions from Advanced Technology Residential Water Heaters: Results of Controlled Experiments

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Abstract

The research summarized in this report is part of a larger effort to evaluate the potential air quality impacts of using liquefied natural gas in California. A difference of potential importance between many imported liquefied natural gas blends and the natural gas blends that have been distributed in California in recent years is the higher Wobbe number of liquefied natural gas. Wobbe number is a measure of the energy delivery rate for appliances that use orifice- or pressure-based fuel metering. The effect of varying natural gas blends and associated Wobbe number on pollutant emissions from residential water heaters was evaluated in controlled experiments. Experiments were conducted on eight storage water heaters, including five with "ultra low-NO_X" burners, and four on-demand (tankless) water heaters, all of which featured ultra low-NO_X burners. Pollutant emissions were quantified as air-free concentrations in the appliance flue and fuel-based emission factors in units of nanogram of pollutant emitter per joule of fuel energy consumed. Emissions were measured for carbon monoxide (CO), nitrogen oxides (NO_X), nitrogen oxide (NO), formaldehyde and acetaldehyde as the water heaters were operated through defined operating cycles using fuels with varying Wobbe number. The reference fuel was Northern California line gas with Wobbe number ranging from 1344 to 1365. Test fuels had Wobbe numbers of 1360, 1390 and 1420. The most prominent finding was an increase in NO_X emissions with increasing Wobbe number: all five of the ultra low-NO_X storage water heaters and two of the four ultra low-NO_X on-demand water heaters had statistically discernible ($p<0.10$) increases in NO_X with increasing fuel Wobbe number. The largest percentage increases occurred for the ultra low-NO_X water heaters. There was a discernible change in CO emissions with changes in Wobbe number for all four of the on-demand devices tested. The on-demand water heater with the highest CO emissions also had the largest CO increase with increasing fuel Wobbe number.

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Executive Summary

Purpose

The research reported herein is part of a larger effort to explore the potential air quality impacts resulting from increasing use of liquefied natural gas (LNG) in California. The current study was developed to focus on pollutant emissions from advanced technology residential water heaters when these devices are operated with fuels having the higher Wobbe numbers associated with many LNG supplies. Wobbe number (WN) is a relative measure of the energy delivery rate of a gas through a fixed orifice to a burner and is an indicator of the interchangeability of fuel gases. This research expands on a recent study by Lawrence Berkeley National Lab (LBNL) that reported on the sensitivity of pollutant emission factors to fuel Wobbe number for conventional technology storage and on-demand (tankless) water heaters. That study measured emissions of carbon monoxide (CO), nitrogen oxides (NO_X), nitric oxide (NO), nitrogen dioxide (NO_2, estimated as the different between NO_X and NO), formaldehyde, and number of particles (PN). The storage water heaters evaluated in that study had low emissions of all pollutants other than NO_X and there was only a slight sensitivity of NO_X to fuel Wobbe number for a subset of the storage water heaters. Several of the on-demand water heaters had moderate or higher emissions of CO, NO_2, and formaldehyde. NO_X was generally lower among the on-demand water heaters but more sensitive to fuel WN.

Since the earlier research was completed, a variety of new technologies have been incorporated into residential water heating products. The focus of the study reported here was to examine the effect of fuel WN on pollutant emissions from these advanced technology water heaters. Performance of "ultra low-NO_X" water heaters that comply with South Coast Air Quality District Rules 1121 and 1146.2 was of particular interest.

Methods

Water heaters utilizing specific technology combinations were identified as targets for testing. These target technologies were communicated to manufacturers who expressed willingness to donate production units for the purposes of advancing the research effort. Of the twelve technology combinations targeted, ten were donated and two were purchased. Eight of the water heaters were storage type, three were on-demand and one was a hybrid. The following technologies were represented:

- 2 Ultra-low NO_X, natural draft storage water heaters
- 2 Ultra-low NO_X, power vent storage water heaters
- 2 Energy Star qualified, induced draft, low NO_X storage water heaters
- 2 Condensing storage water heaters, one ultra-low NO_X and one power-vent low-NO_X
- 2 Ultra-low NO_X, non-condensing on-demand water heaters
- 1 Ultra-low NO_X, condensing on-demand water heater
- 1 Ultra-low NO_X, hybrid on-demand water heater

Experiments were conducted on new water heaters installed in a combustion laboratory at LBNL. Appliances were operated through test cycles designed to capture key variations and transient features of actual use patterns. Appliances were operated with line-supplied natural gas from Pacific Gas & Electric (the local gas utility) as a baseline fuel and with simulated LNG blends. Blends were formulated to represent imported LNG and diluted with nitrogen to achieve Wobbe numbers of roughly 1420, 1395, and 1365, as calculated from fuel heating value in British thermal units [Btu] per standard cubic foot. PG&E line gas was in the range of 1344–1365 Wobbe across experiments. Simulated LNG blends were delivered in premixed cylinders. Premixed blends were 12% ethane, 1.6% propane, and 86.4% methane (1420 Wobbe, blend 3C); 8.0% ethane and 92% methane (1390 Wobbe, blend 1C); and 7.9% ethane, 1.9% nitrogen and 90.2% methane (1360 Wobbe, blend 1N). Each water heater was tested on two separate days with PG&E line gas and also tested with the simulated LNG fuels.

With each fuel, storage water heaters were operated through two 15 minute [min] burns with at least 10 min of non-operation before the first burn and 8 min between burns; on-demand water heaters were operated through water draws of 1, 2, and 4 gallons per min [gpm], each lasting for 8 min with 10 min between the burns.

The exhaust stream for each water heater was monitored to determine time-resolved CO, NO_X, NO, CO_2 and O_2 concentrations, and integrated air samples were collected to determine formaldehyde and acetaldehyde concentrations through both burns. These data were used to calculate air-free exhaust concentrations, which were then combined with fuel flow information to calculate emission factors in units of nanograms of pollutant emitted per Joule of fuel energy consumed (ng/J). These units are equivalent to micrograms of pollutant per kilojoule of fuel energy (μg/kJ).

Measurement results were analyzed to assess whether emission factors for CO, NO_X, NO_2, formaldehyde and acetaldehyde followed any trend with fuel Wobbe number. For each appliance and each pollutant, the analysis identified the best-fit linear relationship between emission factors and Wobbe number. A t-test analysis was then performed to determine if the best-fit line is statistically discernible from a line with slope equal to 0, i.e. to determine the likelihood that there is in fact no trend with Wobbe number. The threshold used for this analysis was $p<0.10$; when this condition is met, there is less than a 10% chance that there is in fact no relationship between emission factor and Wobbe number.

Results

Tables ES-1 and ES-2 provide summary results in terms of pollutant emission factors for each water heater using the average results from the PG&E line gas experiments. The tables also present the statistically discernible trends of emission factors changing with increasing fuel Wobbe number. The impact of Wobbe number is provided for a change of 50 Wobbe number.

The South Coast Air Quality Management District (SCAQMD) has two certifications for water heaters. Rule 1121 (amended 2004) requires residential type natural gas water heaters manufactured and sold on or after January 1, 2008 with heat input rates less than 75,000 Btu/hr be certified to a NO_X emission level less than or equal to 10 ng (calculated as NO_2) per joule of heat output (23 lb per billion Btu of heat output) or 15 ppmv NO_X at 3% O_2, dry (17.5 lb per billion Btu of heat input). Rule 1146.2 (amended 2006) requires water heaters manufactured and sold on or after January 1, 2013 with heat input rates between 75,000 Btu/hr and 400,000 Btu/hr (Type I units) be certified to a NO_X emission level less than or equal to 14 ng (calculated as NO_2) per joule of heat output or 20 ppmv NO_X at 3% O_2, dry. These water heaters are referred to as ultra low-NO_X. Water heaters manufactured and sold prior to and through December 31, 2012 were certified to 40 ng (calculated as NO_2) per joule of heat output or 55 ppmv NO_X at 3% O_2, dry. These water heaters are referred to as low-NO_X.

Table ES-1 shows that the three water heaters that were not rated as ultra low-NO_X – AW04, AW06 and AW07 – had NO_X emissions of 36–38 ng/J with PG&E fuel. Those emission factors are higher than the NO_X emissions measured for conventional technology devices in the recent LBNL study (Singer et al. 2010). These three water heaters use conventional burner technologies but utilize enhancements in venting and heat transfer to extract more energy from the combustion process to improve energy efficiency. Increasing Wobbe number caused small increases in NO_X emissions of these devices, estimated at 2-5% for a 50 Wobbe number change.

Consistent with design intent, the storage water heaters with ultra-low NO_X burner technologies had much lower emissions than those with conventional technology burners. Four of the models had NO_X under 10 ng/J and the fifth had NO_X emissions of 12 ng/J. We note that these results are for the test conditions used in this study and should not be considered as applicable to standards based on regulatory test procedures. Consistent with results obtained by Singer et al. (2010) for the lower-NO_X on-demand water heaters, these ultra-low NO_X water heaters showed substantial and statistically discernible ($p<0.10$) sensitivity to fuel Wobbe number. The storage water heaters with ultra-low NO_X burners had NO_X increases of 15 to 51% with a 50 Wobbe number increase in fuel.

The majority of NO_X was in the form of NO; estimated NO_2 (NO_X-NO) was 2-15% of total NO_X for conventional burners, 12-22% for 4 of 5 ultra-low NO_X devices and 40% for the last device.

Table ES-1. Summary of experiments and results for storage water heaters[1,2]

ID	Description	Rating (Btu/h)	PG&E[3] WN	CO (ng/J)	NO_2 (ng/J)	NO_X (ng/J)	HCHO (ng/J)	Acetald. (ng/J)
AW01	Ultra-low NO_X; natural draft; "round" burner; 38 gal	38,000	1350 1348	0.0 (ns)	1.2 (ns)	*7.5* *2.0*	0.06 (ns)	0.04 (ns)
AW02	Ultra-low NO_X; natural draft; "cake-pan" burner; 40 gal	40,000	1347 1346	-0.9[4] (ns)	1.4 (ns)	*6.3* *1.3*	0.04 (ns)	0.04 (ns)
AW03	Ultra-low NO_X; power vent; "cake-pan" burner; 40 gal	42,000	1348[5]	2.1 (ns)	2.5 (ns)	6.2 1.4	0.15 (ns)	0.11 (ns)
AW04	Condensing; "pancake" burner; 50 gal	76,000	1347 1353	11.3 (ns)	5.2 (ns)	35.2 (ns)	0.02 (ns)	0.07 (ns)
AW05	Ultra-low NO_X; power vent; "round" burner; 40 gal	36,000	1348 1349	1.2 (ns)	1.2 (ns)	9.9 1.5	0.12 (ns)	0.1 (ns)
AW06	Energy Star, induced draft; "pancake" burner; 29 gal	60,000	1352 1348	*1.2* *1.4*	0.9 (ns)	38.1 1.4	0.02 (ns)	0.05 (ns)
AW07	Energy Star, induced draft; "pancake" burner; 40 gal	40,000	1348 1349	1.5 -0.3	4.5 (ns)	36.1 1.7	0.07 (ns)	0.08 (ns)
AW08	Condensing; ultra-low NO_X; "cylinder" burner; 50 gal	100,000	1350 1348	0.6 0.3	1.8 (ns)	*11.6* *5.9*	0.01 (ns)	0.03 (ns)

[1] For CO, NO_2, NO_X, HCHO, and Acetaldehyde, the first value in each cell is the average full burn emission rate for the PG&E line gas tests. The emissions change for a 50 Btu/scf increase in fuel WN, below the average full burn emission rate, is only shown for a p value ≤ 0.10. Results with $p < 0.05$ are italicized. Low p-values indicate statistically significant results

[2] NO_X = nitrogen oxide, CO = carbon monoxide, NO_2 = nitrogen dioxide, HCHO = formaldehyde, Acetald = acetaldehyde; ns = not significant

[3] PG&E Line Gas Wobbe Number is listed for each experiment

[4] Negative value indicates near zero CO and is within instrument linearity (±2% of Full Scale)

[5] Only one experiment was conducted with PG&E line gas

The results in Table ES-1 reveal that, similar to the prior results for conventional technology storage water heaters, advanced technology (ultra-low NO_X, induced draft, and energy efficient condensing) designs have very low emission rates of CO, formaldehyde and acetaldehyde. Only one device – the condensing water heater AW04 – had CO above 10 ng/J. None of the storage water heaters had emissions of either aldehyde exceeding 0.2 ng/J.

Results for the on-demand devices, including the hybrid AT04, are shown in Table ES-2.

With PG&E line gas, three of the four had NO_X emissions in range of 8.7 to 10.6 ng/J; AT03 had substantially higher NO_X emissions of 19.2 ng/J with line gas. Only two of the four devices (AT01 and AT04) had NO_X increase with Wobbe number with statistical discernibility; the increase was 44-45% with a 50 Wobbe number fuel change. Estimated NO2 accounted for 34-52% of total NO_X for these devices.

All four of the on-demand water heaters had CO emissions with PG&E line gas exceed 10 ng/J and NO_2 exceed 3 ng/J. Three had formaldehyde exceed 0.2 ng/J. CO emissions for the four on-demand devices operating with PG&E fuel were 11 to 65 ng/J as compared to a range of CO emissions of 19 to 87 ng/J for the tankless water heaters reported by Singer et al. (2010). One interesting difference in the new data is that the device with highest CO – AT03 – also shows the greatest sensitivity to fuel Wobbe number. This result is driven primarily by emissions for the 2 GPM water flow.

Table ES-2. Summary of experiments and results for on-demand water heaters, adjusted for effect of water flow rate[1,2]

ID	Description	Rating (Btu/h)	PG&E[3] WN	CO (ng/J)	NO_2 (ng/J)	NO_X (ng/J)	HCHO (ng/J)	Acetald. (ng/J)
AT01	Ultra-low NO_X, non-condensing	11,000-180,000	1348 1349	*36.0* *7.2*	4.7 1.7	*10.6* *4.8*	0.6 (ns)	0.23 (ns)
AT02	Ultra-low NO_X, non-condensing	11,000-150,000	1362 1365	*32.1* *-1.5*	4.9 (ns)	9.5 (ns)	*0.50* *-0.1*	0.14 (ns)
AT03	Ultra-low NO_X, condensing	15,000-150,000	1344 1347	*64.5* *34.5*	6.6 (ns)	19.2 (ns)	0.26 (ns)	0.08 (ns)
AT04	Ultra-low NO_X, hybrid	16,000-100,000	1349 1346	*10.9* *7.1*	*3.1* *0.7*	*8.7* *3.8*	0.05 (ns)	0.11 (ns)

[1] For CO, NO_2, NO_X, HCHO, and Acetaldehyde, the first value in each cell is the average full burn emission rate of the PG&E line gas tests. This value averages emissions from the 1, 2, and 4 gallon per minute flow rate burns. The emissions change for a 50 Btu/scf increase in fuel WN, below the average full burn emission rate, is only shown for a p value $\leq$0.10. Emission changes in italics indicate p-values $\leq$ 0.05. Low p-values indicate statistically significant results

[2] NO_X = nitrogen oxide, CO = carbon monoxide, NO_2 = nitrogen dioxide, HCHO = formaldehyde, Acetald = acetaldehyde; ns = not significant

[3] PG&E Line Gas Wobbe Number is listed for each experiment

Task Conclusions

The controlled experiments conducted in this study indicate that for some advanced technology water heaters, emissions of some pollutants are sensitive to the Wobbe number of the fuel. The most prominent sensitivity was an increase in NO_X emissions with increasing Wobbe number. All five of the ultra low- NO_X storage water heaters and two of the four ultra low- NO_X on-demand water heaters had statistically discernible increases in NO_X with fuel Wobbe number. The largest percentage increases occurred for the ultra low-NO_X water heaters. Another prominent result was a statistically discernible change in CO emissions with Wobbe number for all four of the on-demand devices tested. The device with highest CO emissions with line gas also had the largest CO increase (53%) with increasing fuel Wobbe number.

Benefits to California

This research is helping to lay the groundwork for maintaining a safe and reliable natural gas supply in California. The investigation of potential impacts of new supplies, including LNG, allows California to assess and plan for impacts of gas quality on operability and pollutant emission levels for the existing population of appliances in the state. The results presented in this report will aid in state efforts to model future ambient air quality by improving accuracy of emission inventories.

Executive Summary References

Singer, Brett C., Michael G. Apte, Douglas R. Black, Toshifumi Hotchi, Donald Lucas, Melissa M. Lunden, Anna G. Mirer, Michael Spears, and Douglas P. Sullivan. 2010. Natural Gas Variability in California: Environmental Impacts and Device Performance: Experimental Evaluation of Pollutant Emissions From Residential Appliances. CEC- 500- 2009- 099. Also available as LBNL report number LBNL-2897E, Lawrence Berkeley National Laboratory, Berkeley CA.

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1.0 Introduction

The impetus for the research effort was the potential for a substantial increase in the distribution of imported liquefied natural gas (LNG) in California. While the composition and physical properties of both LNG and the domestic natural gas (NG) that has been distributed in California in recent years vary, it is typical for LNG to have substantially higher Wobbe number than domestic NG. Wobbe number (WN) is a measure of energy delivery rate through a fixed orifice. Based on theoretical concerns and limited empirical evidence that higher WN could impact pollutant emission rates (summarized in Singer, 2007), research was initiated with the objective of assessing the potential for an increase in pollutant emissions when LNG is used in existing, installed burners.

The specific research described in this report was conducted as follow-up to a study described in a report by Singer et al. (2010) and accompanying appendices, which are available online from both CEC[1] and LBNL[2]. The earlier research was conducted under CEC contract 500-05-026.

The research summarized in Singer et al. (2010) examined a variety of residential natural gas appliances including storage and on-demand water heaters. Since that research was completed, new technologies have been incorporated into residential water heating products. The focus of the current study was to examine the effect of fuel WN on pollutant emissions from advanced technology water heaters available for purchase in California in 2013.

1.1. Summary of Findings from Prior Research in this Area

This section summarizes findings of an LBNL review of the available reports examining LNG interchangeability for residential appliances (Singer, 2007). The vast majority of information prior to the recent Singer et al. (2010) study focused on safety and operability of so-called "legacy" appliances that use partially premixed burners. The specific effects most studied were ignition, flame stability (e.g., lifting), flame appearance (yellow tipping), carbon monoxide (CO) formation (a result of incomplete combustion), and soot formation. Device performance temperatures, energy or thermal efficiency, and formation of nitrogen oxides (NO_X) have been examined in a few studies. A wide variety of domestic appliances have been studied, including central furnaces, wall and floor furnaces, storage and on-demand water heaters, cooktops, ovens, clothing dryers, and other less common products. Commercial cooking equipment and boilers have been studied to a limited extent. Liquefied natural gas interchangeability evaluations generally have involved laboratory testing in which appliances are operated with (and when appropriate adjusted using) the natural gas historically used in an area, then operated with "substitute" mixtures that simulate LNG blends. Test matrices usually included dilutions of the LNG mixtures with nitrogen, carbon dioxide (CO_2), or air. Testing has been conducted primarily using adaptations of standard procedures, such as the Z21 protocols of the American National Standards Institute (ANSI). Evaluation of exhaust pollutant concentrations resulting from gas quality variability has been reported almost exclusively for stabilized burner operation. The focus of many past studies has been on identifying locally acceptable gas quality limits for safe operation of installed appliances; the limits typically have been expressed in terms of heating

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[1] http://www.energy.ca.gov/research/reports_pubs.html
[2] http://eetd.lbl.gov/publications

value, Wobbe number, and sometimes composition – for example, the fractions of non-methane hydrocarbons and/or inert components (nitrogen, carbon dioxide). In some cases, limits have been developed based on industry standard interchangeability indices (refer to Singer 2007 and references therein for additional details). In cases pertaining to LNG introduction, concern typically has focused on how the installed appliance population that has been operating with domestic or continental natural gas will respond to the introduction of re-vaporized LNG that has higher heating value, higher Wobbe number, and higher concentrations of non-methane hydrocarbons (such as ethane, propane, and butanes).

The extent and severity of effects from distribution and use of LNG depend on the properties of the delivered fuel. In light of recently approved tariff limits, it is expected that LNG supplies will be diluted with nitrogen to achieve a Wobbe number of ≤ 1385 British thermal units per standard cubic foot (Btu/scf) in California and ≤ 1400 Btu/scf in other parts of the United States. Results of previous studies (Singer 2007) suggest the following potential effects associated with distribution and use of LNG blends with Wobbe number as high as 1385–1400 Btu/scf:

- Problems with ignition or flame stability are highly unlikely for the vast majority of appliance burners; problems may result for burners that are already unstable due to poor adjustment, malfunction, and/or deterioration.
- The effect on energy/thermal efficiency is likely to be very small for most applications; the direction of change will vary among appliances.
- Performance problems may be encountered in specialized applications that are mostly associated with commercial use (e.g., timed processes like a chain-drive char-broiler).
- Output and performance temperatures (e.g., of furnace air) may increase in many cases without substantially affecting overall device performance.
- Exhaust CO concentrations will increase for some appliances; the largest increases will occur in appliances that are currently improperly adjusted or otherwise operating with low or insufficient amounts of combustion air.
- NO_X concentrations in exhaust gases may increase slightly for appliances with partially premixed burners and increase substantially for appliances with full or lean premix burners and no feedback control; full premix burners with advanced control of the fuel-air mixture may not be affected.

1.2. Gaps Address by Recent LBNL Study of Residential Appliances

The recent experimental study reported in Singer et al. (2010) aimed to fill gaps in the prior knowledge base. The first gap related to emissions of formaldehyde and ultrafine particles (ultrafine particles are those that have operational (aerodynamic or optical) diameters of < 100 nanometers (nm). These pollutants are known to be emitted from natural gas appliances and are linked to significant health impacts (ASTDR 1999; IARC 2006; Knol et al. 2009; Vinzents et al. 2005). Singer et al. (ibid) used the metric of particle number (PN) concentration since a shift in gas quality could lead to a very large increase in the number of particles emitted without producing a discernible change in mass emissions of elemental carbonaceous material. Preliminary range-finding experiments indicated substantial emission rates of formaldehyde and/or particles (indicated by particle number) from some appliances.

The second gap related to appliance and burner operational cycles. Past studies reported gas quality effects on emissions during stabilized burner operation. Yet it has been known for some time that emissions of some pollutants can be much higher during transient operational modes (burner ignition, device warm-up, and intermittent firing of burners). Transient modes can comprise a substantial fraction of operational time and pollutant emission rates during these periods can be different than rates during stable operation. Singer et al. (ibid) reported examined and reported pollutant levels for appliance operating cycles that included transient effects.

The third gap related to newer and emerging technologies. New standards and goals for energy efficiency and low emissions force changes to appliance designs and influence the market. At the time of the earlier research, there had been a recent rise in market share for on-demand water heaters and condensing furnaces, and regulations were already in place to require ultra low-NO_X water heaters in some parts of California. Singer et al. reported results for emerging technologies that were available for purchase at the time. The current study examines several new water heater technologies that have entered the market in the intervening years.

The fourth major gap was in the study of installed, in-use appliances. There had been several substantial efforts to examine installed appliance performance, including some that followed the introduction of new gas supplies. These efforts typically included an evaluation of basic operational safety and in some cases CO emissions, yet there is little if any publicly available documentation from these field examinations.

The gaps described above translated to the objectives of the prior LBNL experimental effort described by Singer et al. (ibid).

1.3. Results of 2010 LBNL Study of Residential Appliances

Singer et al. (2010) conducted experimental evaluations on five conventional technology storage water heaters, including three in-use devices installed in homes and two new units tested in the laboratory, and six on-demand (tankless) water heaters, including three tested as installed in homes and three new units tested in the laboratory.

The water heaters were operated through test cycles designed to capture key variations and transient features of actual use patterns. Storage water heaters were operated to produce two 15-min periods of continuous burner firing with at least 15 min of standby prior to each burn. On-demand water heaters were operated by drawing water at 1, 2, and 4 gallons per minute for 7-minute periods, with 6 min periods between water draws.

Water heaters were operated with line-supplied natural gas from PG&E as a baseline fuel and with simulated LNG blends. Blends were formulated to achieve Wobbe numbers of roughly 1420, 1390, and in later experiments, 1360 (as calculated from fuel heating value in British thermal units [Btu] per standard cubic foot). Pacific Gas & Electric line gas used in experiments typically was in the range of 1320–1340 Wobbe numbers. Two variations each of the 1420 and 1390 Wobbe number fuels were used. Early lab experiments used site-mixed blends, whereas all field and many lab experiments used premixed cylinders.

The early 1420 Wobbe number blend was roughly 5.8% ethane, 3.0% propane, and 1.1% butanes with a balance of (90.1%) methane. The early 1390 Wobbe number fuel was the 1420 blend diluted with roughly 1.6% nitrogen. Premixed blends were 12% ethane, 1.6% propane, and 86.4% methane (1420 Wobbe number); 8.0% ethane and 92% methane (1390 Wobbe number); and 7.9% ethane, 1.9% nitrogen and 90.2% methane (1360 Wobbe number).

Measurements of pollutant concentrations, carbon dioxide (CO_2), and oxygen levels in exhaust streams were used to calculate air-free concentrations; fuel properties were used to also calculate emission factors related to fuel energy consumption using the units of nanogram of pollutant emitted per Joule of fuel energy. Results were obtained for carbon monoxide (CO), nitrogen oxides (NO_X), nitric oxide (NO), nitrogen dioxide (NO_2, estimated as the difference between NO_X and NO), the number of particles over individual burns (PN), and for formaldehyde (HCHO) over multi-burn cycles. Size-resolved measurements showed that the vast majority of particles were less than 100 nanometers in aerodynamic diameter; that is, they were ultrafine particles.

Bivariate (assuming one variable depends on only one other variable) and multivariate (assuming one variable depends on multiple other variables) linear models were employed to estimate the magnitude and statistical significance of fuel Wobbe number effects on emission rates independent of other factors. Formal statistical analyses were conducted to estimate the effect of fuel Wobbe number on each pollutant emission factor. The dependence of emissions on fuel Wobbe number was assumed to be linear and was calculated per 50 Wobbe number increase. These results can be scaled to estimate impacts for any level of Wobbe number increase up to the bounds of the experimental assessment; that is, to fuels with a Wobbe number of roughly 1420.

The tables below provide summary results including the number of experiments conducted at each fuel Wobbe level, as well as the measured pollutant emission rates with PG&E line gas, and the estimated percent change in emissions for a 50-unit increase in fuel Wobbe number. This increment represents the shift from fuels distributed in much of Northern and Southern California in the years just prior to the study (with typical Wobbe number of roughly 1335) to the regulated limit of 1385 Wobbe number. In the tables, the abbreviation “ns” indicates that no statistically significant trend was observed for a given pollutant on a given burner; lack of a discernible trend is independent of the magnitude of Wobbe number change.

Relative to all appliances examined in the study, the five storage water heaters generally had low emission rates of all pollutants other than NO_X. Fuel WN had a small impact on NO_X for three of the storage water heaters tested: emissions increased on two and decreased for the third. One prominent finding that was not an intended focus of the study was the starkly different pollutant emissions of tankless and storage water heaters. Tankless units had emissions of carbon monoxide and formaldehyde that were orders of magnitude higher on average compared with storage water heaters. This finding suggests that a large shift to tankless technology (in the absence of controls on these emissions) could dramatically impact the baseline emission inventory for carbon monoxide and formaldehyde from natural gas water heating. A major increase in the population of tankless water heaters (with burner technology similar to that evaluated in this study) would also make the carbon monoxide and nitrogen oxide inventories for residential gas water heating much more sensitive to changes in gas quality.

Table 1. Summary of experiments and results[1] for storage water heaters reported in Singer et al. (2010).

ID Site[2]	Description and rating	Age	Fuels (n)	NO_X (ng/J)	CO (ng/J)	NO_2 (ng/J)	HCHO (ng/J)	PN (10^4/J)
WH01 Lab-A	40 gal FVIR; pilot; natural draft; std. burner; 40 kBtu/h	new	PG&E 1390 1420	**13.6** **-2.5%**	0.1 (ns)	**0.30** **-67%**	no data	3.2 (1.0-8.4)
WH01 Lab-B	See above	-	PG&E 1420	26.3 (ns)	*-0.7* *-0.07*	*1.55* *-1%*	0.03 (ns)	23 (15-40)
WH02 Res2	40 gal, pre-FVIR; pilot; natural draft; std. burner; 40 kBtu/h	6	PG&E 1390 1420	**31.9** **+3.7%**	*-0.4* *+0.2*	2.22 (ns)	no data	0.3 (-1.3 to 2.6)
WH03 Res4	50 gal pre-FVIR; piloted; natural draft; std. burner; 40 kBtu/h	4	PG&E 1390 1420	24.0 (ns)	**-1.0** **+0.5**	*0.37* *+65%*	no data	4.7 (2.8-8.9)
WH04 Lab	40 gal induced draft; FVIR; spark igniter (no pilot); 40 kBtu/h	new	PG&E 1390 1420	**29.0** **+2.8%**	**2.0** **-0.5**	**2.18** **-21%**	*0.05* *-14%*	8.7 (4.7-14)
WH05 Res8	42 gal pre-FVIR; pilot; natural draft; std. burner; 34 kBtu/h	17	PG&E (2) 1390 1420	28.8 (ns)	**0.4** **+2.2**	**1.67** **+24%**	0.05 (ns)	22 (11-51)

[1] For NO_X, CO, NO_2 and HCHO, first value in each cell is full burn emission rate with PG&E line gas. For NO_X, NO_2, and HCHO, percent change is shown below the full burn emission rate is for 50 Btu/scf increase in fuel WN adjusted for effect of oven temperature; for CO, the emissions change for a 50 Btu/scf increase in fuel WN is shown below the average full burn CO emission rate; Values shown for PN are the median and range of particle number counts for individual burns across all fuels; changes shown only for p-values ≤ 0.15; p ≤ 0.05 in bold (broader limits for HCHO, see text of report). Low p-values indicate statistically significant results

[2] n = number of experiments; Res = residence, identified by number. WH01 experiments repeated because of low NO_X results in first set; WN = Wobbe number; NOx = nitrogen oxide; CO = carbon monoxide; NO_2 = nitrogen dioxide; HCHO = formaldehyde; PN = particle number; ns = not significant

As a group, the tankless water heaters had much higher emissions of CO, NO_2, and formaldehyde when compared to the storage water heaters. And for each of these pollutants, several of the tankless water heaters showed significant sensitivity to fuel WN. NO_X emissions were lower in many of the tankless water heaters but much more sensitive to fuel WN. Two of the six tankless water heaters—including the one with highest baseline carbon monoxide—had carbon monoxide increase by about 110 percent, and a third had carbon monoxide increase by 22 percent per 50 Wobbe number fuel increase. Nitrogen dioxide was found to increase by 3–19 percent per 50 Wobbe number increase in five of six tankless water heaters and decrease by 3 percent in the sixth. Formaldehyde was estimated to decrease by 5–22 percent for a 50 Wobbe number change in five of six tankless water heaters.

Table 2. Summary of experiments and results[1] for tankless water heaters, adjusted for effect of water flow rate, from Singer et al. (2010).[1,2]

ID Site	Venting and burner range (kBtu/h)[3]	Age	Fuels WN (n)	NO_X (ng/J)	CO (ng/J)	NO_2 (ng/J)	HCHO (ng/J)	PN (10^4/J)
TW01 Lab	direct vent; 19-180	<1[3]	PG&E (2) 1390, 1420	**24.0** **+4.6%**	**50** **-13%**	**8.9** **+2.8%**	**1.5** **-22%**	0.8 (0.1-6.7)
TW02 Res5	ducted; 20-185	6	PG&E 1390, 1420	**16.0** **+45%**	**37** **+109%**	**6.6** **+19%**	*0.72* *-16%*	0.1 (-0.4-0.8)
TW03 Res6	direct vent; 37-165	3	PG&E (2) 1390, 1420	**18.0** **+3.0%**	87 (ns)	**6.1** **+5.3%**	*2.4* *-5.0%*	0.1 (-0.6-14)
TW04 Res7	direct vent; 15-199	4	PG&E (2) 1390, 1420	**9.0** **+31%**	**19** **+22%**	**4.0** **+17%**	**0.25** **-8.6%**	3.1 (0.4-16)
TW05 Lab	direct vent & ducted; 19-199	new	PG&E(2) 1390, 1420	**21.0** **+7.2%**	**47** **-1.3%**	**8.5** **+5.8%**	2.0 (ns)	11.4 (0.9-27)
TW06 Lab	direct vent & ducted; 25-180	new	PG&E (3) 1390 1420 (2)	**31.0** **+17%**	**434** **+111%**	*7.9* *-3.0%*	*0.24* *-6.4%*	1.0 (0.0-15)

[1] For NO_X, CO, NO_2 and HCHO, first value in each cell is mean full burn emission rate with PG&E line gas measured at 1, 2 and 3 or 4 gallons per minute. For NO_X, NO_2, and HCHO, percent change, adjusted for effect of water flow rate, is shown below the full burn emission rate is for 50 Btu/scf increase in fuel WN adjusted for effect of oven temperature; for CO, the emissions change for a 50 Btu/scf increase in fuel WN is shown below the average full burn CO emission rate; Values shown for PN are the median and range of particle number counts for individual burns across all fuels; changes shown only for $p \leq 0.15$; $p \leq 0.05$ in bold (broader limits for HCHO, see text of report). Low p-values indicate statistically significant results. Values shown for PN are the median and range of particle number counts for individual burns across all fuels.

[2] n = number of experiments; Res = residence, identified by number. WH01 experiments repeated because of low NO_X results in first set; WN = Wobbe number; NOx = nitrogen oxide; CO = carbon monoxide; NO_2 = nitrogen dioxide; HCHO = formaldehyde; PN = particle number; ns = not significant

[3] All TWs had ribbon burners with induced draft combustion. All but TW01 were certified to meet 40 ng/J NO_X std. TW01 purchased in 2001 and used for approximately 6 months in portable classroom, then stored at LBNL until used in this study.

1.4. Objectives of Current Study

The objective of this research was to quantify the impact of increasing fuel Wobbe number on pollutant emissions from advanced technology residential water heaters. Performance of "ultra low-NO_X" water heaters that comply with South Coast Air Quality District Rules 1121 and 1146.2 was of particular interest. The advanced technologies that were examined in this study are described below in Section 2.1.3.

2.0 Methods

2.1. Overview of Experimental Approach

The basic approach of this study was to quantify pollutant emissions from storage and on-demand water heaters during operation over defined cycles using line gas from PG&E and simulated LNG blends. Operating cycles were developed to capture features of typical operation using methods developed previously (Singer et al., 2010). In order to capture transient and steady-state pollutant emissions, we averaged emissions for the entire duration of burner operation (full-burn) and during the last 5-miutes of burner operation. Simulated LNG blends were selected based on considerations of composition – i.e., the relative quantities of methane, ethane, propane, butane, and nitrogen (N_2) – and Wobbe number. Water heaters were selected based on considerations of technology and availability. All experiments were conducted in a laboratory at LBNL. Most of the evaluated appliances were donated new. Details are provided in the sections that follow.

2.1.1. Interchangeability Metrics

The primary measures of impact used in this study are exhaust concentrations and emission rates of the following air pollutants: carbon monoxide (CO), nitrogen oxides (NO_X), nitric oxide (NO), nitrogen dioxide (NO_2), formaldehyde (HCHO), and Acetaldehyde. For this study nitrogen dioxide is estimated as the difference between NO_X and NO as measured by a chemiluminescence detector. Pollutant concentrations measured in burner exhaust are normalized to reference conditions of dry, air-free (no excess oxygen) using measurements of O_2 and carbon dioxide (CO_2). Pollutant emission rates are normalized to fuel energy (nanograms of pollutant emitted per Joule of fuel energy, or ng/J); these are calculated from the measured concentrations of pollutants, O_2, and fuel properties.

2.1.2. Fuel Gas Compositions

Both domestic natural gas and LNG vary in composition and energy content, expressed as either heating value or Wobbe number. The Wobbe number – equal to the higher heating value divided by square root of specific gravity – is a measure of the fuel energy supply rate for a burner with orifice fuel control and fixed air supply. Based on the review of past research, this metric is taken as the primary fuel variable for this study. Characteristics of the composition, including the relative concentrations of ethane, propane, butane, and inert components (nitrogen and CO_2) are secondary considerations.

The basic approach for this study was to evaluate each test burner with a core set of four fuels, including PG&E line gas plus three simulated LNG blends. PG&E line gas was treated as the baseline fuel against which potential LNG effects were compared. By recommendation of the California Energy Commission contract manager and the Project (technical) Advisory Committee (PAC), this study examined the interchangeability of LNG blends with Wobbe numbers that exceed the range expected in California in coming years, consistent with previous research (Singer et al., 2009). The primary LNG test blends for all laboratory experiments had Wobbe numbers of 1365, 1396, and 1426 Btu/scf. The Wobbe number for the PG&E line gas varied from 1344 to 1365 Btu/scf.

The fuel blends used for the core set of four experiments are shown in Table 3. For all water heaters, two experiments were conducted using the PG&E line gas on two different days. The PG&E gas line information was taken from the PG&E website for line J01 (PG&E, 2013). The website provided information on the nitrogen (N_2) and carbon dioxide (CO_2) content, but did not include the composition of methane, ethane, propane, butane, or other higher carbon-chained fuels. Specific information about the fuel used in each experiment throughout the study is listed with each water heater summary in Chapters 3 and 4.

Table 3. Properties of fuels used during experiments

Fuel ID:	PG&E[1]	1C[2]	1N[2]	3C[2]
Methane (%)	-	92.0 ± 1	90.4 ± 1	86.4 ± 1
Ethane (%)	-	8.0 ± 1	7.9 ± 1	12.0 ± 1
Propane (%)	-	-	-	1.6 ± 1
Butanes & C5+ (%)	-	-	-	-
Nitrogen (%)	0.60 ± 0.12	-	1.7 ± 1	-
Carbon dioxide (%)	0.74 ± 0.05	-	-	-
Heating value (Btu/scf)	1031 ± 10	1076	1058	1131
Wobbe number (Btu/scf)	1349 ± 5	1396	1365	1426

[1] Mean composition and properties ± standard deviation taken from PG&E Line Gas J01.
[2] Composition of fuel blends and corresponding properties supplied by Praxair.

2.1.3. Appliance Burner Selection

Residential natural gas water heaters traditionally have been divided into the two broad categories: (1) “Storage” designs that preheat and store water in a large tank and (2) On-Demand or “Tankless” appliances that heat water only when needed. The latter have multiple burners with modulating air and fuel supplies to accommodate a range of water flow rates. Recently introduced “Hybrid” models combine the features of Tankless designs with a small storage tank typically less than 2-gallons.

Within each broad category, water heaters are also differentiated by how the combustion products are vented, how the combustion air is introduced to the heater, and whether or not water in the combustion exhaust is condensed to extract more useful heat energy. Storage water heaters typically vent combustion products by relying on buoyant rise of the hot plume (natural draft); using a small fan to overcome additional resistance from heat transfer baffles in the central flue (fan assist); or using a large fan that is designed to positively pressurize the venting system throughout operation (power vent). On-Demand water heaters use a power-vent to exhaust combustion products. Combustion air can either be drawn from the area around the water heater or provided through ducting that can be connected directly to the outdoors for water heaters that are located indoors; the latter are referred to as “direct vent”. Most combinations of the three venting variations, two combustion air supply variations and condensing or non-condensing combustion systems are available in both Storage and On-Demand designs, though some combinations are much more common than others.

To address air quality concerns, most areas of California require that water heater meet strict limits on nitrogen oxides (NO_X) emissions. The most recently promulgated standards are generally referred to as requiring “Ultra-low NO_X” burners; the previous standards are generally described as requiring “Low NO_X” burners. Water heaters with specific technologies were chosen for testing and requested from the manufacturer. Of the twelve water heaters requested, we were able to secure donations for ten and had to purchase the remaining two water heaters. Eight of the water heaters were storage type and four were On-Demand water heaters, including one hybrid. Tested water heaters included the following technology variants:

- 2 Ultra-low NO_X, natural draft storage water heaters
- 2 Ultra-low NO_X, power vent storage water heaters
- 2 Energy Star qualified, induced draft, low NO_X storage water heaters
- 2 Condensing storage water heaters, one ultra-low NO_X and one low-NO_X
- 2 Non-condensing ultra-low NO_X on-demand water heaters
- 1 Condensing ultra-low NO_X on-demand water heater
- 1 Hybrid, ultra-low NO_X on-demand water heater

2.2. Experimental Equipment and Analytical Methods

2.2.1. Overview of Experimental Equipment

The major components of the experimental apparatus used in this study included the following:

- Fuel gas supply and monitoring
- Instrumentation to measure combustion products and pollutants
- Dilution system for formaldehyde sampling
- Exhaust sample collection and conditioning
- Instrumentation to measure appliance operation and sampling conditions
- Data acquisition system

These components are described in the subsections that follow.

2.2.2. Fuel Gas Supply and Monitoring

PG&E line gas was used as the baseline test fuel for all laboratory experiments. Gas cylinders provided by Praxair were used to supply the three LNG blends shown in Table 3. The backpressure regulator for the LNG blends was set to maintain a supply pressure of about 7 in. H_2O. From the backpressure tee, the LNG blend supply line connected to a tee to the supply system for the appliance; the other side of this tee was connected to the PG&E distribution network. Ball valves allowed fuel to be supplied either from the LNG blends or the PG&E

distribution system. Downstream of this tee, fuel flowed through a factory-calibrated temperature-compensating dry gas meter (American Meter AC250-TC) and a dry test meter (Singer DTM-115) en route to the appliance. Most of the transfer lines were ¾-inch steel; the final connection was made with a flexible stainless steel connector sized for the appliance. Fuel flow rate was calculated from timing the fuel flow rate during burner operation using the Singer dry test meter dial (1-L) and a stopwatch. Table 4 provides a summary of the measurement equipment used for all water heaters.

Table 4. **Measurement equipment for all experiments.**

Measured Quantity	**Location(s)**	**Device(s)[1]**
Fuel volume & flow	Fuel flow to appliance during burner operation	American Meter Division, Singer DTM-115 dry gas meter, CFH-Air @ ½" diff, 5 psi W.P., 1- and 1/10-liter dials; flow rate timed by stopwatch
Water volumetric flow	Before water heater at the cold water inlet prior to expansion tank	Omega FTB-4607 pulse meter used for measurement before water heater
Water volumetric flow	After water heater at the hot water supply	A rotameter with ±2% accuracy; used only for on-demand water heater testing
Differential pressure between dilution tube and room	Dilution tube	8 Channel Automated Performance Testing (APT) system
Temperature, air	Air inlet near water heater	Precision NTC thermistor (APT)
Relative humidity	Air inlet near water heater	Thermostat polymer based capacitance RH sensor (APT)
Flue Temperature	Varies with water heater	Thermocouple (J-Type), insulated wire, Omega

[1] APT: Automated Performance Testing System, Energy Conservatory, Minneapolis, MN (energyconservatory.com); American Meter (americanmeter.com), obtained via Miners & Pisani, San Leandro, CA; McMaster-Carr rotameter (http://www.mcmaster.com/); Omega Engineering, Stamford, CT (omega.com)

2.2.3. Instrumentation for Measuring Combustion Products

Instrumentation used for time-resolved measurements of gaseous analytes is listed in Table 5. A Horiba PG250 was used to measure CO, CO_2, O_2, and NO in the exhaust stream of the appliance. In the dilution tube, NO was monitored using the Thermo 42i. A calibration curve, containing several different concentrations of NO/N_2 mixtures, was used for calibration of the Thermo 42i. The dilution ratio was determined by dividing the direct NO measurement from the PG-250 by the dilution tube NO measurement from the Thermo 42i. An EGM-4 was used to measure CO_2 in the lab air used for the dilution system. All instruments were operated for a minimum of one hour and then calibrated prior to conducting the first experiment of the day.

In March 2013, the PG-250 gas analyzer was returned to Horiba for service due to a clogged pump. When the PG-250 returned, it displayed cross-interference problems between the CO and CO_2 analyzers. In a standard nondispersive infrared (NDIR) instrument, a chopper wheel is mounted in front of the absorption detector to continually correct for the offset and gain of the NDIR analyzer. The chopper wheel allows infrared energy to pass through two cells, a reference cell containing a non-absorbing gas such as nitrogen and a sample cell containing the gas of interest. The difference in energy absorbed between these two cells produces an AC signal proportional to the energy difference. Because CO and CO_2 have overlapping infrared absorption spectra, cross-interference in the basic NDIR technique can occur.

In the PG-250, the CO_2 analyzer uses two pyroelectric element sensors to measure light absorbed by CO_2 and light from the reference cell (i.e. light without a non-absorbing gas). The difference between these two signals yields a CO_2 signal and dividing the CO_2 signal by the reference signal corrects for fluctuations due to contamination. The CO_2 signal is then converted to a concentration output. The CO detector is composed of a MAIN side for measuring and a COMP side for compensation for cross-interference. The MAIN side reads the absorption signal from the sampled gas while the COMP side measures the signal of the interfering component, in this case CO_2. The signals are sent to the CPU where they are put through “a number of calculations” (as described in the instrument documentation) to isolate the signal from CO. When calculating the CO signal, the CPU overcompensated for CO_2 interference in its “calculations,” outputting negative values of CO when sampling gas mixtures containing CO_2 but no CO.

In order to correct our measured emissions for this overcompensation error, emissions measurements for known gas mixtures were recorded and a surface fit was generated to correct the measured CO emissions for all water heaters tested after March 2013. A detailed description of the surface fit correlating measured values of CO to actual values of CO with CO_2 present is described in the following section.

Table 5. Instrumentation and calibration levels for gaseous analytes.

Equipment[1]	Analyte	Sample location	Method	Range	Calibration levels & range	Linearity/ Drift[5]
Horiba PG-250	CO_2	Exhaust stream[4]	Non-dispersive infrared	0–5% to 0–20%	0, 5.0% @ 1-10%	1% of full scale
	O_2	Exhaust stream[4]	Paramagnetism	0–5% to 0–25%	0, 16.0% @ 0-25%	
	CO	Exhaust stream[4]	Non-dispersive infrared	0–200 ppm to 0–5000 ppm	0, 32 ppm @ 0-200 ppm	
	NO	Exhaust stream[4]	Chemiluminescence	0–25 ppm to 0–2500 ppm	0, 20.2 ppm[2] @ 0-100 ppm	
Thermo 42i	NO & NO_X	Dilution tube	Chemiluminescence	0–0.05 ppm to 0–100 ppm	0, 1.2 ppm[2,3] @ 0-10 ppm	1% of full scale
PPSystems EGM-4	CO_2	Lab air in lab	Non-dispersive infrared	5000 ppm	Factory calibrated	< 1% of span conc.

[1] 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).

[2] Calibrated from mixture of NO in N_2.

[3] Prior to conducting all experiments, the Thermo 42i was calibrated using 2.4 ppm of NO. The instrument's accuracy was verified by comparing measured values with known NO in N_2 mixtures of 2.4 ppm, 1.9 ppm, 1.4 ppm, 1.2 ppm, and 0.96 ppm NO.

[4] Exhaust sample measured 12 inches into either exhaust vent or water heater flue, depending on the water heater configuration, prior to the addition of dilution air.

[5] Indicators of accuracy; span drift is typically provided for a 24-hour period. If values for linearity and drift differ, larger value is presented.

2.2.4. Correcting for carbon monoxide emission measure by the Horiba PG-250

As described in the previous section, the Horiba PG-250 overcompensated for the CO_2 interference in the CO signal, resulting in lower CO emission measurements. In order to correct for this overcompensation error, emissions measurements for known gas mixtures were recorded and a surface fit was generated to correct the measured CO emissions. Table 6 shows the calibrated gas concentrations along with the measured Horiba CO and CO_2 emissions. Using Matlab, a surface fit of the data was generated for measured CO values less than zero and values greater than zero. Measured CO values less than zero were fit to a second order polynomial described by:

$$\begin{aligned} \mathrm{CO_{Act}[ppm]} = {} & \mathrm{A_1 + A_2(CO_2[\%]) + A_3(CO_{Meas}[ppm]) + A_4(CO_2[\%])^2} \\ & \mathrm{+ A_5(CO_2[\%])(CO_{Meas}[ppm]) + A_6(CO_{Meas}[ppm])^2}, \end{aligned} \tag{1}$$

where the constants and their corresponding 95% confidence intervals are shown in Table 7. This polynomial fit gave an R^2 of 0.999 and a root mean square error (RMSE) of 0.28.

For measured CO values greater than zero, a linear surface fit was used, as shown by,

$$\mathrm{CO_{Act}[ppm]} = \mathrm{a_1} + \mathrm{a_2}(\mathrm{CO_2}[\%]) + \mathrm{a_3}(\mathrm{CO_{Meas}[ppm]}). \qquad (2)$$

Coefficients for Equation (2) and their corresponding 95% confidence bounds are shown in Table 7. This linear fit gave an R^2 of 0.998 and an RMSE of 1.2.

Measured CO emissions presented for water heaters tested after March 2013, which include four storage water heaters and four on-demand water heaters, have been adjusted using these surface fit equations.

Table 6. Listed calibration CO concentrations and measured CO and CO_2 concentrations from Horiba Gas Analyzer.

Measured CO_2 (%)	Measured CO (ppm)	Calibration CO (ppm)
-0.30	0.00	0.00
-0.03	31.00	30.00
-0.03	30.00	30.00
-0.02	62.00	61.08
0.00	104.00	101.80
0.01	1.00	0.00
5.24	-16.00	0.00
5.26	-15.00	0.00
5.50	0.00	7.60
5.51	7.00	15.30
5.47	15.00	26.70
5.38	30.00	38.20
5.22	46.00	53.40
5.20	69.00	75.40
9.87	76.00	91.62
10.06	-30.00	0.00
10.13	-3.00	15.00
10.38	13.00	30.50
10.41	24.00	40.70
10.59	3.00	20.00
10.72	31.00	50.90
13.40	-22.00	10.00
13.55	-22.00	10.00
13.63	-22.00	10.00
15.98	-35.00	6.25

Table 7. Coefficients for CO-CO_2 surface fit equations with 95% confidence bounds.

Coefficient	Coefficient Value	95% Confidence Bounds
A_1	0.1813	(-0.4454, 0.8079)
A_2	0.9548	(0.6065, 1.303)
A_3	0.3186	(0.2066, 0.4305)
A_4	0.07099	(0.03272, 0.1093)
A_5	0.03751	(0.01533, 0.05974)
A_6	0.00413	(0.0006651, 0.007594)
a_1	-0.2197	(-1.761, 1.321)
a_2	1.739	(1.574, 1.904)
a_3	0.9817	(0.9573, 1.006)

2.2.5. Dilution System for Aldehyde Sampling and Analysis

Formaldehyde and acetaldehyde emission rates were determined from time-integrated samples collected on XPosure Aldehyde sampler (Waters Corp., product WAT047205, waters.com). The samplers contain a silica substrate coated with dinitrophenylhydrazine (DNPH) that reacts with aldehydes in the sample to form derivativees that are extracted with 2 mL acetonitrile. Extracts were analyzed by HPLC (Agilent 1200 Series, agilent.com) with UV diode-array detection at 360 nm, following American Society of Testing and Materials (ASTM) Method Number D 5197. Derivative concentrations were determined by comparison to calibration mixtures. Following sample collection, cartridges were stored in a freezer until extraction and analysis.

Because the XPosure Aldehyde samplers are sensitive to moisture content and a large byproduct of combustion is water, we used a dilution sampling system that mixes a small flow of exhaust gas with a much larger flow of air. The dilution sampling system was constructed following the general design of Lipsky and Robinson (Lipsky and Robinson, 2005). In the system, inlet and outlet flows are controlled and balanced to create a slight vacuum that draws sample air. The diluted sample is drawn from the outlet end of the tube through four bulkhead union ports, as shown in Figure 1. The copper tube shown at the center is connected to the exhaust blower fan. Other tubes are connected to analytical instrumentation. The copper tube in the upper left quadrant is clean dilution air supply from the building compressor. This is the same dilution tube used in the experiments described by Singer et al. (2010).

For all experiments, supply air to the dilution tube was provided at pressure by the building compressed air system (lab air), and dilution tube exhaust flow was provided by a vacuum pump. The dilution system is capable of ratios ranging from 10–200. Dilution ratios for the appliance experiments were typically in the range of 10–20. The dilution ratio was determined directly by dividing the concentration of NO in the primary exhaust stream (from which the dilution system draws its sample) and from the diluted air stream. Lab air and room air formaldehyde and acetaldehyde measurements were measured to ensure they contained negligible amounts of aldehydes.

Aldehyde samples were collected from the exhaust stream and from the lab air. The background air concentration was used in the calculation of a formaldehyde emission rate, as described in Section 2.4. The aldehyde sample(s) were sampled continuously for each experiment (i.e., one aldehyde sample per fuel test per water heater). The flow rates of the peristaltic pumps used in the aldehyde sampling system were measured during each sampling event. Prior to each experiment, the flow in and out of the dilution tube was set to obtain the desired sample dilution. Formaldehyde samples were collected after the dilution tube at rates of about1 LPM for the duration of the test. Exact formaldehyde sampling rates are provided in each water heater summary.

In this study, dilution ratios were determined by measurement of NO for the following reasons: (1) background concentrations were low relative to combustion exhaust in both ambient and dilution air, and (2) the chemiluminescence analyzers used to measure NO operate accurately over a large dynamic range.

Figure 1. **Dilution sampler inlet configuration. Front view shows clean dilution air supply (copper pipe) and inlet sample tube (thin, curved stainless steel tube) wrapped with heater. Dark circles on copper pipe behind end cap are supply ports for dilution air in tube. Photo at right shows turbulence-inducing baffles and outlet of sample tube.**

2.3 Experimental Protocols

This section describes the operational protocols employed for the experimental evaluation of fuel interchangeability for residential water heaters. The operational elements included the following:

- Appliance installation and configuration

- Calibration of gas analyzers
- Burner operating protocols (including pre-conditioning)

2.3.1. Appliance Installation and Configuration

All water heaters were installed in the test facilities at LBNL used for LNG interchangeability and energy efficiency experiments. The laboratory test bay was constructed to accommodate both storage and On-Demand water heaters. The test bay included a water supply system and outflow water was routed to a laboratory sink. Exhaust venting for storage and On-Demand water heaters were built to exhaust combustion gases into the laboratory exhaust air system. Water heaters drew room air for combustion. Schematics of sampling configurations for the main water heater technologies are provided in the figures below; detailed photographs of sampling configurations are provided with the individual burner summaries in Chapters 3 and 4.

For each experiment, the following variables were recorded and monitored: flue temperature, flue emissions (including CO, CO_2, NO, and O_2), dilution tube pressure, dilution tube emissions (including NO and NO_x), ambient temperature, relative humidity, ambient CO_2.

Prior to conducting experiments, we tested each water heater to ensure it was operating as expected. These pre-experimental tests included operating the burner for a series of burn cycles while monitoring emissions and flue or vent temperature. Storage water heaters were operated for a minimum of two 20-minute burn cycles. On-Demand water heaters were operated at 1, 2, and 4 GPM for a minimum of 10 minutes at each flow rate. PG&E line gas was used for all pre-experimental tests.

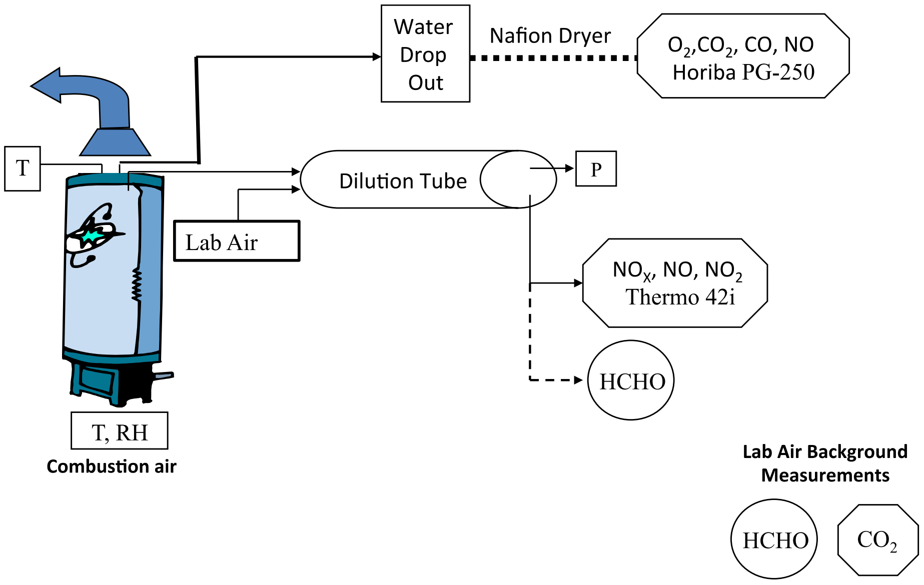

Figure 2. Pollutant sampling configuration for natural draft storage water heaters.

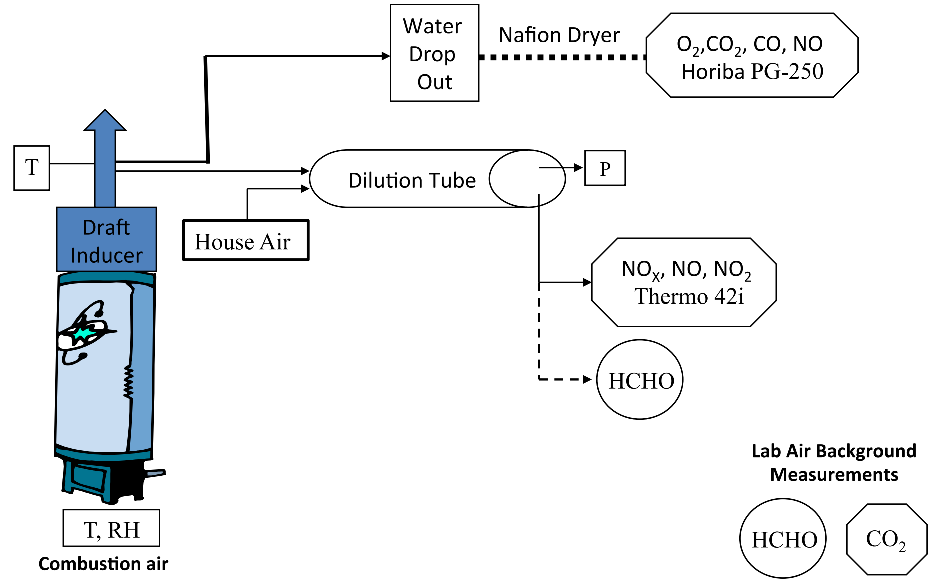

Figure 3. Pollutant sampling configuration for induced draft storage water heaters. Draft inducer location varies with water heater, but emissions are always sampled after the draft inducer.

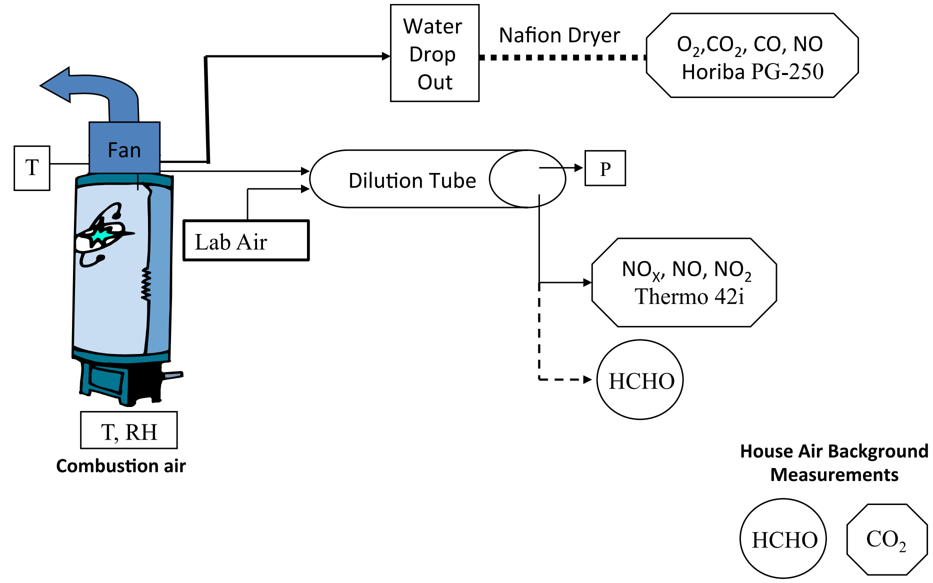

Figure 4. Pollutant sampling configuration for power vent storage water heaters. Emissions are sampled prior to the fan.

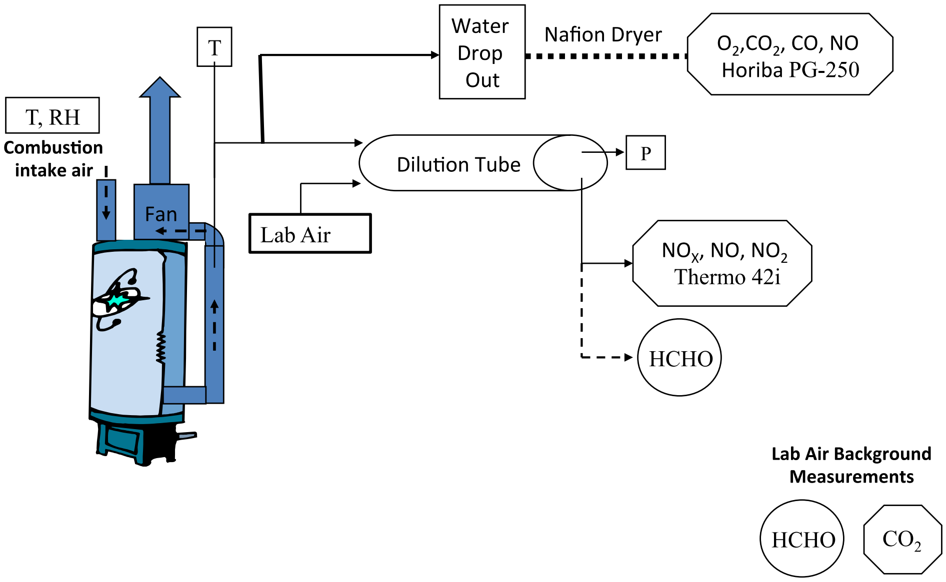

Figure 5. Pollutant sampling configuration for condensing storage water heaters.

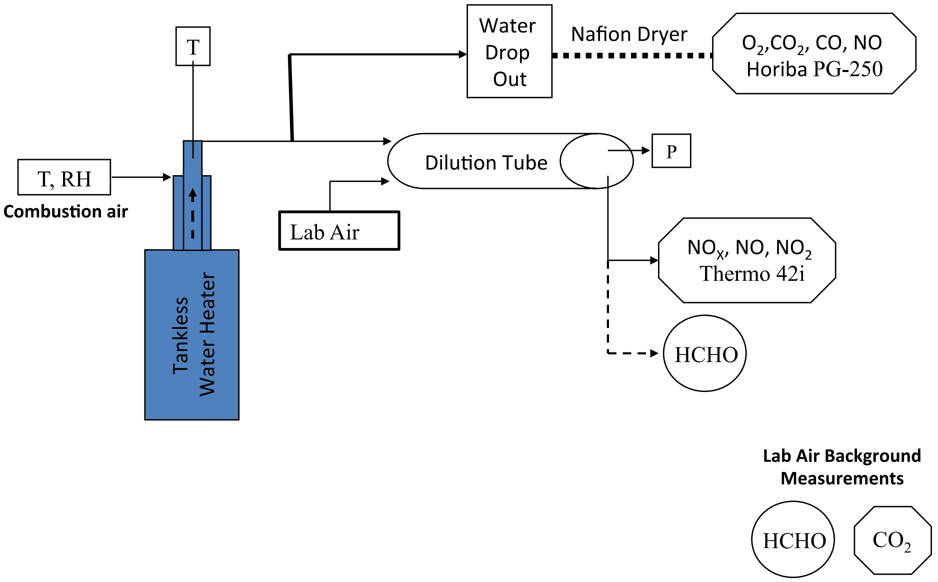

Figure 6. Pollutant sampling configuration for on-demand water heaters AT01 and AT02. Vent is a concentric vent.

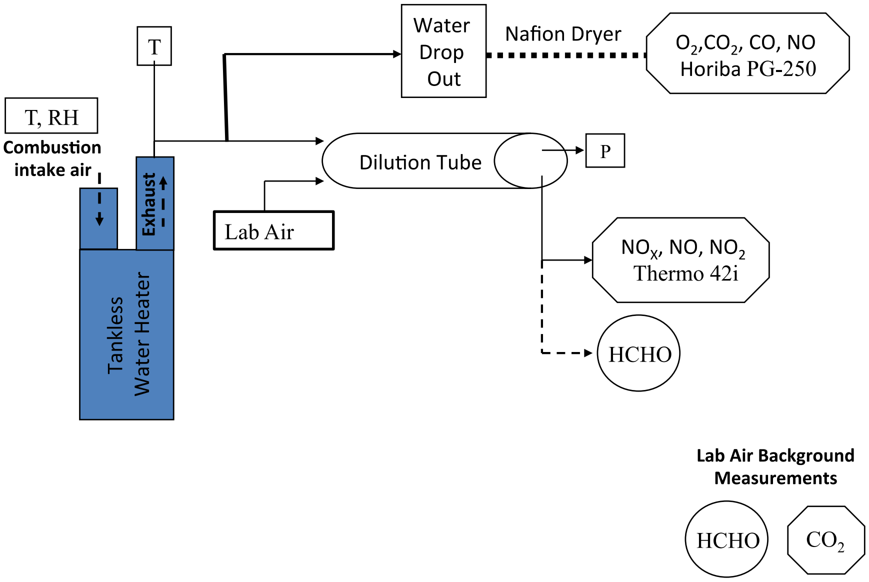

Figure 7. Pollutant sampling configuration for on-demand and hybrid water heaters AT03 and AT04.

2.3.2. Calibrations

Gas analyzers were calibrated on each day experiments were conducted. Certified calibration gases were used for calibration. Ultra-zero air and ultra high purity (UHP, 99.999%) nitrogen were used to zero the Thermo 42i and Horiba PG-250, respectively. For listed ultra-low NO_x water heaters, the Thermo 42i was calibrated using 1.2 ppm NO. For water heaters that were not listed as ultra-low NO_x, the Thermo 42i was calibrated using 2.4 ppm NO. The accuracy of the Thermo 42i was verified prior to each experiment by comparing measured values with known NO in N_2 mixtures of 2.4 ppm, 1.9 ppm, 1.4 ppm, 1.2 ppm, and 0.96 ppm NO. These mixtures were created by using a gas divider and blending the certified 2.4 ppm NO calibration gas with ultra high purity nitrogen. The gas divider allows 10% to 90% dilution of calibration gas with air or nitrogen. All calibration gases were placed into calibration bags to simplify transportation to the instrument. Two types of bags were used: Cali-5-Bond (calibrated.com/bags) and SKC Series 232 Tedlar bags (skcinc.com/prod/232-01). Bag size was selected to provide a sufficient quantity of gas to allow multiple field calibrations. Calibration bags were emptied and refilled frequently to maintain purity of the calibration gas. Further details of the calibration gases used for the Thermo 42i and the Horiba PG-250 are shown in **Table 8**.

Table 8. Calibration gases used for LNG interchangeability experiments

Analyte	Conc.	Rated Precision	Balance	Supplier	Direct	Gas Divider
CO_2	5%	±2%	Air	Airgas	X	
O_2	16%	±1%	N_2	Scott-Marrin	X	
CO	32 ppmv	not avail.	N_2	Scott Specialty	X	
NO	20.2 ppmv	±1%	N_2	Scott Specialty	X	
NO	2.4 ppmv[1]	±1%	N_2	Airgas	X	
NO	1.9 ppmv[2]	±1%	N_2	Airgas		X
NO	1.4 ppmv[2]	±1%	N_2	Airgas		X
NO	1.2 ppmv[2]	±1%	N_2	Airgas		X
NO	0.96 ppm[2]	±1%	N_2	Airgas		X

[1] The supplier's analysis rated this as 2.4 ppm nitrogen oxides, 2.34 ppm NO.

[2] The gas divider was used to create this concentration by blending the 2.4 ppm NO gas cylinder with ultra pur nitrogen.

2.3.3. Burner Operating Cycles

Burner experimental operating cycles were developed with the objective of capturing key features of realistic use patterns with a total cycle time that would allow completion of three to four experiments – with setup and calibration – in a single day. These experiments were not designed to test the compliance of the water heaters to standards and codes. Appliances generally were operated through multiple burns, each following a designated cooling period. Water heaters were operated for at least one day prior to conducting experiments.

For all water heaters, a purge burn, lasting at least 5-minutes, was conducted prior to starting the experiments. The purpose of the purge burn is to flush the system and ensure that the first experimental burn uses the test fuel. A purge burn was conducted even if fuel was not switched from previous experiments. During the purge burn, the dilution ratio was adjusted to the desired range using NO measurements from the Horiba PG-250 and the Thermo 42i. The dilution ratio was adjusted to ensure the dilution tube was under a slightly negative pressure (around -100 Pa) and the Thermo 42i NO reading was in the same range as the calibration gas. After the purge burn, each water heater was turned off and allowed to cool at least 10-minutes prior to conducting experiments.

When testing storage water heaters, water was drawn either prior to or during an experiment to ensure the burner would stay on for the duration of the experiment. For each storage water heater, two 15-minute experimental burns were conducted and intended to serve as replicates. In between each burn, the burner was shut off and allowed to cool for 8-minutes. The water heater burner was turned on and off by using the thermostat or the power button, if available.

For On-Demand water heaters, hot water flow was measured before and after the water heater. During installation, a rotameter was placed at the hot water outlet of the water heater and was used to instantaneously check desired flow rate for each burn. The hot water flow rates were checked during the purge burn of each experiment.

On-Demand water heaters were operated at three different flow rates intended to cover the vast majority of typical use. The standard flow rates were 1, 2, and 4 gallons per minute (GPM), with 8-minute burns following 10-minute cooling periods. Prior to the start of formal experiments, burners usually were operated through a series of short range-finding burns to determine appropriate dilution ratio, instrument range, and calibration levels. When fuels were switched, burners were fired for short periods to purge the previous fuel from external and internal transfer lines. The burners were turned on and off by opening and closing the solenoid controlling the hot water supply.

2.4 Data Reduction and Calculation of Metrics

The data obtained from each experiment included the following:

- Fuel supply parameters including supply pressure, appliance manifold pressure, and volumetric fuel use rates
- Ambient and combustion air temperature (T) and relative humidity (RH)
- Sampling system conditions, including exhaust air T at the point of pollutant sampling, dilution tube vacuum
- Time-resolved concentrations of exhaust constituents (O_2, CO_2, CO, NO, NO_X, and NO_2) measured during periods of burner operation and background periods
- Time-integrated concentrations of formaldehyde and acetaldehyde in exhaust and background air

With the exception of aldehyde samples and gas composition, all data noted above were sampled in 2-second intervals. Raw data were saved by the Labview system as tab-delimited text files. For each experiment, individual data files were imported into and analyzed by a Matlab code to produce results as described below. The following sections describe the calculations performed on the primary data to obtain the results that are presented in Chapters 3 and 4.

2.4.1 Fuel Supply Parameters

Fuel flow rate (ft^3 h^{-1}) calculated from fuel consumption measured for each burn divided by time of burn. The fuel consumption was measured using the dry gas meter and a stopwatch, as described in Section 2.2. The firing rate was determined by multiplying the calculated fuel flow rate and higher heating value of the fuel. Fuel flow rate and firing rate were calculated over the entire burn and the final 5 min of each burn.

2.4.2 Ambient and Combustion Air Conditions

Temperature and relative humidity of the combustion supply air generally were consistent through the course of an experiment. Temperature and relative humidity were averaged over the burner-operation period.

2.4.3 Pollutant Emission Metrics

Pollutant concentrations were averaged over varying periods to calculate concentrations at reference conditions (air-free and 3% O_2) and emission rates. For all pollutants other than the aldehydes, concentrations were averaged over the final five minutes of burner operation as an indication of burner operation under stable conditions, and for the entirety of each burn including the initial, transient period. Formaldehyde emission rates were calculated for the period of sampling including all burns but not the purge burns; this calculation required the average exhaust CO_2 measured over the same period. Pollutant concentrations thus were averaged over the periods described above and for one or two background periods to account for any pollutants contained in combustion air. Background air CO_2 was measured throughout an experiment with a separate analyzer, i.e., not the combustion exhaust analyzer.

2.4.4 Pollutant Concentrations Normalized to Reference Conditions

Pollutant concentrations were calculated for the reference conditions of air-free (0% O_2) over the last 5-minutes of burner operation and for the entire period of each burn. The adjustment to air-free concentrations can be done using either the measured O_2 or the measured CO_2 and calculated theoretical dry CO_2 to adjust other analytes to dry, air-free conditions. Both approaches should provide approximately the same answer. However, results can differ based on imprecision in the measurements of O_2 and CO_2. For all analytes (i.e., CO and NO_X) in this report, air-free concentrations were determined using the measured O_2. The air-free concentration C_i of pollutant i was calculated using the measured O_2 concentration as,

$$\mathrm{C_i(@0\%O_2)} = \left(\mathrm{C_{i,msd}} - \mathrm{C_{i,bkg}}\right)\left[\frac{20.95}{20.95 - \mathrm{O_{2,msd}}(\%)}\right]\mathrm{DR}, \tag{3}$$

where $C_{i,msd}$ is the concentration of i, $O_{2,msd}$ is the concentration of O_2 (both measured over the period of interest), $C_{i,bkg}$ is the background concentration of pollutant i, and DR is the dilution ratio. For analytes sampled at the same location as O_2, DR = 1. For analytes measured in the dilution sampling system, DR is the measured ratio of NO or NO_X in the primary exhaust sample stream and in the dilution system.

The theoretical value of air-free exhaust CO_2 can be calculated from the composition as follows:

$$\text{Theoretical } \mathrm{CO_2}(\text{air} - \text{free}) = \frac{\sum \mathrm{n_i[CO_2]}}{\sum \mathrm{n_i N_{total,i}}}, \tag{4}$$

where n_i are the mole fractions of i fuel components, $[CO_2]_i$ are the moles of exhaust CO_2 produced per mole of i in the fuel, and $N_{total,i}$ are the total moles of exhaust gas per mole of i in the fuel (assuming complete combustion). Air-free CO_2 can be expressed on a wet or dry basis (H_2O included or excluded from products). The PG-250 analyzer that was used to collect CO_2 has an internal water removal system to remove the humidity that was present in dilute sampling. A more substantial water-removal system was used when sampling direct exhaust streams. Thus, the analytes measured with the PG-250 (CO_2, CO, NO) should always be considered on a dry basis.

The Thermo 42i NO_X analyzer sampled from a dilute stream with no water removal. The concentrations of NO, NO_2, and NO_X from this analyzer can be adjusted to a dry basis using the measured humidity, converted to a mole fraction in air. Alternately, the NO_X values can be presented without adjustment; these differ by approximately 2%–4% from the values on a dry basis. Theoretically, the discrepancy between wet and dry exhaust NO_X values should be consistent for all experiments with a given appliance and sampling configuration.

Table 9 provides values for $[CO_2]_i$ and $N_{total,i}$ for the major fuel components. One should note that for the PG&E line gas, the percentages of carbon fuel chains (i.e. methane, ethane, propane, etc.) were not available. Therefore, we assumed that the theoretical moles of CO_2 produced were 1.0 (i.e. the fuel is predominately methane).

Table 9. Calculation of exhaust CO_2 production from natural gas components

Component	**Balanced Equation**	**$[CO_2]_i$**	**$N_{total,i}$ (dry)**	**$N_{total,i}$ (wet)**
Methane (CH_4)	$CH_4 + 2(O_2+3.78N_2) \rightarrow CO_2 + 2H_2O + 2(3.78)N_2$	1	8.56	10.56
Ethane (C_2H_6)	$C_2H_6 + 3.5(O_2+3.78N_2) \rightarrow 2CO_2 + 3H_2O + 3.5(3.78)N_2$	2	15.23	18.23
Propane (C_3H_8)	$C_3H_8 + 5(O_2+3.78N_2) \rightarrow 3CO_2 + 4H_2O + 5(3.78)N_2$	3	21.90	25.90
Butane (C_4H_{10})	$C_4H_{10} + 6.5(O_2+3.78N_2) \rightarrow 4CO_2 + 5H_2O + 6.5(3.78)N_2$	4	28.57	33.57
Pentane (C_5H_{12})	$C_5H_{12} + 8(O_2+3.78N_2) \rightarrow 5CO_2 + 6H_2O + 6.5(3.78)N_2$	5	35.24	41.24
CO_2	$CO_2 \rightarrow CO_2$	1	1	1
N_2	$N_2 \rightarrow N_2$	0	1	1

Pollutant measurements can be adjusted to air-free values ($C_{i,AF}$) using the ratio of measured to theoretical (calculated) air-free CO_2:

$$C_i(\text{air} - \text{free}) = C_{i,AF} = \left(C_{i,msd} - C_{i,bkg}\right)\left[\frac{CO_2(\text{air} - \text{free})}{CO_{2,msd} - CO_{2,bkg}}\right]DR, \qquad (5)$$

where $CO_{2,bkg}$ is the value measured in the combustion supply air (generally around 500 ppm or 0.05%) and $C_{i,bkg}$ is the background value of species *i* measured before and after burner operation (generally insignificant compared with $C_{i,msd}$), and DR is the dilution ratio. For analytes sampled directly with CO_2, DR = 1. For analytes measured in the dilution sampling system, DR was the measured value for this system. Background CO_2 was generally much smaller than sample CO_2 in direct exhaust sampling (CO_2 = 4%–10%).

2.4.5 Pollutant Emission Rates Normalized to Fuel Energy

Emission rates were normalized to fuel energy to account for variations in energy density associated with fuel composition changes. The calculation is presented in Equation 5, which includes both the input terms and the required unit conversions:

$$E_i\left[\frac{\mu g}{KJ}\right] = \frac{\left(\dfrac{10^{-6}\text{mol i}}{\text{mol air}}\right)}{\left(\dfrac{10^{-2}\text{mol } CO_2}{\text{mol air}}\right)}\left(\frac{\text{mol } CO_2}{\text{MJ fuel}}\right)\left(\frac{\text{gram i}}{\text{mol i}}\right)\left(\frac{\text{MJ}}{10^3\text{KJ}}\right)\left(\frac{10^6\mu g}{\text{gram}}\right)DR. \qquad (6)$$

The first term on the right-hand side of the equation is the ratio of background-corrected (or air-free) concentration of analyte *i* (in ppm) to the concentration of *CO_2* (in percent). The second term on the right-hand side is calculated based on fuel composition, as shown below in the following equations. The third term on the right-hand side is the molecular mass of the analyte. The fourth and fifth terms are unit conversions. Dilution ratio enters as above: for pollutants sampled alongside exhaust CO_2 a value of 1 is used; for pollutants sampled in the dilution system, the value is calculated using the ratio of NO or NO_X measured in both direct and dilute exhaust streams. This equation is written for the case of near-complete combustion; it can be more generically formulated to consider exhaust carbon – including both CO and CO_2 – rather than carbon dioxide alone. The distinction is important only in cases of very high CO emissions, on the order of thousands of parts per million.

Rearranging Equation (6) yields the following:

$$\mathrm{E_i}\left[\frac{\mu\mathrm{g}}{\mathrm{KJ}}\right] = \left(\frac{\mathrm{C_{i,AF}[ppm]}}{\mathrm{Theor.\,CO_2[\%]}}\right)\left(\frac{\mathrm{mol\ CO_2}}{\mathrm{MJ\ fuel}}\right)(\mathrm{M_i})(10^{-1})\mathrm{DR}. \tag{7}$$

For illustration, consider experiments using a natural gas with 95.8% methane, 2.14% ethane, 0.29% propane, 0.10% butanes, 0.85% N_2, and 0.84% CO_2; this fuel has a Wobbe number of 1333 Btu/scf, a theoretical CO_2 dry exhaust fraction of 0.1183, and 1.11 moles (mol) CO_2 per MJ of fuel energy. Inserting these values into Equation (7) above, and considering the case of CO (molecular mass of 28 grams per mole [g/mol]) sampled directly (DR = 1) yields the following:

$$\mathrm{E_i}\left[\frac{\mu\mathrm{g}}{\mathrm{KJ}}\right] = \left(\frac{\mathrm{C_{i,AF}[ppm]}}{11.83}\right)(1.11)(28)(10^{-1})(1) = (0.262)\mathrm{C_{i,AF}[ppm]}.$$

For this fuel, a dry air-free concentration of 1000 ppm corresponds to a CO emission rate of 262 ng/J.

2.4.6 Aldehyde Emission Rates Normalized to Fuel Energy

This section demonstrates the calculation of formaldehyde and acetaldehyde emission rates. The objective was to calculate the mass (μg) of formaldehyde (HCHO) or acetaldehyde emitted per quantity of fuel energy used (MJ); the logic of the calculation is demonstrated for formaldehyde:

$$\frac{\mu\mathrm{g\ HCHO}}{\mathrm{MJ\ fuel\ energy}} = \left(\frac{\mathrm{mol\ HCHO}}{\mathrm{mol\ CO_2}}\right)\left(\frac{\mathrm{mol\ CO_2}}{\mathrm{MJ\ fuel\ energy}}\right)\left(\frac{\mu\mathrm{g\ HCHO}}{\mathrm{mol\ HCHO}}\right). \tag{8}$$

The first term on the right-hand side of the equation is the relative concentration of HCHO to CO_2 in the exhaust stream. CO_2 is measured in the primary exhaust stream (direct in flue or from outlet of collection hood). Formaldehyde is measured alongside CO_2 in the sampling manifold for the collection hood exhaust stream and measured in the dilution system for appliances with concentrated exhaust. The calculation of formaldehyde is complicated by the need to account for removal of HCHO in the dilution air for dilution system sampling and the consideration that the formaldehyde sample may include periods when the burner was not operating.

2.4.7 Formaldehyde Measured in the Dilution Sampling System

Presented first is the more complicated situation in which HCHO was measured in the dilution sampling system. To calculate the HCHO concentration in the primary exhaust stream where

CO_2 is measured, the calculation considers contributions to the HCHO measured in the dilution system. The description starts with a mass balance for HCHO in the dilution stream:

Mass of HCHO in dilution tube =

mass contributed by combustion (when burner on) +

mass in excess combustion air +

mass from room air pulled into sample line when burner off +

mass from dilution air.

The first three terms represent contributions via the sample inlet. The generic calculation considers the time-averaged concentration of formaldehyde in the sample flow into the dilution system (C_{sample}), which results from the three contributions listed. In Equation 13, Q_{sample} is the flow rate through the sample inlet. $C_{dil.air}$ is the concentration of HCHO in dilution air, which is equal to $(1-\eta)C_{ambient}$ where η is the removal efficiency of HCHO in the supply air.

$$\mathrm{C_{tube}} = \frac{\mathrm{C_{sample} Q_{sample}} + \mathrm{C_{dil.air} Q_{dil.air}}}{\mathrm{Q_{sample}} + \mathrm{Q_{dil.air}}} = \frac{\mathrm{C_{sample} Q_{sample}}}{\mathrm{Q_{sample}} + \mathrm{Q_{dil.air}}} + \frac{\mathrm{C_{dil.air} Q_{dil.air}}}{\mathrm{Q_{sample}} + \mathrm{Q_{dil.air}}} \qquad (9)$$

The flow terms can be expressed in terms of the measured dilution ratio (DR), which is equal to the total flow over the sample flow (Q_T / Q_{sample}) where $Q_T = Q_{sample} + Q_{dil.air}$. DR was calculated from the ratio of NO or NO_X concentrations measured in the direct exhaust and in the dilution tube. $Q_{dil.air}$ was measured with the rotameter reading on the clean air supply to the dilution system.

Equation (9) can be restated using the measured dilution ratio, as follows:

$$\mathrm{C_{tube}} = \frac{\mathrm{C_{sample}}}{\mathrm{DR}} + \mathrm{C_{dil.air}}\left(1 - \frac{1}{\mathrm{DR}}\right) \qquad (10)$$

Equation (10) may be rearranged to get the following:

$$\mathrm{C_{sample}} = (\mathrm{DR})\mathrm{C_{tube}} - (1-\eta)(\mathrm{DR}-1)\mathrm{C_{ambient}} \qquad (11)$$

Using the approximation that $Q_{dil.air}/(Q_{sample}+Q_{dil.air})$ is close to one, Equation (11) can be rearranged as follows:

$$\mathrm{C_{sample}} = (\mathrm{C_{tube}} - (1-\eta)\mathrm{C_{ambient}})\mathrm{DR} \qquad (12)$$

The equations above apply when the dilution air is being drawn from the room or other ambient source. However, for all experiments presented in this report, the dilution air was drawn from the on-site compressed air supply (lab air). Initially, room air formaldehyde was sampled along with the lab air, but the HCHO concentration in the lab air was found to be below the room air concentrations. Therefore, we stopped sampling formaldehyde in the room air and assumed contributions of formaldehyde from lab air were negligible. Applying this assumption to Equation (12) yields the following:

$$\mathrm{C_{sample}} = (\mathrm{C_{tube}})\mathrm{DR} \tag{13}$$

Because HCHO in the lab air is negligible, the HCHO in the exhaust sample flow to the dilution system, C_{sample}, comes from two sources: production related to combustion, C_{exh}, and formaldehyde entering with combustion air, C_{room}, (excess air plus air entering sample line when burner is off). Note that C_{exh} is the average contribution from combustion to the air entering the sample inlet of the dilution system not the concentration in pure exhaust (since all of the burners tested had excess air in the flue). Therefore, the average exhaust concentration can be calculated as follows:

$$\mathrm{C_{exh}} = \mathrm{C_{sample}} - \mathrm{C_{room}} \tag{14}$$

Here C_{exh} is the time-averaged contribution to the exhaust stream from combustion; this term was divided by the time-averaged combustion contribution of CO_2 in the exhaust stream over the period of HCHO sampling. The ratio of HCHO to CO_2 concentrations yields the first term on the right side of Equation (8), shown below in more detail:

$$\left[\frac{\text{moles HCHO}}{\text{moles CO}_2}\right] = \frac{\mathrm{C_{exh(HCHO)}}\left[\frac{\text{moles HCHO}}{\text{moles air}}\right]}{\left(\mathrm{CO_{2,exh}} - \mathrm{CO_{2,bkg}}\right)\left[\frac{\text{moles CO}_2}{\text{moles air}}\right]} \tag{15}$$

Here the CO_2 concentration is adjusted by subtracting the amount entering in combustion and excess air. The adjustment was small when there was little excess air, but increased with the amount of time sampled with the burner off and with the excess air level. The adjustment for ambient air was typically less than 500 ppm or 0.05%; that is, a small fraction of exhaust CO_2 in the range of 2%–12%. Fuel gas may have CO_2 at up to the 1% by volume level. Considering the stoichiometry of approximately 10 volumes of air needed to combust 1 volume of fuel, this translates to an upper limit of about 0.1% in the exhaust. Excess air reduces this contribution.

3.0 Storage Water Heater Results

Eight storage water heaters were used for the LNG interchangeability experiments. The following table provides a summary of the storage water heaters tested and key aspects of their respective technologies. Published information and results for each storage water heater are provided in the following sections.

Table 10. Storage water heaters evaluated experimentally for fuel interchangeability

ID	Technology[1]	Manufacturer & Model	Serial Number	Rating (Btu/h)	Fuels Evaluated[2]
AW01	Ultra-low NO_X; natural draft; “round” burner; 38 gal	Rheem 22V40FN	RHUN0212U10743	38,000	PG&E (2), 1C, 1N, 3C
AW02	Ultra-low NO_X; natural draft; “cake-pan” burner; 40 gal	A. O. Smith GNR-40	1152T470906	40,000	PG&E (2), 1C, 1N, 3C
AW03	Ultra-low NO_X; power vent; “cake-pan” burner; 40 gal	A. O. Smith GPNH-40	1226T473088	42,000	PG&E (2), 1C, 1N, 3C(2)
AW04	Condensing; “pancake” burner; 50 gal	A. O. Smith Pro-Max GPHE-50	1234M000235	76,000	PG&E (2), 1C, 1N, 3C
AW05	Ultra-low NO_X; power vent; “round” burner; 40 gal	Rheem 42VP40FN	RHUNM191308669	36,000	PG&E (2), 1C, 1N, 3C
AW06	Energy Star qualified, induced draft; “pancake” burner; 29 gal	Rheem XR90 43V30-60	RHLNQ441217522	60,000	PG&E (2), 1C, 1N
AW07	Energy Star qualified, induced draft; “pancake” burner; 40 gal	A. O. Smith Effex GAHH-40	1231A002000	40,000	PG&E (2), 1C, 1N, 3C
AW08	Condensing; ultra-low NO_X; “cylinder” burner; 50 gal	A. O. Smith Vertex 100 GDHE-50	1237M001769	100,000	PG&E (2), 1C, 1N, 3C

[1] Ultra-low NO_X implies the water heater meets SCAQMD rule 1121 for water heaters with ratings less than 75,000 Btu/h or SCAQMD rule 1146.2 for water heaters with ratings greater than 75,000 Btu/h.

[2] One experiment per fuel, except as indicated in parentheses.

3.1 Results for AW01

3.1.1 Summary of Experiments. This ultra low-NO_x, natural draft, storage water heater was purchased new and installed in the test facilities at LBNL used for LNG interchangeability and energy efficiency experiments (see Figure 8). Table 11 provides a summary of the burner information. In November 2012, five experiments were conducted on this unit. Two experiments were conducted on the same day using PG&E line gas (WN=1348) and fuel mixture 3C (WN =1426). On the following day, three experiments were conducted using fuel mixture 1N (WN=1365), fuel mixture 1C (WN=1396), and PG&E line gas (WN=1350). Composition and properties of each fuel are presented in Table 12. Environmental conditions were similar on both days. Pressure at the dry gas meter was 7 inches of water for all fuels tested. Flue temperature was measured 13-inches below the top of the central flue. Emissions measurements were taken in the water heater flue prior to the draft diverter. The burner was turned on and off by switching the dial between temperature setting “B” and pilot.

3.1.2 Summary of Results. Tables and figures that follow provide detailed results from the LNG interchangeability experiments for storage water heater AW01. Overall, CO emission rates during main burner operation were extremely low after the first minute of operation, approaching zero. The sudden drop in signal during the second burn of the line gas test on 11/13/2012 (experiment A004) is due to the burner shutting off because the water in the tank reached the thermostat setting. Water was immediately drained from the tank and the thermostat was turned up in order to restart the burner. After a few minutes of draining, to ensure the burner remained on for the duration of the test, the thermostat was set to its original position (B or 140 deg F). The burner was shut off by turning the dial back to pilot. For each experiment, NO_X was primarily in the form of NO. Full burn emission rates, shown in Table 18, were <1 ng/J for CO, 7-10.5 ng/J for NO_X, 0.04-0.07 ng/J for HCHO, and 0.03-0.04 ng/J for Acetaldehyde. For this water heater, NO_x emissions varied linearly with Wobbe Number, as shown in Figure 14.

Figure 8. **Installation for storage water heater AW01. The dilution tube is shown next to draft diverter resting on top of the water heater behind the copper piping. The Thermo 42i and house-air line are located behind the water heater (not shown).**

Table 11. **Published information for water heater AW01.**

Burner ID	AW01
Burner category	Ultra Low NO_x, natural draft storage water heater
Technology	"Round" burner with pilot; SCAQMD rule 1121-compliant, complies with 10 ng/J NO_x emissions
Appliance manufacturer	Rheem
Model	Fury Ultra Low NO_x (Model 22V40FN)
Serial number	RHUN0212U10743
Capacity	38 gal.
Recovery rating	38.4 gal per h
Energy factor rating	0.60
Design manifold Press	5 in. H_2O
Burner ratings (Btu/h)	38,000

Table 12. Composition of fuels for interchangeability experiments for storage water heater AW01.

Exp.	Fuel	Date	N_2 (%)	CO_2 (%)	HHV (Btu/scf)	Wobbe Number
A001	1C+	11/14/12	0.00	0.00	1076	1396
A002	1N+	11/14/12	1.70	0.00	1058	1365
A003	3C+	11/13/12	0.00	0.00	1131	1426
A004	PG&E*	11/13/12	0.40**	0.68**	1023	1348
A005	PG&E*	11/14/12	0.39**	0.69**	1024	1350

+ All information provided by Praxair.

* Gas quality information provided by PG&E online pipeline data, line J01 (downloaded 11/14/2012).

** Values are given in mol % not volume %.

Table 13. Burner operating parameters for experiments with storage water heater AW01.

Exp.	Burn times		Fuel flow rate ($ft^3 h^{-1}$)		Firing rate (kBtu/h)	
	Burn 1	Burn 2	B1	B2	B1	B2
A001	11:25:10-11:40:02	11:48:26-12:03:26	35.6	35.5	38.3	38.2
A002	10:11:47-10:26:38	10:35:02-10:50:03	35.7	35.3	37.7	37.3
A003	16:51:41-17:07:09	17:14:58-17:29:58	34.8	34.4	39.3	39.0
A004*	15:19:09-15:34:12	15:42:25-15:57:20	36.1	35.2	37.0	36.0
A005	14:19:05-14:34:19	14:43:58-14:58:48	36.4	36.0	37.3	36.9

* For A004 Burn 2, the water thermostat reached temperature and shut off the burner. Water was immediately drained from the tank and the thermostat was turned up in order to restart the burner. The thermostat was turned back down to its original temperature after enough water had been drained to keep the burner on. The burner was shut off by turning the dial back to pilot.

Table 14. Aldehyde measurement times with storage water heater AW01*.

Fuel	Experiment	Date	Aldehyde Start Time	Aldehyde Stop Time	Total Liters Sampled
Lab Air**	-	11/13/12	10:54	13:20	139.9
Lab Air**	-	11/14/12	9:24	11:21	114.0
1C	A001	11/14/12	11:25	12:14	48.5
			11:25	12:14	52.9
1N	A002	11/14/12	10:10	10:57	46.7
			10:10	10:57	49.8
3C	A003	11/13/12	16:52	17:39	44.6
			16:52	17:39	51.9
PG&E	A004	11/13/12	15:19	16:03	43.9
			15:19	16:03	49.5
PG&E	A005	11/14/12	14:20	15:25	64.2
			14:20	15:25	69.9

*Two Aldehyde measurements were taken on the dilution tube for each experiment.
**Aldehyde was measured directly from the lab air supply.

Table 15. Combustion air conditions[1] for experiments with water heater AW01.

Exp.	T, burn 1 (°C)	T, burn 2 (°C)	RH, burn 1 (%)	RH, burn 2 (%)
A001	20.0 ± 0.1	20.3 ± 0.1	44.1 ± <1	43.8 ± <1
A002	19.7 ± 0.1	19.7 ± 0.1	44.7 ± <1	44.6 ± <1
A003	20.2 ± 0.1	20.4 ± 0.1	24.5 ± <1	23.5 ± <1
A004	20.3 ± 0.1	20.6 ± 0.1	34.7 ± <1	32.6 ± <1
A005	20.5 ± 0.1	20.7 ± 0.1	43.5 ± <1	41.3 ± <1

[1] Mean ± standard deviation measured over period of two sampling burns, measured next to water heater near the air intake.

Table 16. Sampling system conditions for experiments with water heater AW01.

Exp.	Flue Temperature[1] (°C)		Dilution Ratio[2]	
	Burn 1	Burn 2	Burn 1	Burn 2
A001	443 ± 10	439 ± 24	18	18
A002	437 ± 20	432 ± 30	17	16
A003	439 ± 30	439 ± 30	17	17
A004	433 ± 20	435 ± 13	16	15
A005	429 ± 17	435 ± 16	17	17

[1] Measured at 13-inches below top of central flue; mean over last 5 min of each burn.
[2] Calculated by comparing NO measured in gas manifold (PG-250) and dilution sampler (Thermo 42i) over last 5 min of each burn.

Table 17. Calculated air-free concentrations (using O_2) over last 5 min of each burn, water heater AW01.[1]

Exp	Fuel	Wobbe	CO (ppm)		NO_2[2] (ppm)		NO_X[2] (ppm)	
			B1	B2	B1	B2	B1	B2
A001	1C	1396	-1	-1	4	4	25	24
A002	1N	1365	-1	-1	4	4	22	21
A003	3C	1426	-1	-1	3	3	27	26
A004	PG&E	1348	-1	-1	2	2	20	18
A005	PG&E	1350	-1	-1	4	4	20	21

[1] Negative value indicates near zero CO and is within instrument linearity (±2% of Full Scale)

[2] Emissions measured from Thermo 42i.

Table 18. Calculated emission rates over entirety of each burn, water heater AW01.

Exp	Fuel	Wobbe	CO (ng/J)		NO_2[1] (ng/J)		NO_X[1] (ng/J)		HCHO (ng/J)	Acetaldehyde (ng/J)
			B1	B2	B1	B2	B1	B2		
A001	1C	1396	0.0	-0.1	1.7	1.6	10.0	9.3	0.05	0.04
A002	1N	1365	-0.1	-0.1	1.6	1.5	8.6	8.4	0.05	0.03
A003	3C	1426	0.0	-0.2	1.1	1.1	10.5	10.5	0.04	0.04
A004	PG&E	1348	0.0	0.1	1.0	0.8	7.5	6.9	0.07	0.04
A005	PG&E	1350	0.0	-0.1	1.5	1.5	8.0	7.9	0.04	0.04

[1] Calculation assumes molecular mass of NO_2 for NO_x (46 g/mol); emissions measured from Thermo 42i.

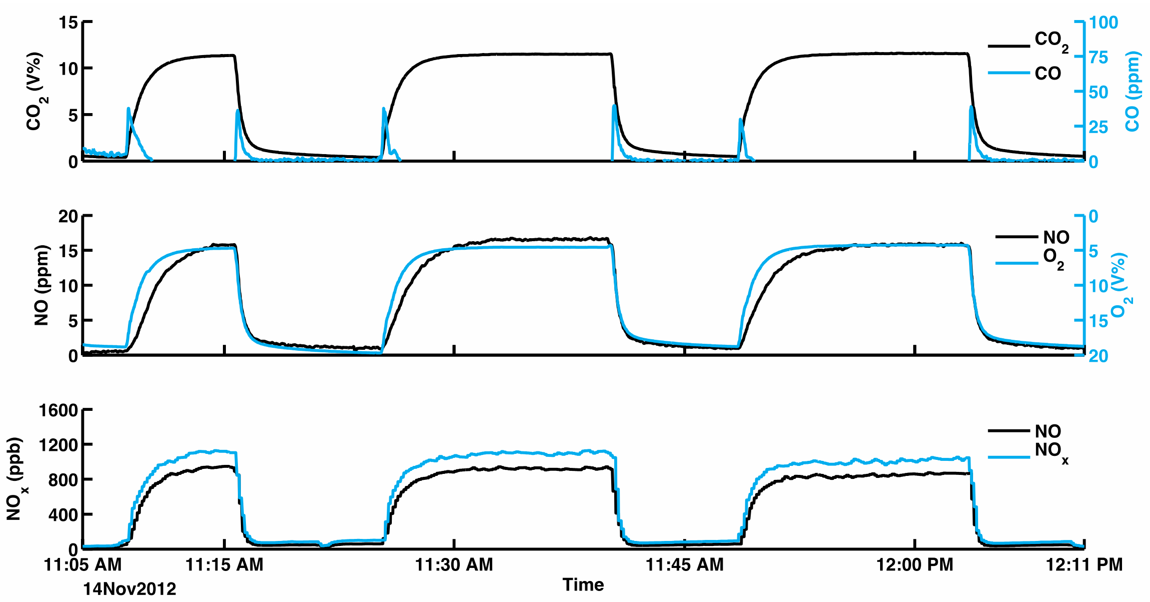

Figure 9. Measured analyte concentrations for storage water heater AW01 with fuel 1C (A001). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn.

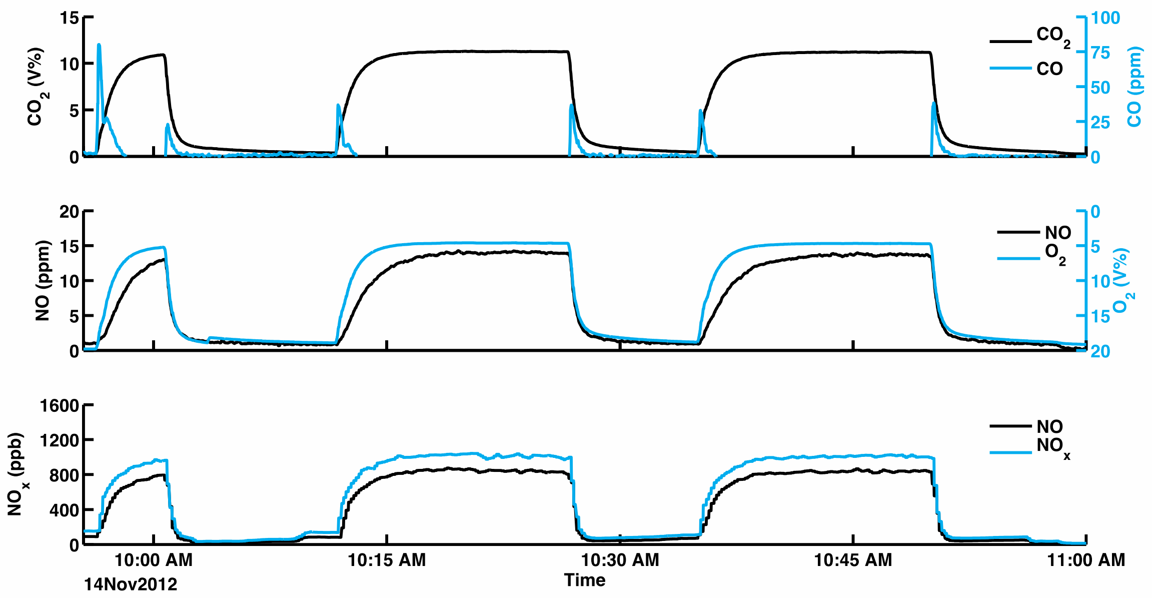

Figure 10. **Measured analyte concentrations for storage water heater AW01 with fuel 1N (A002). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn.**

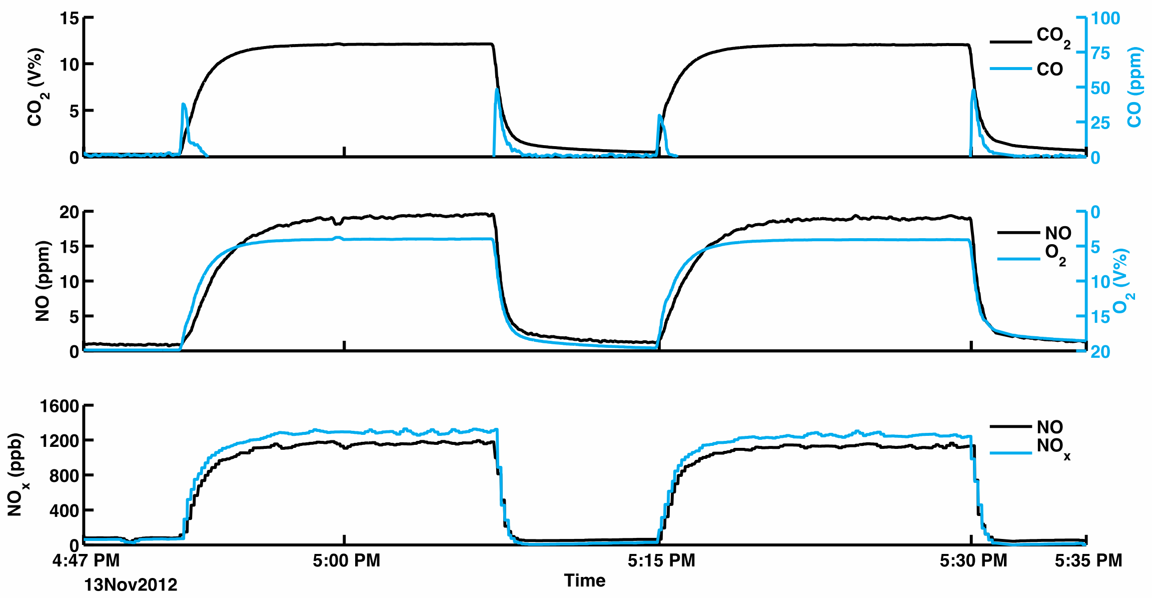

Figure 11. **Measured analyte concentrations for storage water heater AW01 with fuel 3C (A003). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The purge burn was not recorded and is not shown above.**

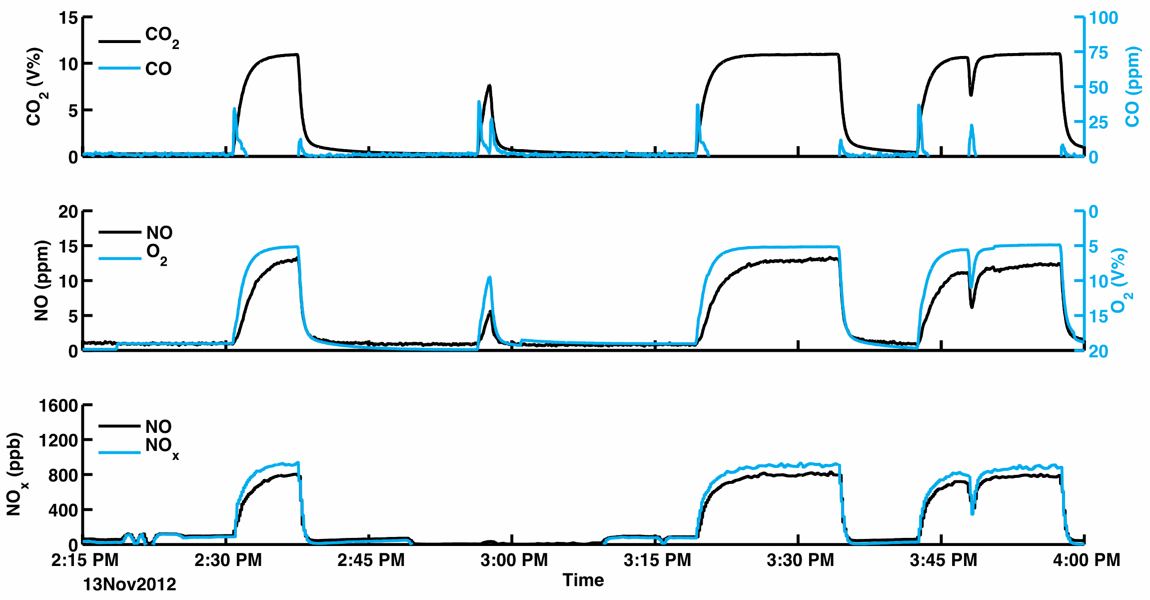

Figure 12. Measured analyte concentrations for storage water heater AW01 with PG&E line gas (A004). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn. The second short peak was a false start. At 3:47 PM, the burner shut off because the water temperature reached thermostat setting. Water was immediately drained and the thermostat setting was increased to force the burner back on.

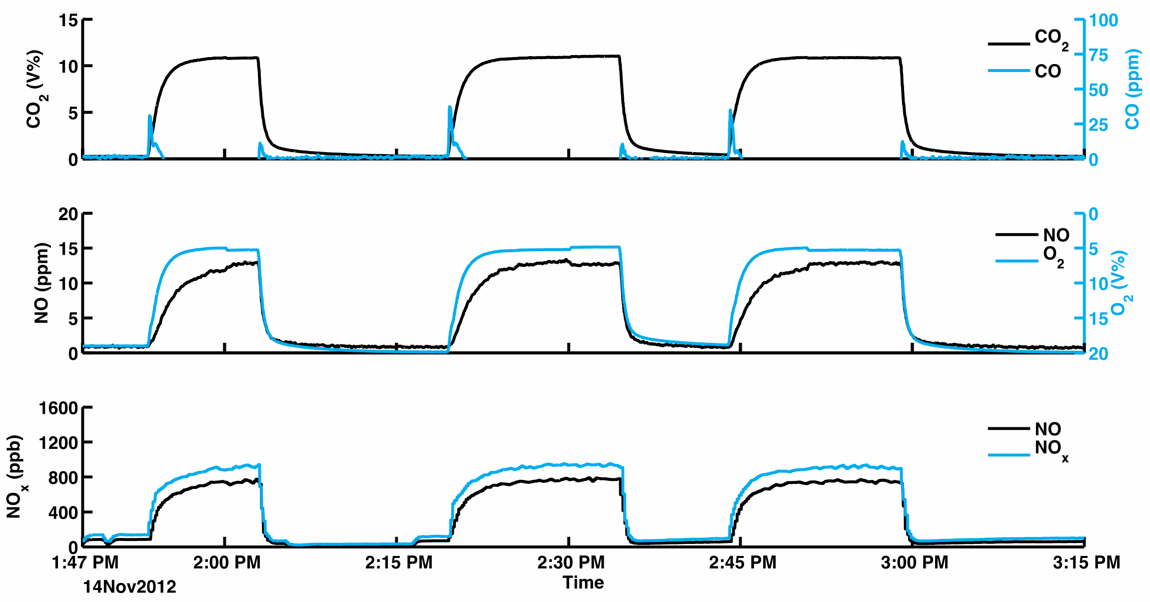

Figure 13. Measured analyte concentrations for storage water heater AW01 with fuel PG&E, repeated (A005). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn.

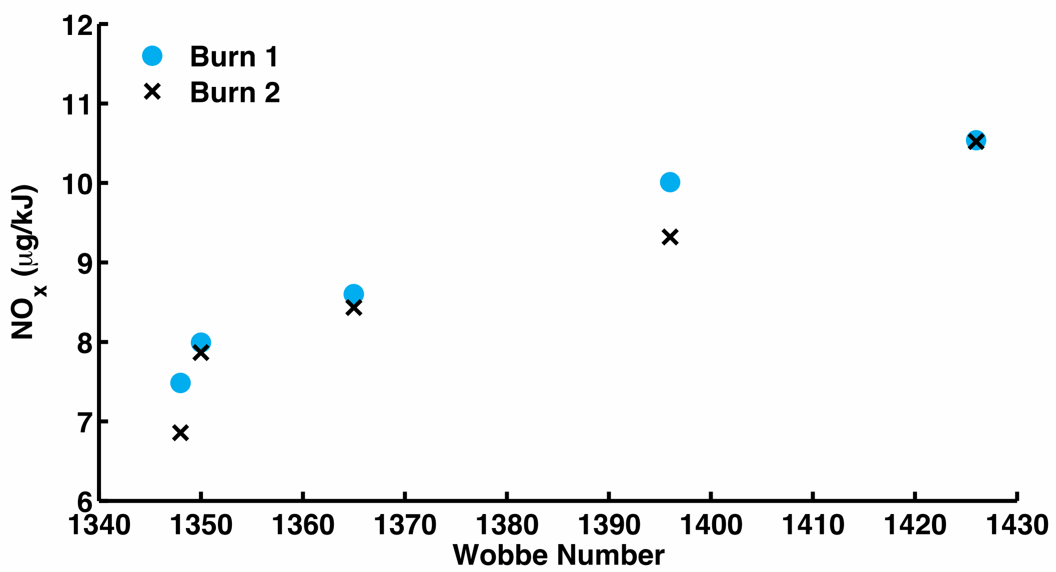

Figure 14. **NO_x as a function of Wobbe Number for storage water heater AW01. The fuels show a linear correlation between NO_x and Wobbe Number for each burn. NOx measurements between burns of same fuels vary slightly.**

3.2 Results for AW02

3.2.1 Summary of Experiments. This ultra-low NO_x, natural draft, storage water heater was donated new and installed in the test facilities at LBNL used for LNG interchangeability and energy efficiency experiments. Table 19 provides a summary of the burner information. When conducting pre-experimental tests, the water heater showed unusually large amounts of CO, a very high flue temperature, emitted a strong odor, and made an unusual whistling noise. We immediately shut down the water heater and reported the problem to A.O. Smith. The technician at A.O. Smith informed us that the fuel orifice installed on the unit was likely too large and sent the correct sized orifice. The technician also stated that during initial operation, the coating in the flue will melt onto the burner and condensation will occur for the first 40 minutes of operation. After receiving the new orifice, we pulled out the burner to find black flue glass imbedded onto the burner (see Figure 15), as predicted by the A.O. Smith technician. After installing the new orifice and replacing the burner, the water heater was operated for 1.5 hours prior to the fuel interchangeability tests. During the 1.5 hour testing period, CO was higher than expected (~8ppm), but after 40 minutes of operation, CO dropped below 1ppm. Condensate continually fell down the flue onto the burner for the duration of the first four experiments, even when the water inside the tank reached the set temperature. At the end of the last experiment, condensate ceased falling on the burner.

In January 2013, five experiments were conducted on this unit. One experiment was conducted on January 25, 2013 using the PG&E line gas (WN=1346). Three days later, on January 28, 2013, an experiment was conducted using fuel mixture 1C (WN =1396). Two days later, on January 30, 2013, three experiments were conducted using fuel mixture 1N (WN=1365), fuel mixture 3C (WN=1426), and PG&E line gas (WN=1347). Ambient temperature was similar on all days. The relative humidity on January 25, 2013 was quite a bit higher (57%) than the other experimental days (~40%). Composition and properties of each fuel are presented in Table 20. Flue temperature was measured 14-inches below the top of the water heater.

3.2.2 Summary of Results. Tables and figures that follow provide detailed results from the LNG interchangeability experiments for storage water heater AW02. Overall, CO emission rates during main burner operation were extremely low after the first minute of operation for all experiments. In some cases when the burner reached steady-state operation, the PG 250 CO reading dropped below zero due to the interference from CO_2, as described in Section 2. The sudden drops in signal during the purge burns on 01/25/2013 and 01/28/2013 are due to the burner shutting off because the tank reached the thermostat setting. We immediately drained water and turned up the temperature to get the burner to ignite. After a few minutes of draining, to ensure the burner remained on for the duration of the test, the thermostat was set to its original position (B or ~140 deg F).

The flame on the burner never reached a “soft blue” color because the water heater continued to spill condensate down the flue onto the burner. On the last day during the last run, the condensation stopped. The manual states that, “Once the water reaches a temperature of 120°F and the tank warms up (usually 1-2 hours), the condensation will stop.” When testing fuels 1C, 1N, and 3C, the pressure in the line through the gas meter was 6 inches of water during operation. For the PG&E line gases, the pressure in the gas meter was 7 inches of water during operation. The drop in pressure between the PG&E line and the gas cylinders is due to the higher demand of fuel from this water heater. When the water heater was not operating, the gas pressure was 7 inches of water for all fuels. For each experiment, NO_X was primarily in the form of NO. Full burn emission rates, shown in Table 26, were <1 ng/J for CO, 6-8 ng/J for NO_X, 0.04-0.06 ng/J for HCHO, and 0.04-0.05 ng/J for Acetaldehyde. When comparing the Wobbe Number to NO_x, the results show a sharp increase for the highest Wobbe Number fuel (3C). Fuel 1C (Wobbe=1396) is not clearly different from fuel 1N or the PG&E line gas. Additionally, NO_x does not appear to increase with Wobbe Number from 1346 to 1396, as shown in Figure 22.

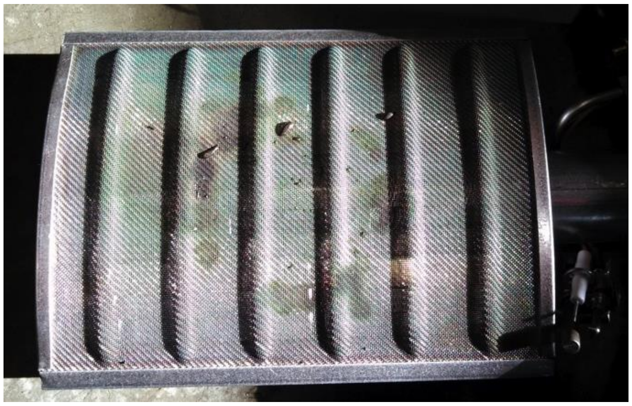

Figure 15. **Image of A.O. Smith GNR-40 burner removed after initial firing. Black flue glass was found melted onto the top of the burner. The orifice was replaced to the appropriate size for natural gas operation.**

Figure 16. **Experimental apparatus installed for storage water heater AW02. Dilution sampling tube is shown next to draft diverter resting on top of the water heater behind the copper piping. The Thermo 42i and house-air line are located behind the water heater (not shown).**

Table 19. **Published information for water heater AW02.**

Burner ID	AW02
Burner category	Ultra Low NO_x, natural draft storage water heater
Technology	"Cake Pan" burner with pilot; SCAQMD rule 1121-compliant, complies with 10 ng/J NO_x emissions
Appliance manufacturer	A. O. Smith
Model	ProMax® Ultra Low NO_x (Model GNR-40)
Serial number	1152T470906
Capacity	40 gal.
Recovery rating	41.5 gal per h
Energy factor rating	0.62
Design manifold Press	5 in. H_2O
Burner ratings (Btu/h)	40,000

Table 20. **Composition of fuels for interchangeability experiments for storage water heater AW02.**

Exp.	Fuel	Date	N_2 (%)	CO_2 (%)	HHV (Btu/scf)	Wobbe Number
B001	1C+	01/28/13	0.00	0.00	1076	1396
B002	1N+	01/30/13	1.70	0.00	1058	1365
B003	3C+	01/30/13	0.00	0.00	1131	1426
B004	PG&E*	01/25/13	0.59**	0.72**	1025	1346
B005	PG&E*	01/30/13	0.63**	0.72**	1027	1347

+ All information provided by Praxair.
* Gas quality information provided by PG&E online pipeline data, line J01 (downloaded 01/31/2013).
** Values are given in mol % not volume %.

Table 21. **Burner operating parameters for experiments with storage water heater AW02.**

Exp.	Burn times		Fuel flow rate (ft^3 h^{-1})		Firing rate (kBtu/h)	
	Burn 1	Burn 2	B1	B2	B1	B2
B001	15:37:35-15:52:30	16:01:25-16:16:30	37.4	37.5	40.2	40.4
B002	11:13:41-11:28:27	11:37:47-11:52:30	36.6	36.5	38.7	38.6
B003	12:38:16-12:53:31	13:02:01-13:16:58	39.1	39.1	44.2	44.2
B004	11:37:36-11:52:18	12:02:01-12:16:56	40.5	40.3	41.5	41.4
B005	13:55:36-14:10:31	14:19:29-14:34:32	40.4	40.4	41.5	41.5

Table 22.Aldehyde measurement times with storage water heater AW02[*].

Fuel	Experiment	Date	Aldehyde Start Time	Aldehyde Stop Time	Total Liters Sampled
Lab Air[**]	-	01/25/13	13:05	15:43	168.6
Lab Air[**]	-	01/28/13	16:27	19:07	161.0
Lab Air[**]	-	01/30/13	10:27	12:31	115.3
1C	B001	01/28/13	15:33	16:24	51.0
			15:33	16:24	55.8
1N	B002	01/30/13	11:09	12:00	47.3
			11:09	12:00	52.6
3C	B003	01/30/13	12:34	13:25	48.0
			12:34	13:25	53.4
PG&E	B004	01/25/13	11:27	12:27	60.0
			11:27	12:27	66.1
PG&E	B005	01/30/13	13:51	14:43	49.3
			13:51	14:43	55.5

[*] Two Aldehyde measurements were taken on the dilution tube for each experiment.

[**] Aldehyde was measured directly from the lab air supply.

Table 23. Combustion air conditions[1] for experiments with water heater AW02.

Exp.	T, burn (°C)	T, burn 2 (°C)	RH, burn 1 (%)	RH, burn 2 (%)
B001	19.5 ± 0.1	19.6 ± 0.1	36.2 ± <1	37.2 ± <1
B002	19.7 ± 0.1	19.9 ± 0.1	41.0 ± <1	41.1 ± <1
B003	20.2 ± 0.1	20.2 ± 0.1	39.9 ± <1	39.2 ± <1
B004	19.6 ± 0.1	19.8 ± 0.1	57.1 ± <1	56.4 ± <1
B005	20.2 ± 0.1	20.2 ± 0.1	38.2 ± <1	38.3 ± <1

[1] Mean ± standard deviation measured over period of two sampling burns, measured next to water heater near the air intake.

Table 24. Sampling system conditions for experiments with water heater AW02.

Exp.	Sample Location T (°C)[1]		Dilution Ratio[2]	
	Burn 1	Burn 2	Burn 1	Burn 2
B001	292 ± 15	290 ± 20	14	14
B002	287 ± 20	286 ± 21	14	13
B003	301 ± 21	301 ± 22	14	14
B004	306 ± 19	300 ± 19	13	13
B005	300 ± 18	296 ± 20	13	13

[1] Measured at sample location 13-inches below top of central flue; mean over last 5 min of each burn.

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

Table 25. Calculated air-free concentrations (using O_2) over last 5 min of each burn, water heater AW02.

Exp	Fuel	Wobbe	CO[1] (ppm)		NO_2[1] (ppm)		NO_X[2] (ppm)	
			B1	B2	B1	B2	B1	B2
B001	1C	1396	-4	-4	5	4	17	17
B002	1N	1365	-2	-2	5	5	16	15
B003	3C	1426	-6	-6	4	4	22	21
B004	PG&E	1346	-1	-2	4	4	17	16
B005	PG&E	1347	-10	-10	4	4	17	17

[1] Negative values due to CO_2 interference and overcompensation from CPU in the PG 250.

[2] Emissions measured from Thermo 42i.

Table 26. Calculated emission rates over entirety of each burn, water heater AW02.

Exp	Fuel	Wobbe	CO (ng/J)		NO_2[1] (ng/J)		NO_X[1] (ng/J)		HCHO (ng/J)	Acetaldehyde (ng/J)
			B1	B2	B1	B2	B1	B2		
B001	1C	1396	0.6	0.4	1.9	1.7	6.5	6.6	0.06	0.05
B002	1N	1365	0.7	0.3	2.0	1.9	6.2	6.1	0.07	0.05
B003	3C	1426	-0.6	-1.0	1.6	1.7	8.5	8.6	0.04	0.05
B004	PG&E	1346	0.2	-0.3	1.4	1.3	6.5	6.0	0.04	0.04
B005	PG&E	1347	-1.5	-1.8	1.5	1.5	6.4	6.1	0.04	0.04

[1] Calculation assumes molecular mass of NO_2 for NO_x (46 g/mol); emissions measured from Thermo 42i.

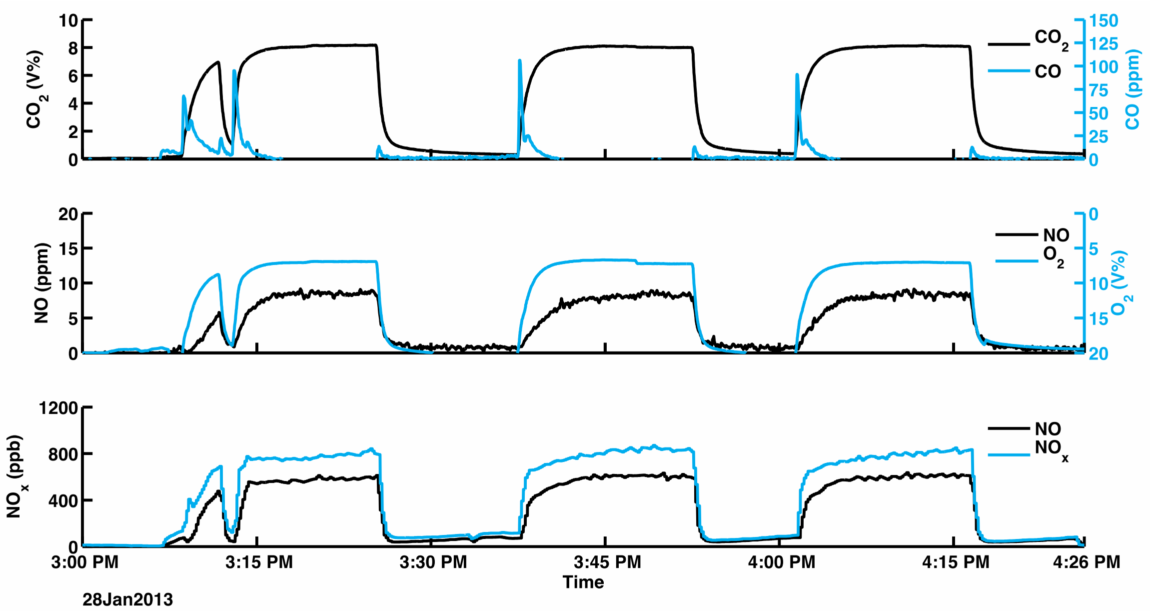

Figure 17. Measured analyte concentrations for storage water heater AW02 with fuel 1C (B001). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first peaks shown are the purge burn (from 3:08 PM – 3:25 PM).

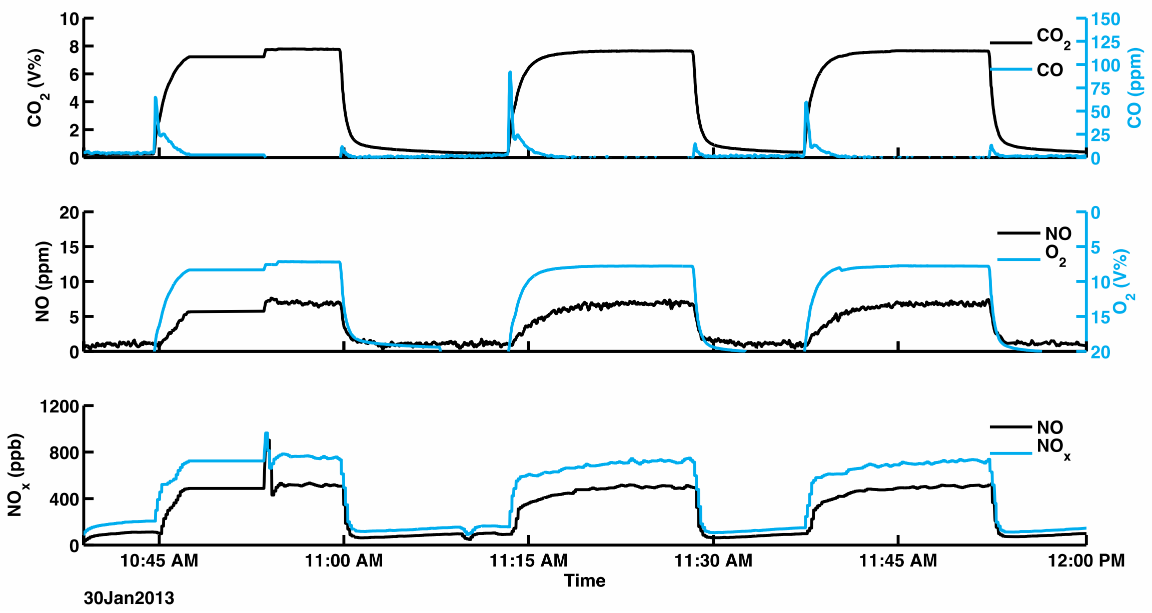

Figure 18. **Measured analyte concentrations for storage water heater AW02 with fuel 1N (B002). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn. During the purge burn, a spike in NO$_x$ was observed by the Thermo 42i (bottom panel). This could be due to the transition between fuels.**

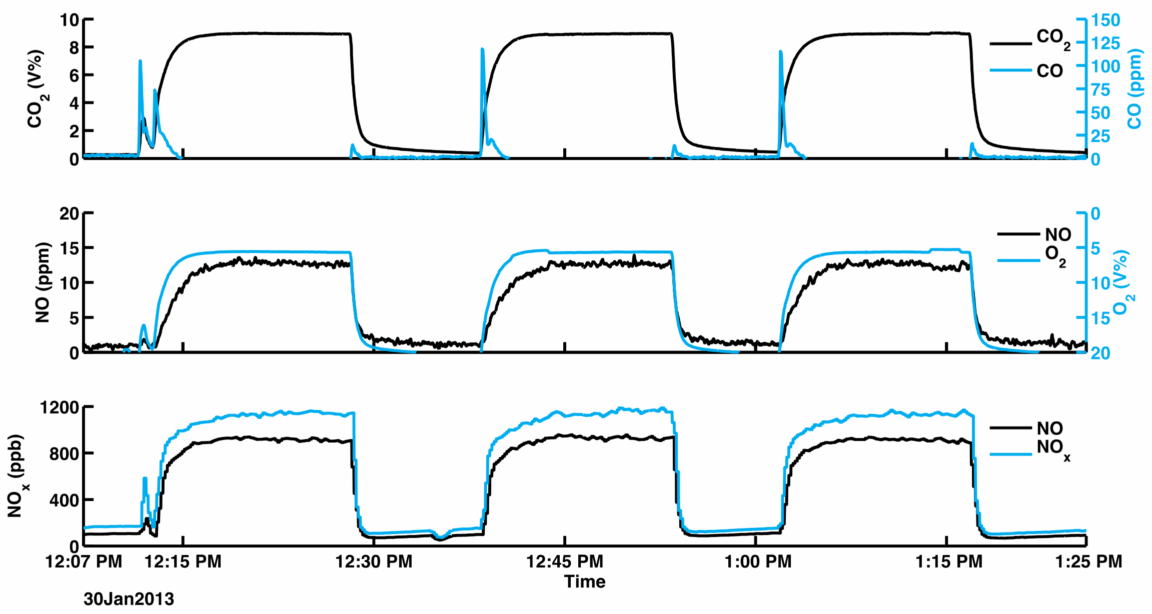

Figure 19. **Measured analyte concentrations for storage water heater AW02 with fuel 3C (B003). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn.**

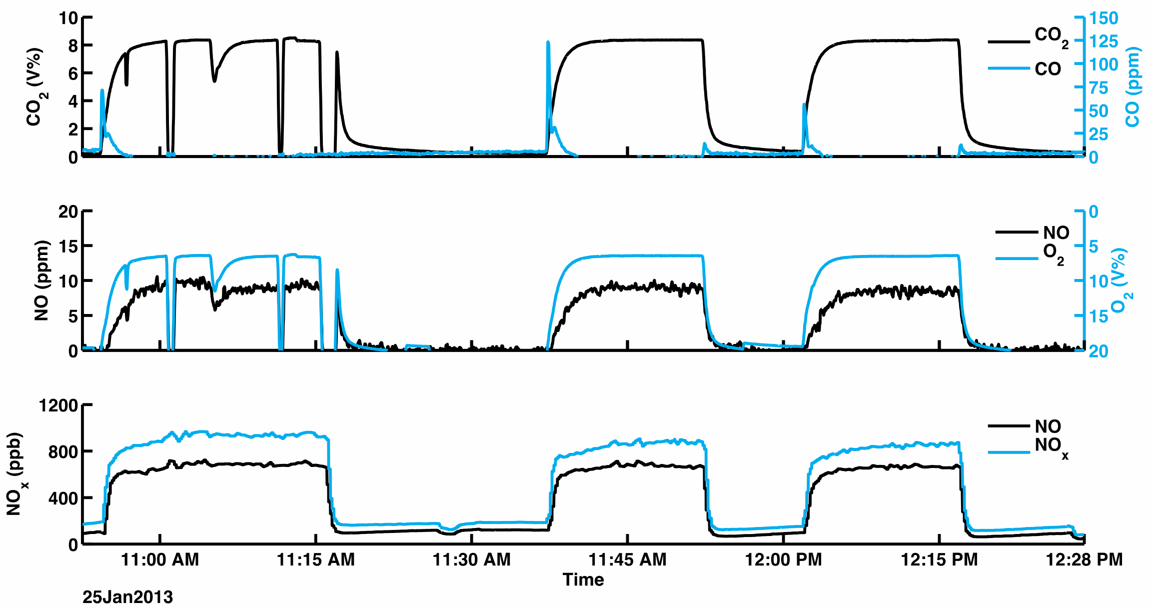

Figure 20. Measured analyte concentrations for storage water heater AW02 with PG&E gas (B004).The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn. The sharp drops in emissions during the purge burn are due to communication errors between the PG250 and the computer. The problems were resolved for the fuel interchangeability experiments.

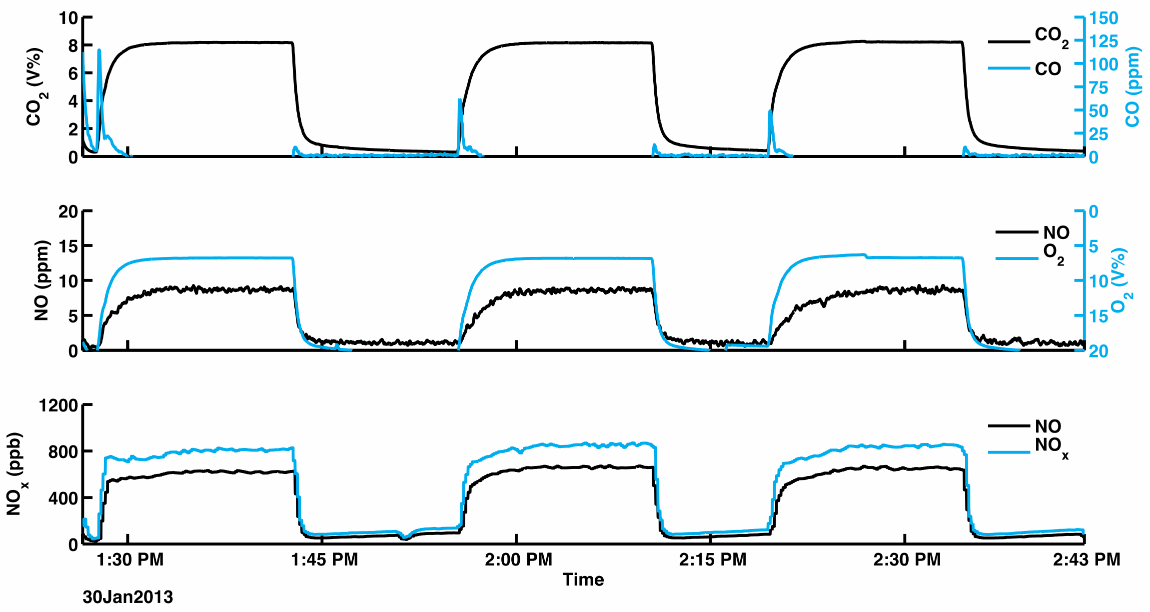

Figure 21. Measured analyte concentrations for storage water heater AW02 with fuel PG&E, repeat (B005). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn.

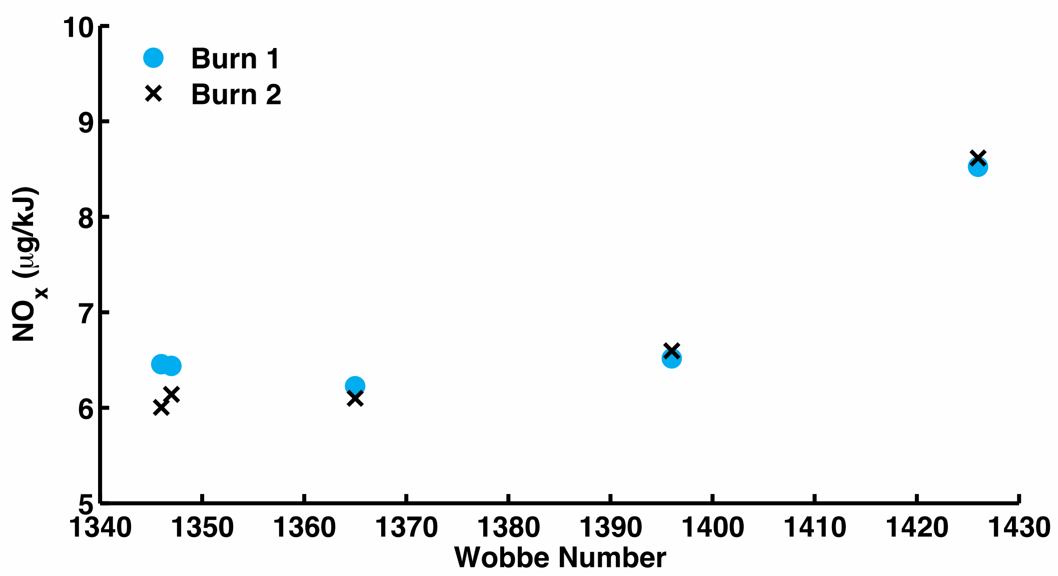

Figure 22. NO$_x$ as a function of Wobbe Number for storage water heater AW02. NO$_x$ does not vary for fuels with a Wobbe Number less than 1400. NO$_x$ does increase for fuel 3C.

3.3 Results for AW03

3.3.1 Summary of Experiments. This ultra-low NO_x, power vent, storage water heater was donated new and installed in the test facilities at LBNL used for LNG interchangeability and energy efficiency experiments (see Figure 23). Table 27 provides a summary of the burner information. Because the water heater is power vented, the emissions sample lines and flue thermocouples were installed prior to the blower, in the flue (see Figure 24). Two thermocouples were installed 14 inches into the flue on opposite sides of the turbulator. One of the thermocouples was positioned under a fin of the turbulator while the other thermocouple remained in the exhaust gas stream, not shielded by a turbulator fin. The thermocouple shielded by the fin gave higher temperature readings than then thermocouple in the exhaust stream due to the cooling effect from the fan-induced flow in the flue.

In February 2013, six experiments were conducted on this unit. Two experiments were conducted on February 20, 2013, one using the PG&E line gas (WN=1348) and one using fuel mixture 3C (WN=1426). Two days later, on February 22, 2013, four experiments were conducted using fuel mixture 1C (WN =1396), fuel mixture 1N (WN=1365), fuel mixture 3C (WN=1426), and the PG&E line gas (WN=1347). Composition and properties of each fuel are presented in Table 28. After the first day of testing, the water heater insulation became saturated with water due to a leak where thermocouples measured water temperature inside the tank. Water also collected at the bottom of the water heater near the burner. In order to prevent damage to the burner or water heater, the water heater was left off and allowed to dry for two days before conducting the second set of experiments.

While calibrating the Horiba on February 22, 2013 (Day 2), we observed that the NO calibration bag had a leak, indicating the Horiba was not correctly calibrated for experiments conducted on February 20, 2013 (Day 1). The Horiba analyzer readings for the NO calibration gas were about 5 ppm lower than expected, indicating a leak in the calibration bag. For Day 2, the Horiba was calibrated with a new calibration bag of NO. Because the Horiba results for NO from Day 1 were recorded when the instrument was not calibrated correctly, the corresponding data was omitted from this report. Ambient temperature and relative humidity were similar on both testing days. Flue temperature was measured 14 inches below the top of the water heater on each side of the turbulator. Pressure at the dry gas meter was 7 inches of water for all fuels tested.

3.3.2 Summary of Results. Tables and figures that follow provide detailed results from the LNG interchangeability experiments for storage water heater AW03. CO emission rates during main burner operation were relatively low after the first minute of operation. The cause of the excess noise in the NO signal is unknown. However, the noise was consistent for each experiment conducted with this water heater. Prior to testing fuel mixture 3C on February 22, 2013, the water heater was completely drained of hot water and filled with cold tap water. The orifice whistled a little during start-up and slightly higher CO emissions from the first burn were observed. For each experiments, NO_X was primarily in the form of NO. Full burn emission rates, shown in Table 34, were <3 ng/J for CO, 5-8 ng/J for NO_X, 0.11-0.17 ng/J for HCHO, and 0.08-0.11 ng/J for Acetaldehyde. The results showed a gradual increase in NO_x with Wobbe Number, as shown in Figure 29.

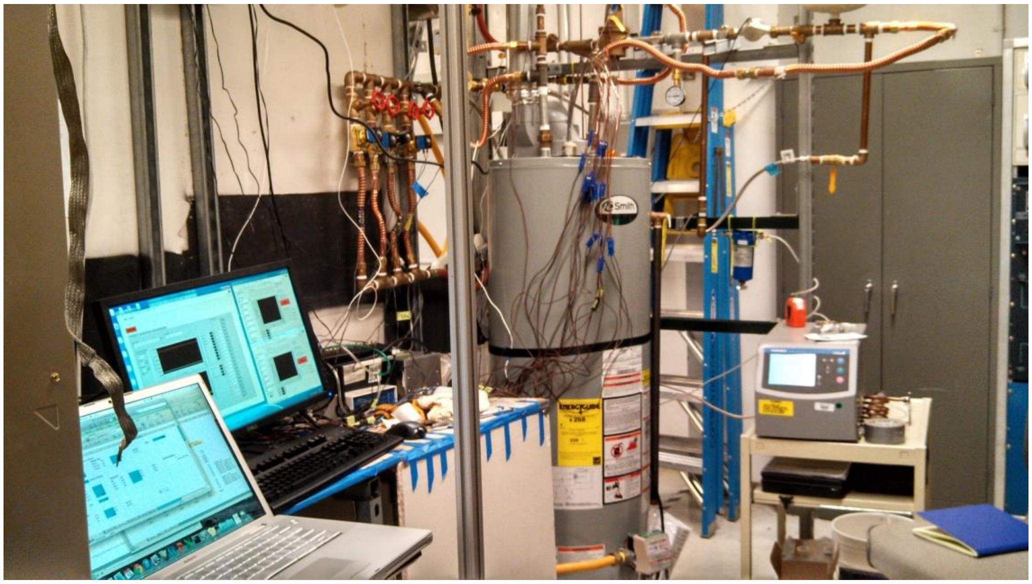

Figure 23. **Experimental apparatus installed for storage water heater AW03. Dilution sampling tube is located behind the water heater and samples before the fan. The Thermo 42i and house-air line are located behind the water heater (not shown).**

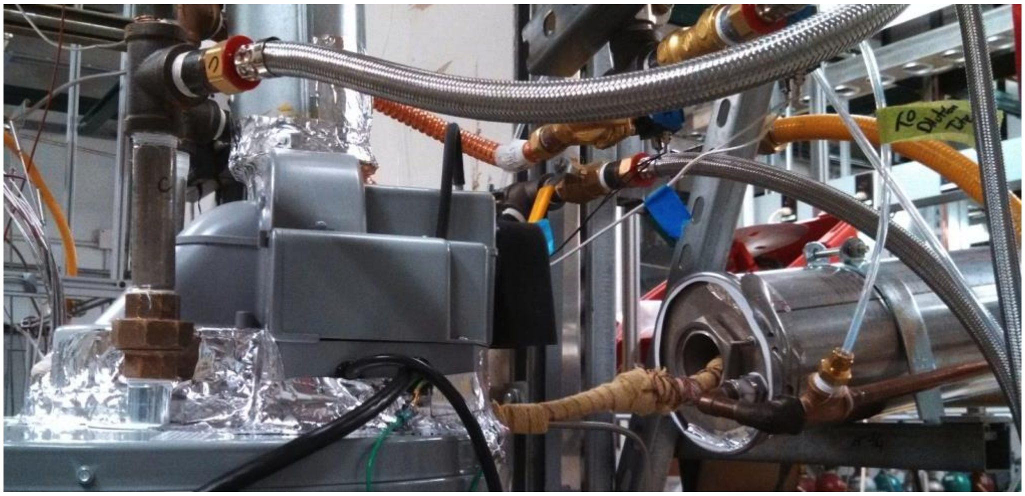

Figure 24. **Dilution tube and emissions sampling setup for storage water heater AW03. Dilution and emissions sampling tubes are located behind the water heater and sample emissions prior to the fan 12-inches into the flue.**

Table 27. Published information for water heater AW03.

Burner ID	AW03
Burner category	Ultra low NO_x, power vent, storage water heater
Technology	"Cake Pan" burner with hot surface ignitor (no pilot); power vent; SCAQMD rule 1121-compliant, complies with 10 ng/J NO_x emissions.
Appliance manufacturer	A.O. Smith
Model	Pro-Max Ultra Low NO_x (Model GPNH-40)
Serial number	1226T473088
Capacity	40 gal.
Recovery rating	43.0 gal per h
Energy factor rating	0.68
Design manifold Press	5 in. H_2O
Burner ratings (Btu/h)	42,000

Table 28. Composition of fuels for interchangeability experiments for storage water heater AW03.

Exp.	Fuel	Date	N_2 (%)	CO_2 (%)	HHV (Btu/scf)	Wobbe Number
C001	1C$^+$	02/22/13	0.00	0.00	1076	1396
C002	1N$^+$	02/22/13	1.70	0.00	1058	1365
C003	3C$^+$	02/22/13	0.00	0.00	1131	1426
C004	PG&E*	02/22/13	0.60**	0.67**	1024	1347

$^+$ All information provided by Praxair.

* Gas quality information provided by PG&E online pipeline data, line J01 (downloaded 02/24/2013).

** Values are given in mol % not volume %.

Table 29. **Burner operating parameters for experiments with storage water heater AW03.**

Exp.	Burn times		Fuel flow rate (ft^3 h^{-1})		Firing rate (kBtu/h)	
	Burn 1	Burn 2	B1	B2	B1	B2
C001	15:26:10-15:41:29	15:50:09-16:05:09	41.0	40.8	44.2	43.9
C002	13:40:21-13:55:38	14:03:35-14:18:50	40.9	40.7	43.3	43.0
C003	17:02:22-17:17:38	17:26:28-17:41:08	39.8	39.7	45.0	44.9
C004	12:00:58-12:15:54	12:23:30-12:38:51	41.3	41.2	42.3	42.2

Table 30. Aldehyde measurement times with storage water heater AW03[*].

Fuel	Experiment	Date	Aldehyde Start Time	Aldehyde Stop Time	Total Liters Sampled
Lab Air[**]	-	02/20/13	10:46	13:03	138.5
Lab Air[**]	-	02/22/13	11:44	14:21	156.2
1C	C001	02/22/13	15:21	16:15	47.8
			15:21	16:15	61.3
1N	C002	02/22/13	13:34	14:28	46.9
			13:34	14:28	60.7
			16:35	17:27	58.0
3C	C003	02/22/13	16:58	17:48	45.3
			16:58	17:48	52.4
			14:17	15:17	66.8
PG&E	C004	02/22/13	11:57	12:47	43.2
			11:57	12:47	54.7

[*] Two Aldehyde measurements were taken on the dilution tube for each experiment.

[**] Aldehyde was measured directly from the lab air supply.

Table 31. **Combustion air conditions[1] for experiments with water heater AW03.**

Exp.	T, burn 1 (°C)	T, burn 2 (°C)	RH, burn 1 (%)	RH, burn 2 (%)
C001	19.2 ± 0.1	19.3 ± 0.1	36.2 ± <1	37.2 ± <1
C002	19.4 ± 0.1	19.5 ± 0.1	36.3 ± <1	34.9 ± <1
C003	18.7 ± 0.1	18.8 ± 0.1	40.3 ± <1	41.5 ± <1
C004	19.2 ± 0.1	19.5 ± 0.1	39.6 ± <1	38.6 ± <1

[1] Mean ± standard deviation measured over period of two sampling burns, measured next to the water heater near the air intake.

Table 32. Sampling system conditions for experiments with water heater AW03.

Exp.	Flue Temperature 1 (°C)[1]		Flue Temperature 2 (°C)[2]		Dilution Ratio[3]	
	Burn 1	Burn 2	Burn 1	Burn 2	Burn 1	Burn 2
C001	160 ± 3	165 ± 7	118 ± 11	118 ± 15	19	18
C002	166 ± 6	168 ± 2	127 ± 11	131 ± 4	20	19
C003	166 ± 4	167 ± 4	126 ± 12	119 ± 8	19	18
C004	162 ± 4	167 ± 3	107 ± 8	112 ± 2	19	18

[1] Measured in flue 14-inches below top of central flue under turbulator fin; mean over last 5 min of each burn.

[2] Measured in flue 14-inches below top of central flue, in exhaust stream away from turbulator fin (opposite side of Sample Location T1); mean over last 5 min of each burn.

[3] Calculated by comparing NO measured in gas manifold (PG-250) and dilution sampler (Thermo 42i) over last 5 min of each burn.

Table 33. Calculated air-free concentrations (using O_2) over last 5 min of each burn, water heater AW03.

Exp	Fuel	Wobbe	CO (ppm)		NO_2[1] (ppm)		NO_X[1] (ppm)	
			B1	B2	B1	B2	B1	B2
C001	1C	1396	5	6	6	6	18	18
C002	1N	1365	5	4	6	6	16	16
C003	3C	1426	10	6	7	6	20	17
C004	PG&E	1347	4	2	5	5	15	13

[1] Emissions measured from Thermo 42i.

Table 34. Calculated emission rates over entirety of each burn, water heater AW03.

Exp	Fuel ID	Wobbe	CO (ng/J)		NO_2[1] (ng/J)		NO_X[1] (ng/J)		HCHO (ng/J)	Acetaldehyde (ng/J)
			B1	B2	B1	B2	B1	B2		
C001	1C	1396	2.0	1.4	2.7	2.6	7.2	7.1	0.12	0.09
C002	1N	1365	2.3	1.5	2.5	2.4	6.4	6.2	0.13	0.11
C003	3C	1426	2.6	1.9	2.8	2.6	7.8	7.1	0.11	0.08
C004	PG&E	1347	2.2	1.4	2.1	2.1	5.8	5.3	0.13	0.10

[1] Calculation assumes molecular mass of NO_2 for NO_x (46 g/mol); Emissions measured from Thermo 42i.

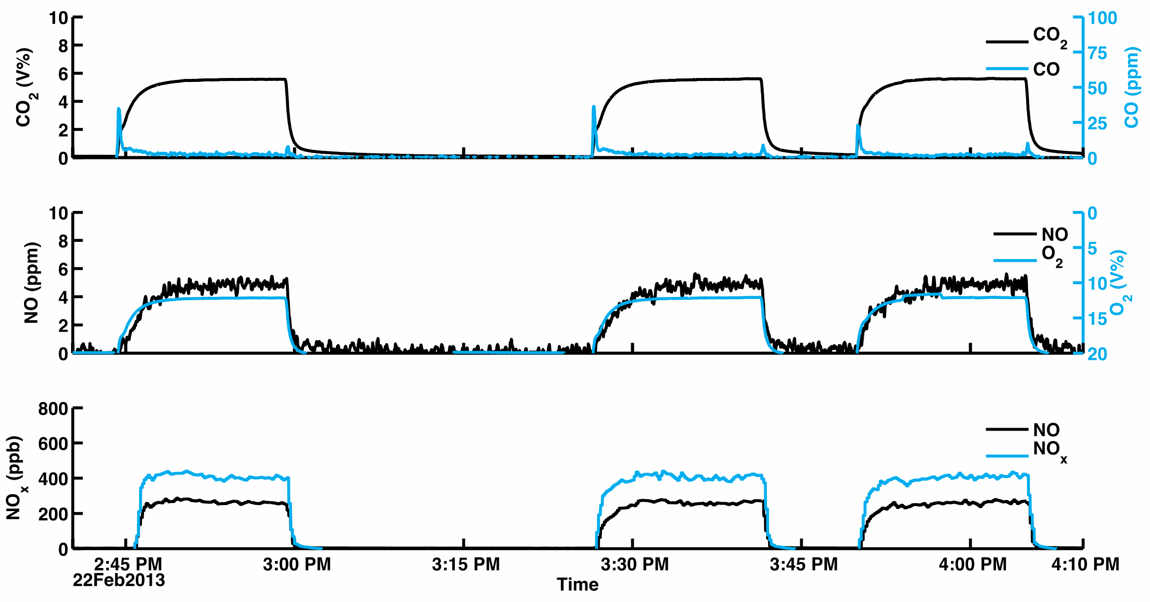

Figure 25. **Measured analyte concentrations for storage water heater AW03 with fuel 1C (C001). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn.**

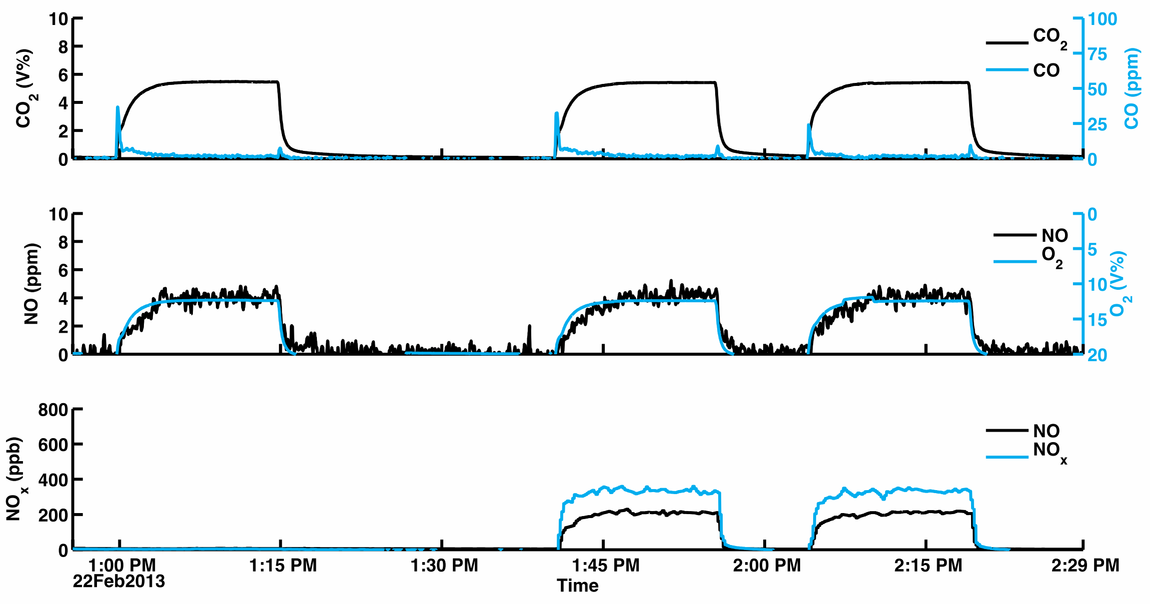

Figure 26. **Measured analyte concentrations for storage water heater AW03 with fuel 1N (C002). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn. During the purge burn, the Thermo 42i was not connected.**

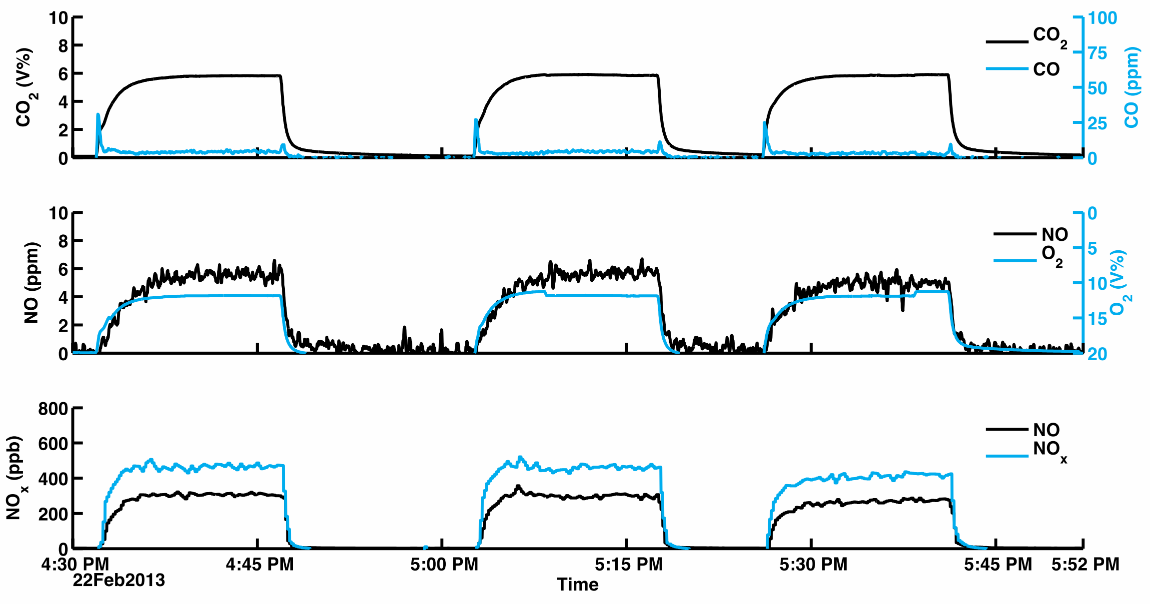

Figure 27. **Measured analyte concentrations for storage water heater AW03 with fuel 3C, repeat (C003). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn. The hot water heater was completely replaced with cold prior to this test and the water temperature inside the tank was about 19°C.**

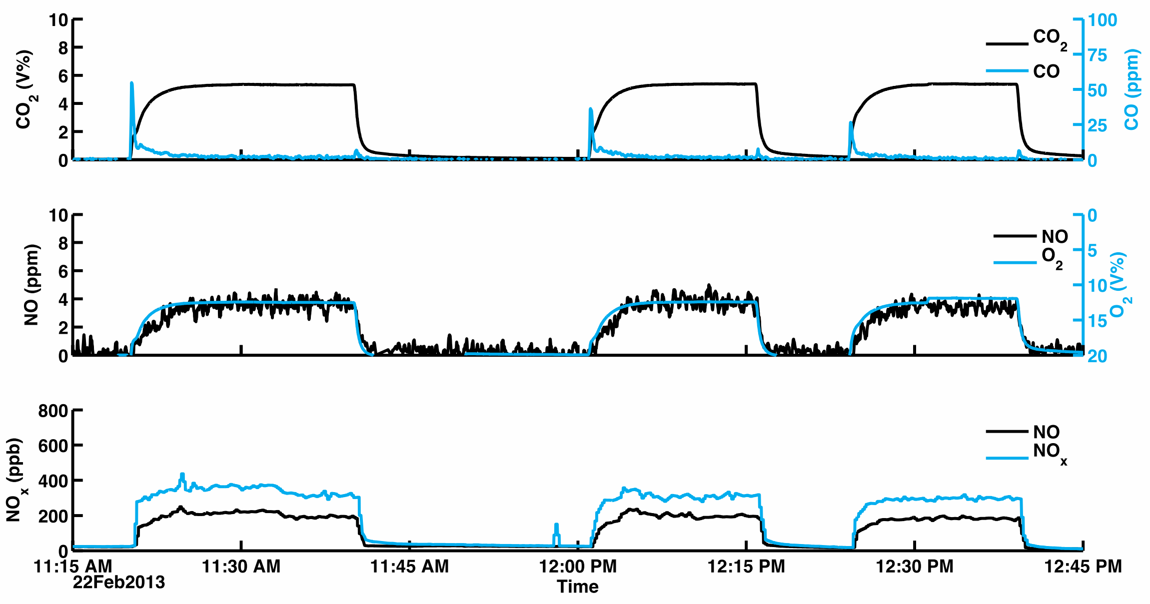

Figure 28. **Measured analyte concentrations for storage water heater AW03 with fuel PG&E, repeat (C004). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn. The short spike in NO$_x$ just prior to testing was a communication error between the computer and the Thermo 42i.**

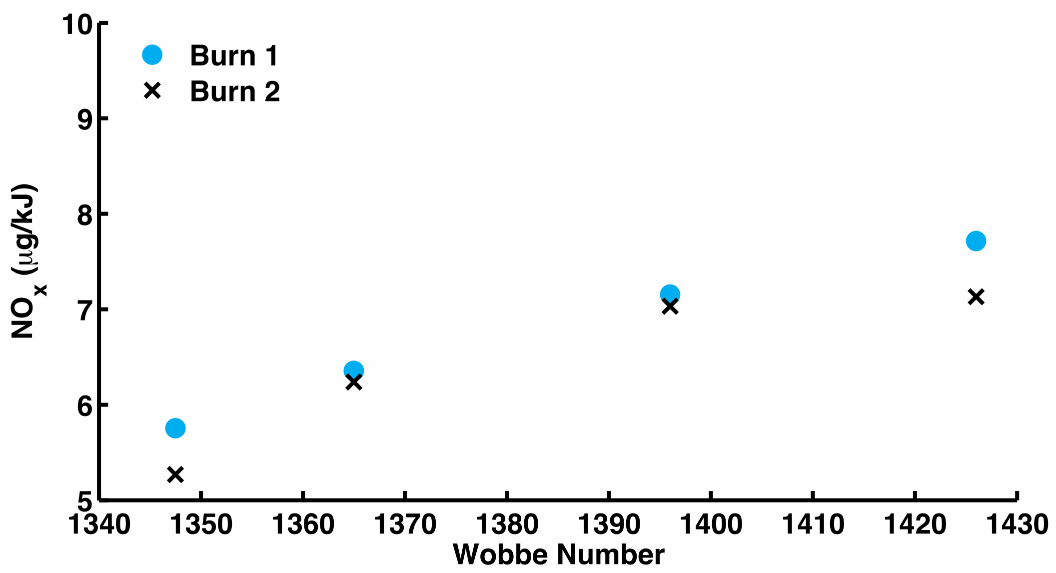

Figure 29. NO_x as a function of Wobbe Number for storage water heater AW03. The fuels show a linear correlation between NOx and Wobbe Number for each burn.

3.4 Results for AW04

3.4.1 Summary of Experiments. This direct-vent, condensing water heater was donated new and installed in the test facilities at LBNL used for LNG interchangeability and energy efficiency experiments (see Figure 30). Table 35 provides a summary of the burner information. This water heater is not an ultra-low NO_x water heater (i.e. not compliant with SCAQMD rule 1146.2) and was tested to compare previously compliant technology with newer, ultra-low NO_X compliant technology. Because the water heater is power-vented, the emissions sample lines and flue thermocouples were installed prior to the fan, 6-inches below the elbow in the PVC piping (see Figure 31). One thermocouple was installed after the elbow using a drain port. The thermocouple was placed so that it would not contact the sidewalls of the PVC piping or the emission sample lines. During each experiment, the water heater condensed about 2-4 quarts of water. Because this water heater is designed to condense the water, the thermocouple casing was saturated during data collection.

In April 2013, five experiments were conducted on this unit over two consecutive days. The first experiment was conducted on April 2, 2013 using the PG&E line gas (WN=1353). The following day, on April 3, 2013, four experiments were conducted using fuel mixture 1C (WN =1396), fuel mixture 1N (WN=1365), fuel mixture 3C (WN=1426), and the PG&E line gas (WN=1347). Composition and properties of each fuel are presented in Table 36.

When conducting the first experiment with PG&E line gas, water was continuously drawn from the water heater to keep the burner operating. For fuel mixtures 1C, 1N, and 3C, water was not drawn from the water heater when the burner was operated. Instead, water was drawn prior to each burn and then shut-off before the burner was operated. When testing the PG&E line gas on 04/03/2013, water was not drawn during the first burn, but drawn continuously during the first 13 minutes of the second burn. The thermostat was set to the hottest temperature setting, “C”, for all experiments. When testing fuel mixture 1C, the Horiba gas analyzer was disconnected during the first four minutes of the purge burn. Therefore, Figure 32 does not capture the emissions for the entire purge burn. Ambient temperature and relative humidity were similar on both testing days. Pressure at the dry gas meter was 7 inches of water for all fuels tested.

3.4.2 Summary of Results. Tables and figures that follow provide detailed results from the LNG interchangeability experiments for storage water heater AW04. During these experiments, the Horiba gas analyzer overcompensated for CO_2 interference in the CO signal, resulting in negative CO emission measurements. In order to correct for this overcompensation, the surface fit equations described in Section 2.2.4 were used to adjust the measured CO and reported in the tables that follow. After the first minute of operation, CO emission rates during main burner operation were relatively low. For the second burn of experiment D005 (repeated PG&E line-gas experiment), water was drawn continuously for the first 13 minutes of the experiment. The results show emission concentrations were not affected by drawing water. However, the flue temperature dropped, as shown in Table 39. During this experiment, the flue temperature closely followed the outlet temperature of the water.

For each experiment, at least 85% of NO_X was in the form of NO. Full burn emission rates, shown in Table 42, were 10.0–13.3 ng/J for CO and 35–37 ng/J for NO_X. The exhaust contained very little formaldehyde (0.02 ng/J) and acetaldehyde (0.06–0.08 ng/J). The low concentrations of formaldehyde are likely due to the condensate removing formaldehyde from the exhaust. NO_x remained almost constant with Wobbe Number (see Figure 37).

Figure 30. **Experimental apparatus installed for storage water heater AW04. Dilution sampling tube is located behind the water heater and sampled before the fan. The Thermo 42i and house-air line are located behind the water heater (not shown).**

Figure 31. **Dilution tube and emissions sampling setup for storage water heater AW04. Dilution tube and emissions were sampled 12-inches below the elbow prior to the blower. Temperature was measured in an extra drain port 6-inches below the elbow.**

Table 35. Published information for water heater AW04.

Burner ID	AW04
Burner category	Condensing, storage water heater
Technology	“Pancake” burner with hot surface ignitor (no pilot); NOT compliant with SCAQMD rule 1146.2, does not comply with 14 ng/J NO_x emissions; power vent; condensing
Appliance manufacturer	A.O. Smith
Model	Vertex (Model GPHE-50)
Serial number	1234M000235
Capacity	50 gal.
Recovery rating	92 gal per h
Energy factor rating	None listed
Design manifold Press	4 in. H_2O
Burner ratings (Btu/h)	76,000

Table 36. Composition of fuels for interchangeability experiments for storage water heater AW04.

Exp.	Fuel	Date	N_2 (%)	CO_2 (%)	HHV (Btu/scf)	Wobbe Number
D001	1C[+]	04/03/13	0.00	0.00	1076	1396
D002	1N[+]	04/03/13	1.70	0.00	1058	1365
D003	3C[+]	04/03/13	0.00	0.00	1131	1426
D004	PG&E[*]	04/02/13	0.46[**]	0.79[**]	1037	1353
D005	PG&E[*]	04/03/13	0.57[**]	0.73[**]	1027	1347

[+] All information provided by Praxair.

[*] Gas quality information provided by PG&E online pipeline data, line J01 (downloaded 04/03/2013).

[**] Values are given in mol % not volume %.

Table 37. **Burner operating parameters for experiments with storage water heater AW04.**

Exp.	Burn times		Fuel flowrate (ft^3 h^{-1})		Firing rate (kBtu/h)	
	Burn 1	Burn 2	B1	B2	B1	B2
D001	14:59:01-15:14:01	15:23:10-15:38:15	68.4	67.8	73.6	73.0
D002	16:37:16-16:52:16	17:00:45-17:15:46	68.3	67.7	72.2	71.7
D003	18:06:38-18:21:39	18:30:24-18:45:24	66.6	66.1	75.3	74.8
D004	13:36:17-13:51:22	13:59:54-14:14:54	68.1	68.2	70.6	70.6
D005	19:32:33-19:47:33	19:56:31-20:11:39	69.2	68.9	71.1	70.7

Table 38. Aldehyde measurement times with storage water heater AW04[*].

Fuel	Experiment	Date	Aldehyde Start Time	Aldehyde Stop Time	Total Liters Sampled
Lab Air[**]	-	04/02/13	12:50	15:57	176.7
Lab Air[**]	-	04/03/13	14:17	16:31	123.6
1C	D001	04/03/13	14:54	15:47	52.9
			14:54	15:47	61.5
1N	D002	04/03/13	16:32	17:23	52.1
			16:32	17:23	59.1
3C	D003	04/03/13	18:03	18:53	49.5
			18:03	18:53	57.7
PG&E	D004	04/02/13	13:30	14:25	55.3
			13:30	14:25	63.9
PG&E	D005	04/03/13	19:28	20:22	52.4
			19:28	20:22	63.5

[*] Two Aldehyde measurements were taken on the dilution tube for each experiment.
[**] Aldehyde was measured directly from the lab air supply.

Table 39. **Combustion air conditions[1] for experiments with water heater AW04.**

Exp.	T, burn 1 (°C)	T, burn 2 (°C)	RH, burn 1 (%)	RH, burn 2 (%)
D001	20.2 ± 0.1	20.3 ± 0.1	56.4 ± <1	55.2 ± <1
D002	19.9 ± 0.1	19.9 ± 0.1	53.3 ± <1	52.6 ± <1
D003	19.3 ± 0.1	19.3 ± 0.1	52.7 ± <1	52.2 ± <1
D004	19.8 ± 0.1	20.0 ± 0.1	56.3 ± <1	55.1 ± <1
D005	18.8 ± 0.1	18.7 ± 0.1	52.0 ± <1	51.9 ± <1

[1] Mean ± standard deviation measured over period of two sampling burns, measured next to the water heater near the air intake.

Table 40. Sampling system conditions for experiments with water heater AW04.

Exp.	Flue Temperature[1] (°C)		Dilution Ratio[2]	
	Burn 1	Burn 2	Burn 1	Burn 2
D001	45 ± 2	45 ± 1	27	26
D002	42 ± 2	42 ± 2	23	31
D003	44 ± 2	45 ± 2	24	27
D004	42 ± 1	46 ± 1	28	27
D005	41 ± 2	32 ± 1	27	27

[1] Measured in flue (PVC-piping) 12-inches below elbow prior to blower; mean over last 5 min of each burn.

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

Table 41. Calculated air-free concentrations (using O_2) over last 5 min of each burn, water heater AW04.

Exp	Fuel	Wobbe	CO[1] (ppm)		NO_2[2] (ppm)		NO_X[2] (ppm)	
			B1	B2	B1	B2	B1	B2
D001	1C	1396	34	34	16	13	93	87
D002	1N	1365	36	36	12	10	89	88
D003	3C	1426	34	35	9	13	85	90
D004	PG&E	1353	33	32	14	14	89	90
D005	PG&E	1347	36	40	13	10	91	85

[1] CO emissions adjusted using surface fit given by Equation (2).

[2] Emissions measured from Thermo 42i.

Table 42. Calculated emission rates over entirety of each burn, water heater AW04.

Exp	Fuel	Wobbe	CO[1] (ng/J)		NO_2[2] (ng/J)		NO_X[2] (ng/J)		HCHO (ng/J)	Acetaldehyde (ng/J)
			B1	B2	B1	B2	B1	B2		
D001	1C	1396	11.4	11.3	5.7	4.9	37.0	36.1	0.02	0.08
D002	1N	1365	12.6	11.9	5.0	5.0	36.5	36.6	0.02	0.07
D003	3C	1426	11.5	11.3	4.6	5.0	36.0	36.7	0.02	0.06
D004	PG&E	1353	10.5	10.0	5.3	5.2	34.8	34.9	0.02	0.07
D005	PG&E	1347	11.5	13.3	5.0	5.2	35.8	35.3	0.02	0.07

[1] CO emissions calculated using adjusted ppm CO from surface fit given by Equation (2).

[2] Calculation assumes molecular mass of NO_2 for NO_x (46 g/mol). Emissions measured from Thermo 42i.

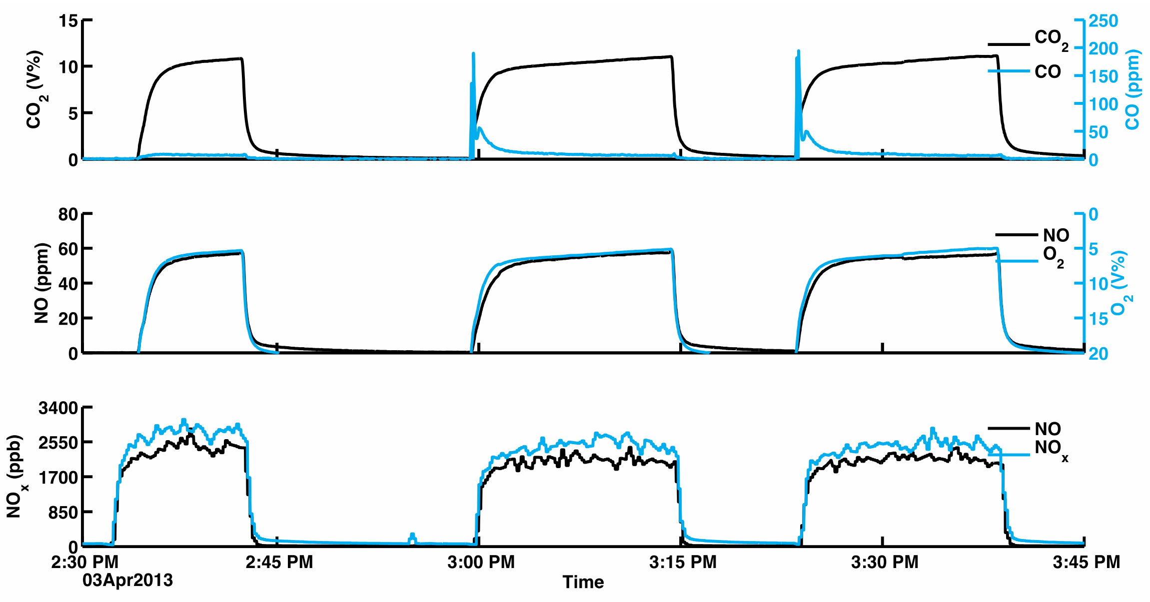

Figure 32. Measured analyte concentrations for storage water heater AW04 with fuel 1C (D001). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn.

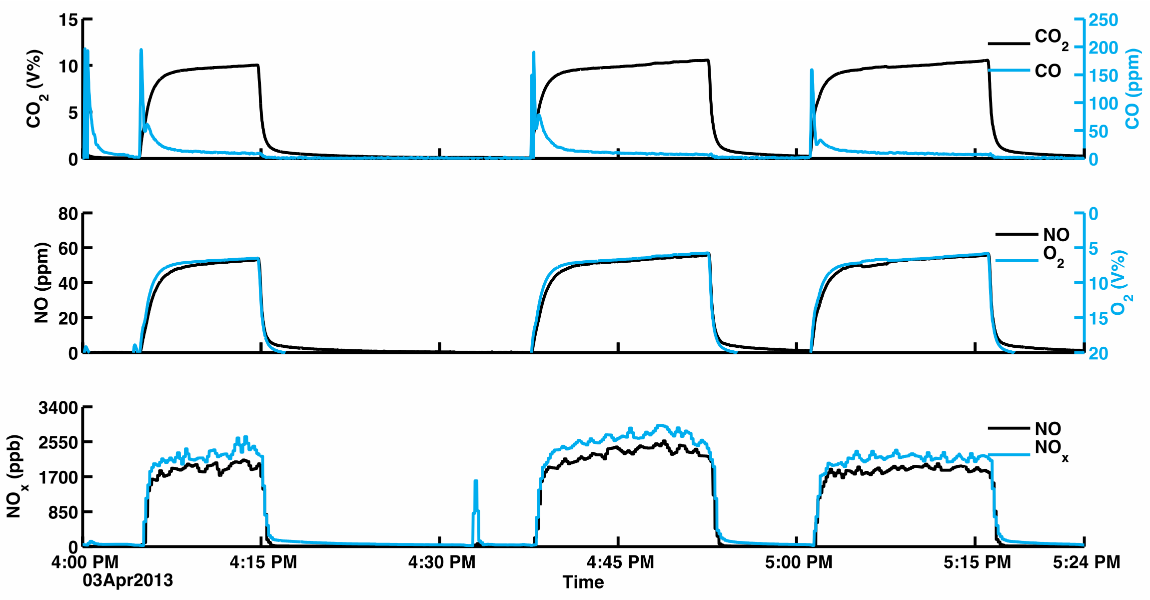

Figure 33. Measured analyte concentrations for storage water heater AW04 with fuel 1N (D002). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn. The first spike in CO prior to the purge burn was a false start. The short spike in NO$_x$ just prior to testing was a communication error between the computer and the Thermo 42i.

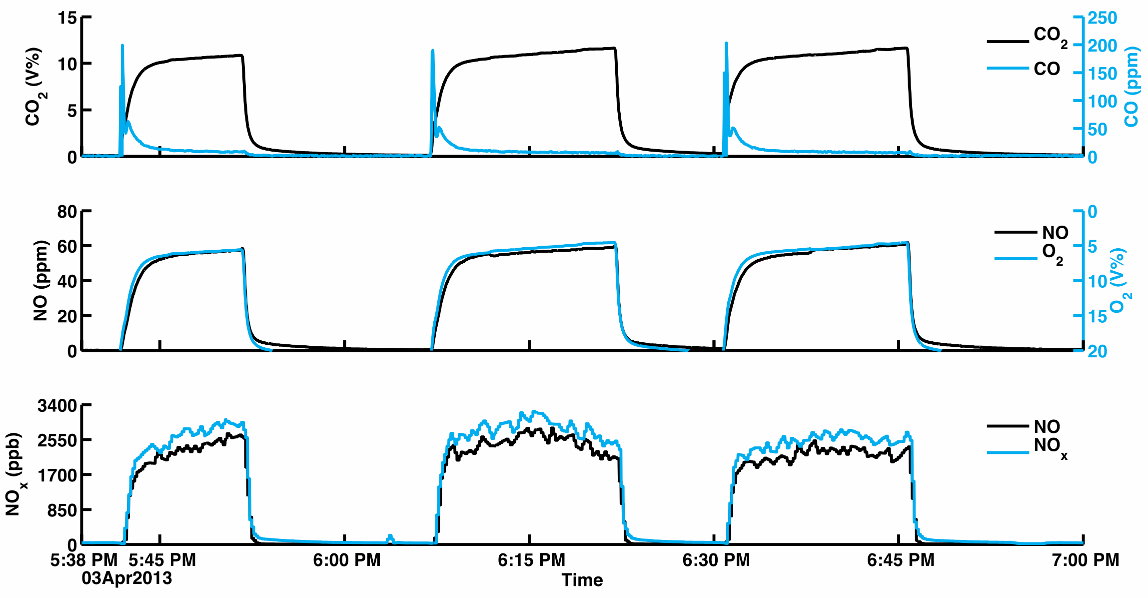

Figure 34. Measured analyte concentrations for storage water heater AW04 with fuel 3C (D003). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn.

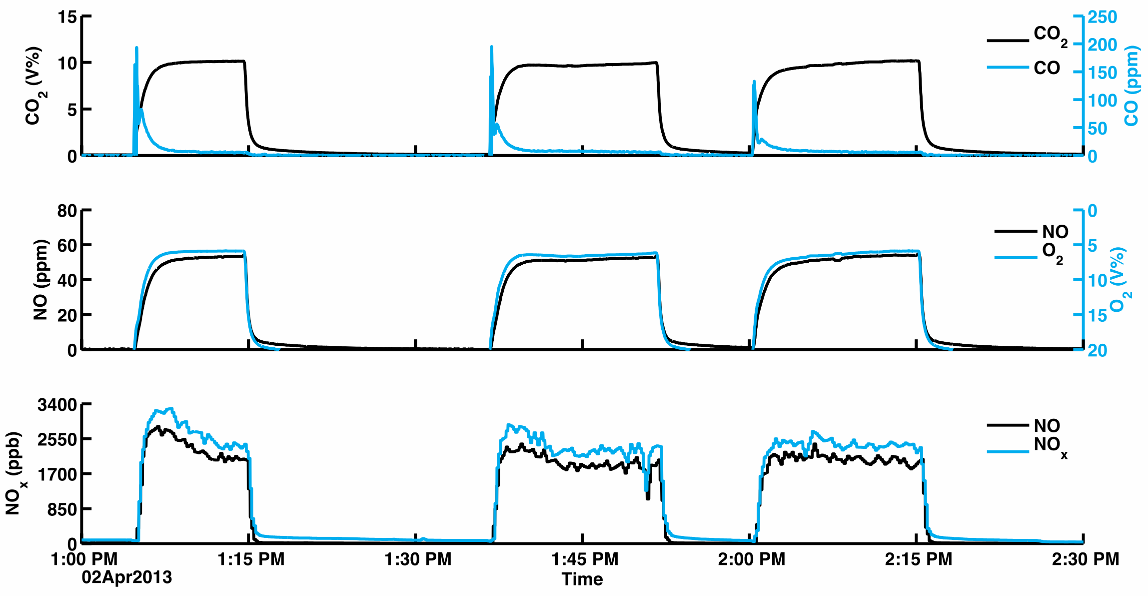

Figure 35. Measured analyte concentrations for storage water heater AW04 with PG&E gas (D004). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn.

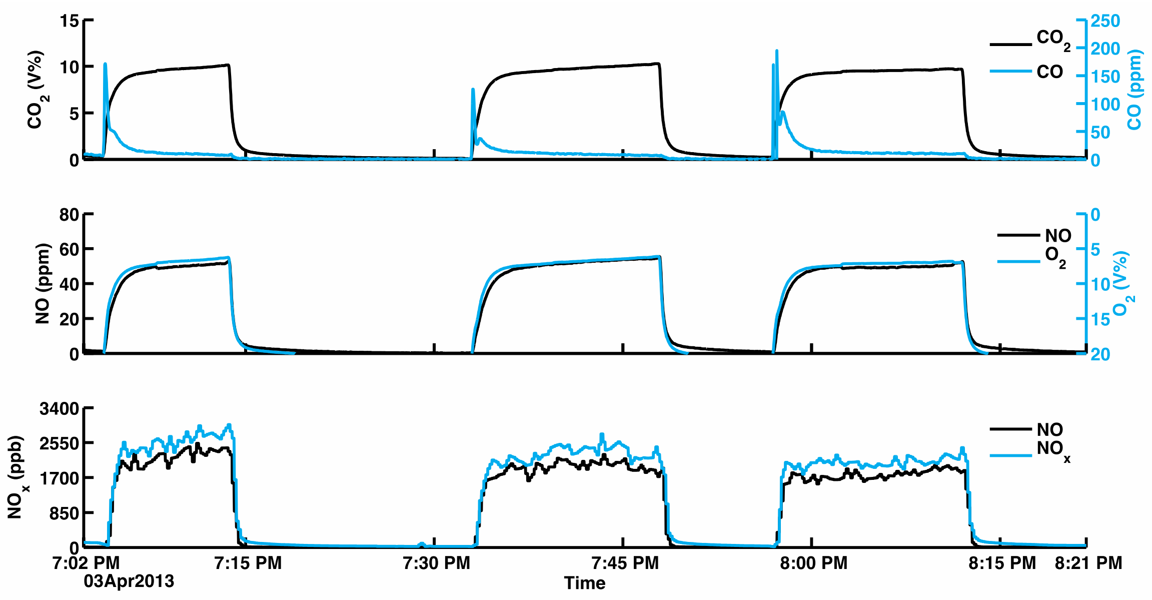

Figure 36. Measured analyte concentrations for storage water heater AW04 with fuel PG&E, repeat (D005). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn.

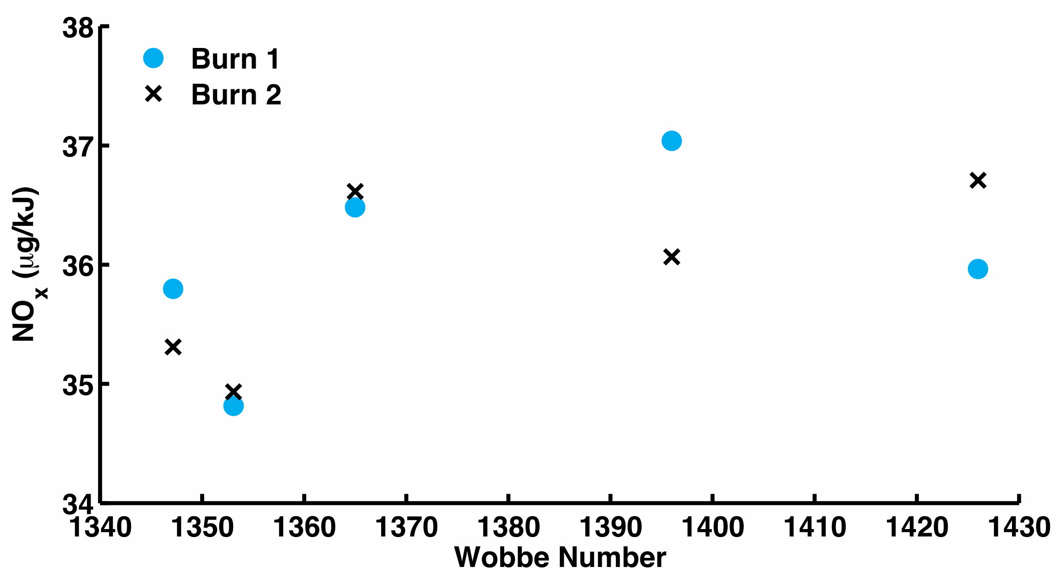

Figure 37. NO$_x$ as a function of Wobbe Number for storage water heater AW04. NO$_x$ concentrations do not vary much with Wobbe Number. However, NO$_x$ shows some variation between Burn 1 and Burn 2.

3.5 Results for AW05

3.5.1 Summary of Experiments. This ultra-low NO_X, power vent storage water heater was donated new and installed in the test facilities at LBNL used for LNG interchangeability and energy efficiency experiments (see Figure 38). The outer casing of the water heater was damaged during shipping, as shown in Figure 41; however, the damaged casing did not affect operation or performance. Table 43 provides a summary of the burner information. The water heater was operated for several days prior to the fuel interchangeability experiments. Because the water heater is power-vented, the emissions sample lines and flue thermocouples were installed prior to the fan in the central flue of the appliance (see Figure 39). The two thermocouples were installed 12-inches into the central flue, however one of the thermocouples failed when operating the water heater prior to the fuel interchangeability experiments. Emissions were also sampled 12-inches into the central flue.

In September 2013, five experiments were conducted on this unit over two consecutive days. Three experiments were conducted on September 19, 2013 using the PG&E line gas (WN=1348), fuel mixture 1N (WN=1365), and fuel mixture 3C (WN=1426). The following day, on September 20, 2013, two experiments were conducted using fuel mixture 1C (WN =1396) and the PG&E line gas (WN=1348). Composition and properties of each fuel are presented in Table 44. Environmental conditions were similar on both days. Pressure at the dry gas meter was 7 inches of water for all fuels tested. The burner was turned on and off by switching the dial between the hottest temperature setting and pilot. For all experiments, water was not drawn from the water heater when the burner was operated. Instead, water was drawn prior to each burn and then shut-off before the burner was operated. The thermostat was set to the hottest temperature setting during burner operation.

3.5.2 Summary of Results. Tables and figures that follow provide detailed results from the LNG interchangeability experiments for storage water heater AW05. For all experiments, the Horiba gas analyzer overcompensated for CO_2 interference in the CO signal, resulting in negative CO emission measurements. In order to correct for this overcompensation, the surface fit equations described in Section 2.2.4 were used to adjust the measured CO and reported in the tables that follow. At the beginning of each burn, the CO spiked and then dropped to lower concentrations after the first minute of operation. For each experiment, at least 85% of NO_X was in the form of NO. For fuel mixture 1C, at least 92% of the NO_X was in the form of NO. Full burn emission rates, shown in Table 50, ranged from 0.9 to 1.7 ng/J for CO and 9.4 to 12.6 ng/J for NO_X. The exhaust contained between 0.10 and 0.13 ng/J of formaldehyde and between 0.10 and 0.13 ng/J of acetaldehyde. NO_x increased slightly with Wobbe Number and did not vary much between burns of each fuel mixture (see Figure 47).

Figure 38. **Experimental apparatus installed for storage water heater AW05. Dilution sampling tube is located behind the water heater and sampled before the fan. The Thermo 42i and house-air line are located behind the water heater (not shown).**

Figure 39. **Dilution tube and emissions sampling setup for storage water heater AW05. Dilution tube, emissions, and temperature were sampled 12-inches into the flue prior to the blower.**

Figure 40. **Dilution and emission sampling line setup for water heater AW05. Dilution and emissions sampling tubes were installed prior to the fan and 12-inches into the flue.**

Figure 41. **Damage on casing of water heater. Tank and fuel system were not affected by casing damage.**

Table 43. Published information for water heater AW05.

Burner ID	AW05
Burner category	Ultra-low NO_X; power vent storage water heater
Technology	"Round" burner with a hot surface ignitor (no pilot); SCAQMD rule 1121 compliant, complies with 10 ng/J NO_x emissions; power vent
Appliance manufacturer	Rheem
Model	Power Vent 42VP40FN
Serial number	RHUNM191308669
Capacity	40 gal.
Recovery rating	36.4 gal per h
Energy factor rating	0.67 (Energy Star Qualified)
Design manifold Pressure	4 in. H_2O
Burner ratings (Btu/h)	36,000

Table 44. Composition of fuels for interchangeability experiments for storage water heater AW05.

Exp.	Fuel	Date	N_2 (%)	CO_2 (%)	HHV (Btu/scf)	Wobbe Number
E001	1C[+]	09/20/13	0.00	0.00	1076	1396
E002	1N[+]	09/19/13	1.70	0.00	1058	1365
E003	3C[+]	09/19/13	0.00	0.00	1131	1426
E004	PG&E[*]	09/19/13	0.66[**]	0.78[**]	1032	1348
E005	PG&E[*]	09/20/13	0.63[**]	0.82[**]	1032	1348

[+] All information provided by Praxair.

[*] Gas quality information provided by PG&E online pipeline data, line J01 (downloaded 09/20/2013).

[**] Values are given in mol % not volume %.

Table 45. **Burner operating parameters for experiments with storage water heater AW05.**

Exp.	Burn times		Fuel flowrate (ft^3 h^{-1})		Firing rate (kBtu/h)	
	Burn 1	Burn 2	B1	B2	B1	B2
E001	12:51:35-13:06:36	13:14:46-13:29:47	34.4	34.2	37.0	36.8
E002	13:55:57-14:10:56	14:19:46-14:34:39	34.2	34.4	36.2	36.4
E003	12:23:55-12:38:56	12:47:24-13:02:26	33.5	33.3	37.9	37.6
E004	10:56:33-11:11:37	11:19:57-11:35:01	34.6	34.4	35.8	35.5
E005	11:15:04-11:30:07	11:38:17-11:53:20	34.7	34.4	35.8	35.5

Table 46. Aldehyde measurement times with storage water heater AW05[*].

Fuel	Experiment	Date	Aldehyde Start Time	Aldehyde Stop Time	Total Liters Sampled
Lab Air[**]	-	09/19/13	10:07	12:10	119.4
Lab Air[**]	-	09/20/13	10:17	12:18	120.5
1C	E001	09/20/13	12:40	13:40	67.8
			12:40	13:40	72.5
1N	E002	09/19/13	13:47	14:45	66.5
			13:47	14:45	71.4
3C	E003	09/19/13	12:16	13:12	62.6
			12:16	13:12	69.3
PG&E	E004	09/19/13	10:49	11:43	59.1
			10:49	11:43	66.2
PG&E	E005	09/20/13	11:01	12:01	64.0
			11:01	12:01	70.8

[*] Two Aldehyde measurements were taken on the dilution tube for each experiment.

[**] Aldehyde was measured directly from the lab air supply.

Table 47. **Combustion air conditions[1] for experiments with water heater AW05.**

Exp.	T, burn 1 (°C)	T, burn 2 (°C)	RH, burn 1 (%)	RH, burn 2 (%)
E001	20.5 ± 0.1	20.7 ± 0	61.8 ± 0.1	61.4 ± 0.1
E002	22.2 ± 0.1	22.5 ± 0	51.8 ± 0.2	50.5 ± 0
E003	21.7 ± 0	22.0 ± 0.1	53.8 ± 0.1	53.1 ± 0.1
E004	20.7 ± 0.1	21.2 ± 0.1	51.7 ± 0.1	51.7 ± 0.3
E005	19.8 ± 0.1	20.3 ± 0.1	60.9 ± 0.1	60.3 ± 0.1

[1] Mean ± standard deviation measured over period of two sampling burns, measured next to the water heater near the air intake.

Table 48. Sampling system conditions for experiments with water heater AW05.

Exp.	Flue Temperature 1 (°C)*		Dilution Ratio**	
	Burn 1	Burn 2	Burn 1	Burn 2
E001	258 ± 0.6	264 ± 1.2	16	16
E002	255 ± 0.6	256 ± 0.7	12	12
E003	264 ± 0.7	264 ± 0.8	13	12
E004	251 ± 0.5	252 ± 0.8	13	12
E005	255 ± 0.6	255 ± 0.8	16	16

* Measured in flue 12-inches below elbow prior to blower; mean over last 5 min of each burn.

** Calculated by comparing NO measured in gas manifold (PG-250) and dilution sampler (Thermo 42i) over last 5 min of each burn.

Table 49. Calculated air-free concentrations (using O_2) over last 5 min of each burn, water heater AW05.

Exp	Fuel	Wobbe	CO[1] (ppm)		NO_2[2] (ppm)		NO_X[2] (ppm)	
			B1	B2	B1	B2	B1	B2
E001	1C	1396	1	1	2	2	26	27
E002	1N	1365	2	2	4	4	28	28
E003	3C	1426	3	3	4	4	32	32
E004	PG&E	1349	2	2	4	4	28	28
E005	PG&E	1348	0	1	2	2	25	25

[1] CO emissions adjusted using surface fit given by Equation (1).

[2] Emissions measured from Thermo 42i.

Table 50. Calculated emission rates over entirety of each burn, water heater AW05.

Exp	Fuel	Wobbe	CO[1] (ng/J)		NO_2[2] (ng/J)		NO_X[2] (ng/J)		HCHO (ng/J)	Acetaldehyde (ng/J)
			B1	B2	B1	B2	B1	B2		
E001	1C	1396	1.6	1.0	0.9	0.8	10.3	10.8	0.11	0.10
E002	1N	1365	1.5	1.4	1.6	1.6	10.8	10.9	0.13	0.13
E003	3C	1426	1.7	1.6	1.8	1.8	12.6	12.6	0.11	0.12
E004	PG&E	1349	1.2	1.6	1.6	1.6	10.4	10.5	0.13	0.11
E005	PG&E	1348	1.2	0.9	0.8	0.7	9.4	9.4	0.11	0.10

[1] CO emissions calculated using adjusted ppm CO from surface fit given by Equation (1).

[2] Calculation assumes molecular mass of NO_2 for NO_x (46 g/mol). Emissions measured from Thermo 42i.

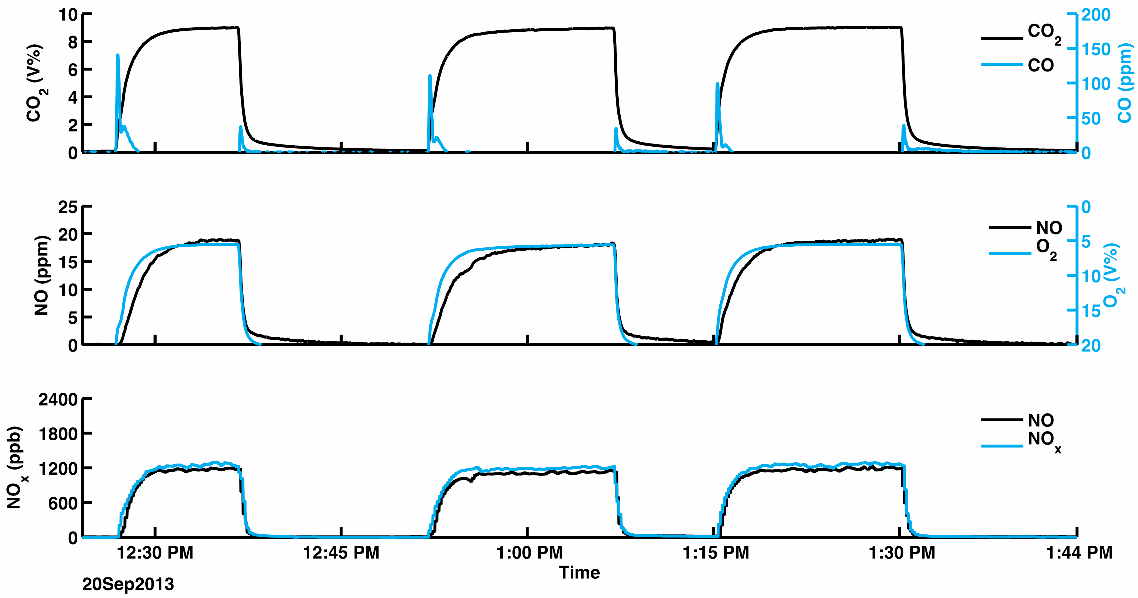

Figure 42. Measured analyte concentrations for storage water heater AW05 with fuel 1C (E001). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn.

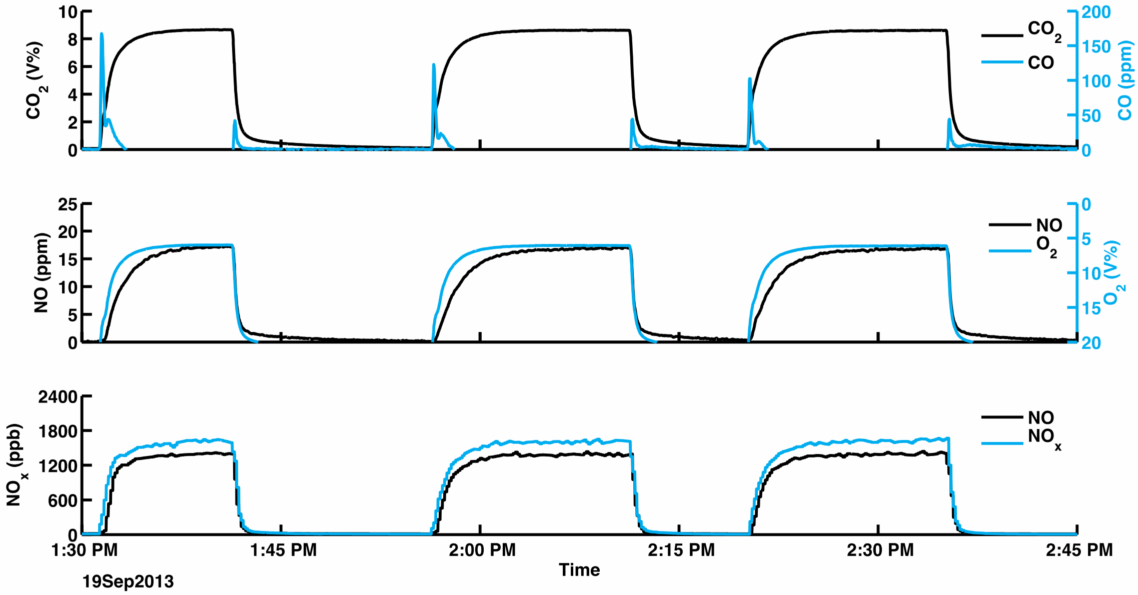

Figure 43. Measured analyte concentrations for storage water heater AW05 with fuel 1N (E002). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system(Thermo 42i). The first large, steady peak is the purge burn.

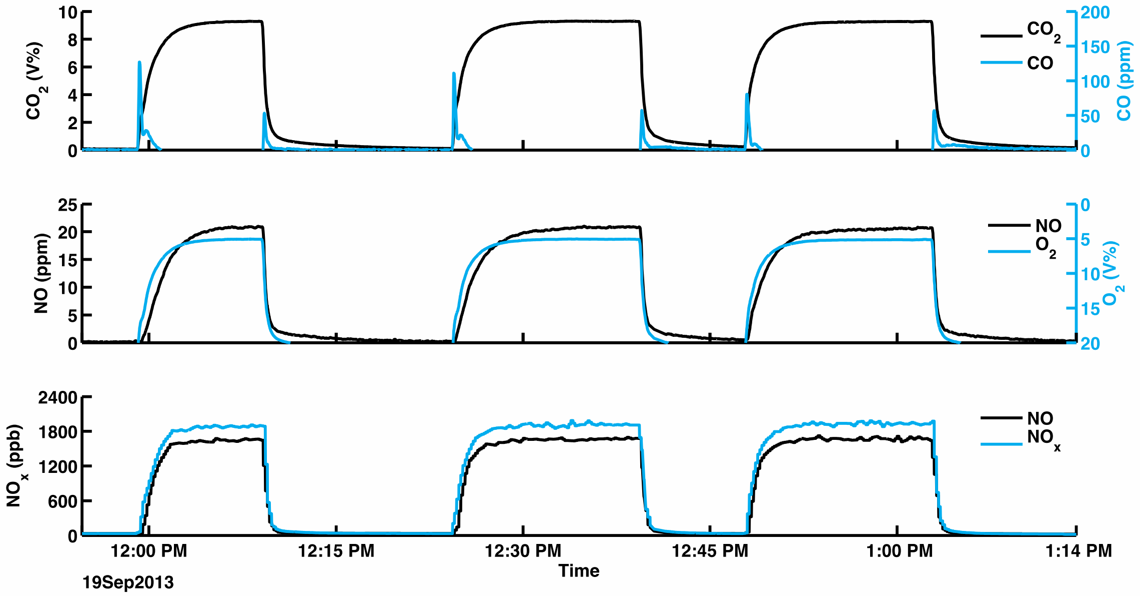

Figure 44. Measured analyte concentrations for storage water heater AW05 with fuel 3C (E003). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system(Thermo 42i). The first large, steady peak is the purge burn.

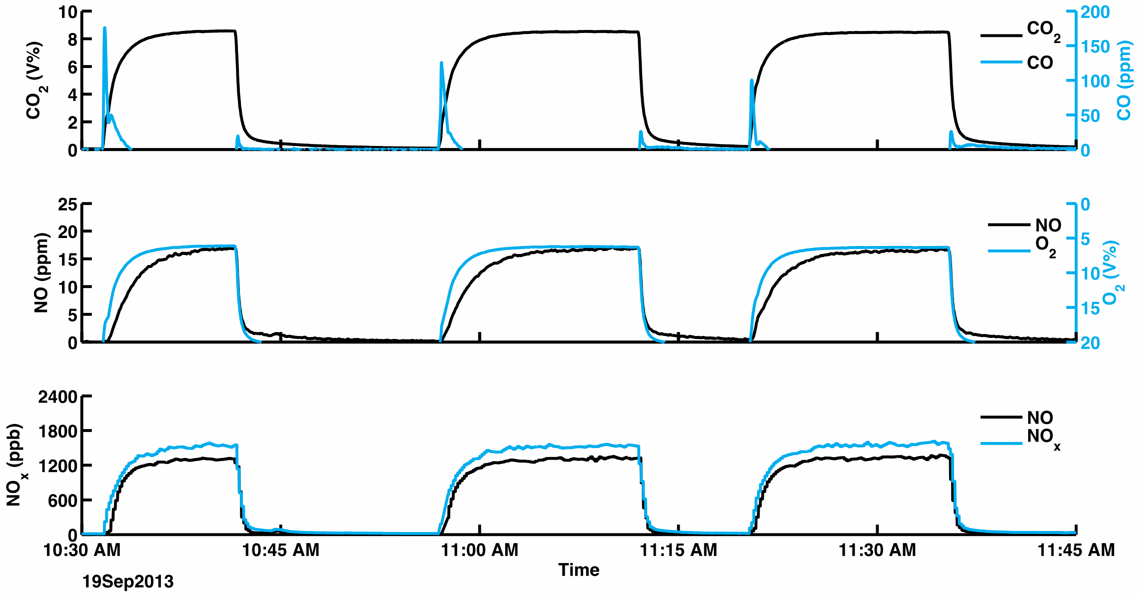

Figure 45. Measured analyte concentrations for storage water heater AW05 with PG&E gas (E004). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn.

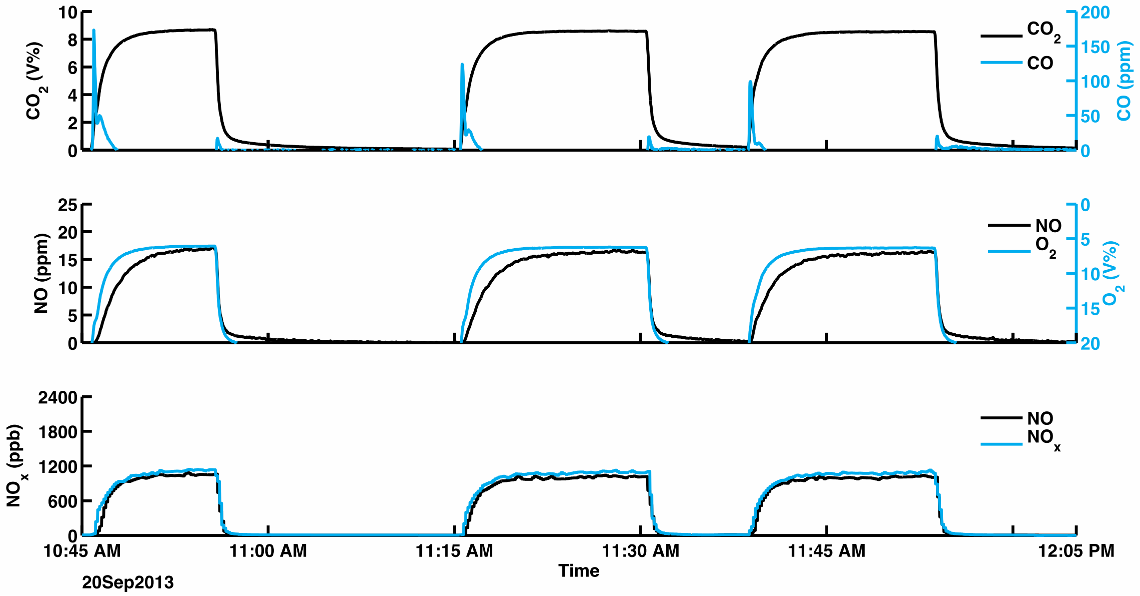

Figure 46. Measured analyte concentrations for storage water heater AW05 with fuel PG&E, repeat (E005). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn.

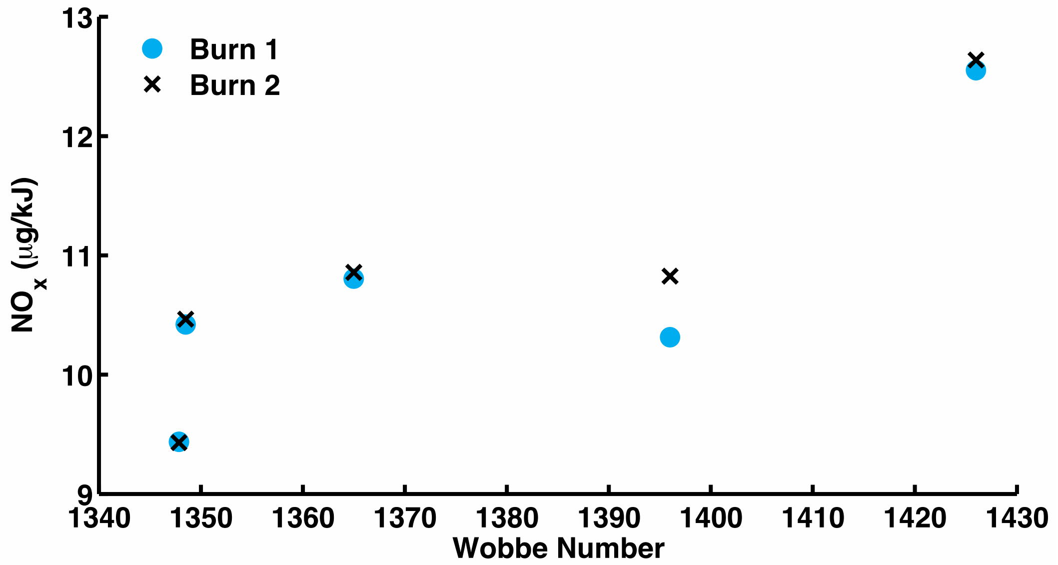

Figure 47. NO_x as a function of Wobbe Number for storage water heater AW05. NO_x concentrations increase slightly with a large increase in Wobbe number and shows little variance between Burn 1 and Burn 2.

3.6 Results for AW06

3.6.1 Summary of Experiments. This induced draft, water heater, which was not compliant with SCAQMD rule 1121, was donated new and installed in the test facilities at LBNL used for LNG interchangeability and energy efficiency experiments (see Figure 48). This water heater was tested for comparing fuel sensitivity of previously compliant technology with newer, ultra-low NO_X compliant technology. Table 51 provides a summary of the burner information. Two thermocouples were installed 12-inches into the exhaust vent. Emissions were also sampled 12-inches into the exhaust vent (see Figure 49).

In October and November of 2013, four experiments were conducted on this unit. Two experiments were conducted on October 24, 2013 using the PG&E line gas (WN=1348) and fuel mixture 1C (WN=1396). On November 4, 2013, two experiments were conducted using fuel mixture 1N (WN =1365) and the PG&E line gas (WN=1352). This water heater was not tested with fuel mixture 3C (WN=1426). Composition and properties of each fuel are presented in Table 52. Environmental conditions were similar on both days. Pressure at the dry gas meter was 7 inches of water for all fuels tested. For all experiments, water was not drawn from the water heater when the burner was operated. Instead, water was drawn prior to each burn and then shut-off before the burner was operated. Additionally, the thermostat was set to the hottest temperature setting during burner operation. The burner was turned on and off by switching the dial between the hottest temperature setting and pilot.

3.6.2 Summary of Results. Tables and figures that follow provide detailed results from the LNG interchangeability experiments for storage water heater AW06. For all experiments, the Horiba gas analyzer overcompensated for CO_2 interference in the CO signal, resulting in negative CO emission measurements. In order to correct for this overcompensation, the surface fit equations described in Section 2.2.4 were used to adjust the measured CO and reported in the tables that follow. At the beginning of each burn, the CO spiked and then dropped to lower concentrations after the first minute of operation. For experiments conducted on November 4, 2013, the Thermo 42i measured slightly more NO than NO_X. This error could be from neglecting to zero NO during calibration or measurement error from the instrument. For experiments conducted on October 24, 2013, at least 92% of NO_X was in the form of NO. Full burn emission rates, shown in Table 58, ranged from 1.2 to 2.8 ng.J for CO and 37.4 to 39.7 ng/J for NO_X. The exhaust contained very little formaldehyde (less than 0.02 ng/J) and acetaldehyde (less than 0.06 ng/J). NO_X increased slightly with Wobbe Number and did not vary much between burns of each fuel mixture (see Figure 54), with the exception of the first burn of the PG&E line gas on October 24, 2013.

Figure 48. **Experimental apparatus installed for storage water heater AW06. Dilution sampling tube is located behind the water heater and sample in the vent. The Thermo 42i and house-air line are located behind the water heater (not shown).**

Figure 49. **Dilution tube and emissions sampling setup for storage water heater AW06. Dilution tube, emissions, and temperature were sampled 12-inches into the vent. The fan draws in combustion air from the bottom of the water heater.**

Table 51. **Published information for water heater AW06.**

Burner ID	AW06
Burner category	Energy Star qualified, induced draft storage water heater
Technology	“Pancake” burner; with hot surface ignitor (no pilot); NOT compliant with SCAQMD rule 1121, does not comply with 10 ng/J NO_x emissions
Appliance manufacturer	Rheem
Model	XR90 (43V30-60)
Serial number	RHLNQ441217522
Capacity	29 gal.
Recovery rating	61 gal per h
Energy factor rating	0.70 (Energy Star qualified)
Design manifold Press	5.0 in. H_2O
Burner ratings (Btu/h)	60,000

Table 52. Composition of fuels for interchangeability experiments for storage water heater AW06.

Exp.	Fuel	Date	N_2 (%)	CO_2 (%)	HHV (Btu/scf)	Wobbe Number
F001	1C+	10/24/13	0.00	0.00	1076	1396
F002	1N+	11/04/13	1.70	0.00	1058	1365
F003	PG&E*	10/24/13	0.53**	0.73**	1028	1348
F004	PG&E*	11/04/13	0.42**	0.69**	1031	1352

+ All information provided by Praxair.

* Gas quality information provided by PG&E online pipeline data, line J01 (downloaded 11/04/2013).

** Values are given in mol % not volume %.

Table 53. Burner operating parameters for experiments with storage water heater AW06.

Exp.	Burn times		Fuel flowrate (ft^3 h^{-1})		Firing rate (kBtu/h)	
	Burn 1	Burn 2	B1	B2	B1	B2
F001	13:50:11-14:05:12	14:13:13-14:28:11	57.1	56.5	61.5	60.8
F002	14:31:09-14:46:09	14:54:23-15:09:23	56.6	56.4	59.9	59.7
F003	13:11:17-13:26:16	13:26:16-13:49:47	57.4	57.3	59.0	58.8
F004	12:11:00-12:26:00	12:34:43-12:49:42	57.5	57.4	59.3	59.2

Table 54. Aldehyde measurement times with storage water heater AW06*.

Fuel	Experiment	Date	Aldehyde Start Time	Aldehyde Stop Time	Total Liters Sampled
Lab Air**	-	10/24/13	12:42	14:51	134.0
Lab Air**	-	11/04/13	11:41	13:52	132.2
1C	F001	10/24/13	13:44	14:36	59.3
			13:44	14:36	64.0
1N	F002	11/04/13	14:25	15:14	55.1
			14:25	15:14	60.1
PG&E	F003	10/24/13	12:48	13:56	76.3
			12:48	13:56	82.7
PG&E	F004	11/04/13	12:07	13:21	84.1
			12:07	13:21	90.8

*Two Aldehyde measurements were taken on the dilution tube for each experiment.

**Aldehyde was measured directly from the lab air supply.

Table 55. Combustion air conditions[1] for experiments with water heater AW06.

Exp.	T, burn 1 (°C)	T, burn 2 (°C)	RH, burn 1 (%)	RH, burn 2 (%)
F001	20.7 ± 0.3	21.2 ± 0.1	28.5 ± 0.3	27.8 ± 0.2
F002	19.9 ± 0.2	20.2 ± 0.2	48.9 ± 0.4	48.2 ± 0.4
F003	19.9 ± 0.2	20.0 ± 0.2	48.8 ± 0.4	48.1 ± 0.5
F004	20.4 ± 0.2	20.6 ± 0.2	26.5 ± 0.1	26.7 ± 0.2

[1] Mean ± standard deviation measured over period of two sampling burns, measured next to the water heater near the air intake.

Table 56. Sampling system conditions for experiments with water heater AW06.

Exp.	Flue Temperature 1 (°C)[1]		Flue Temperature 2 (°C)[2]		Dilution Ratio[3]	
	Burn 1	Burn 2	Burn 1	Burn 2	Burn 1	Burn 2
F001	158 ± 1.2	159 ± 1.0	150 ± 1.3	150 ± 1.1	18	18
F002	157 ± 1.3	158 ± 1.2	148 ± 1.3	149 ± 1.2	16	16
F003	156 ± 1.1	157 ± 1.1	148 ± 1.0	149 ± 1.2	17	17
F004	156 ± 1.2	157 ± 1.1	148 ± 1.2	149 ± 1.2	18	18

[1] Measured in flue (PVC-piping) 12-inches below elbow prior to blower; mean over last 5 min of each burn.

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

Table 57. Calculated air-free concentrations (using O_2) over last 5 min of each burn, water heater AW06.

Exp	Fuel	Wobbe	CO[1] (ppm)		NO_2[2] (ppm)		NO_X[2] (ppm)	
			B1	B2	B1	B2	B1	B2
F001	1C	1396	9	8	-2	-3	99	99
F002	1N	1365	6	5	7	7	94	95
F003	PG&E	1348	4	4	7	8	95	95
F004	PG&E	1352	4	4	-4	-4	97	97

[1] CO emissions adjusted using surface fit given by Equation (1).

[2] Emissions measured from Thermo 42i. Negative NO_2 values could be a result of miscalibration.

Table 58. Calculated emission rates over entirety of each burn, water heater AW06.

Exp	Fuel	Wobbe	CO[1] (ng/J)		NO_2[2] (ng/J)		NO_X[2] (ng/J)		HCHO (ng/J)	Acetaldehyde (ng/J)
			B1	B2	B1	B2	B1	B2		
F001	1C	1396	2.8	2.2	-1.1	-1.2	39.2	39.7	0.02	0.06
F002	1N	1365	2.1	1.9	3.2	3.1	38.0	38.4	0.02	0.05
F003	PG&E	1348	1.2	1.3	3.0	3.1	39.2	37.4	0.02	0.06
F004	PG&E	1352	1.4	1.2	-1.3	-1.4	37.9	38	0.01	0.05

[1] CO emissions calculated using adjusted ppm CO from surface fit given by Equation (1).

[2] Calculation assumes molecular mass of NO_2 for NO_x (46 g/mol). Emissions measured from Thermo 42i. Negative NO_2 values could be a result of miscalibration.

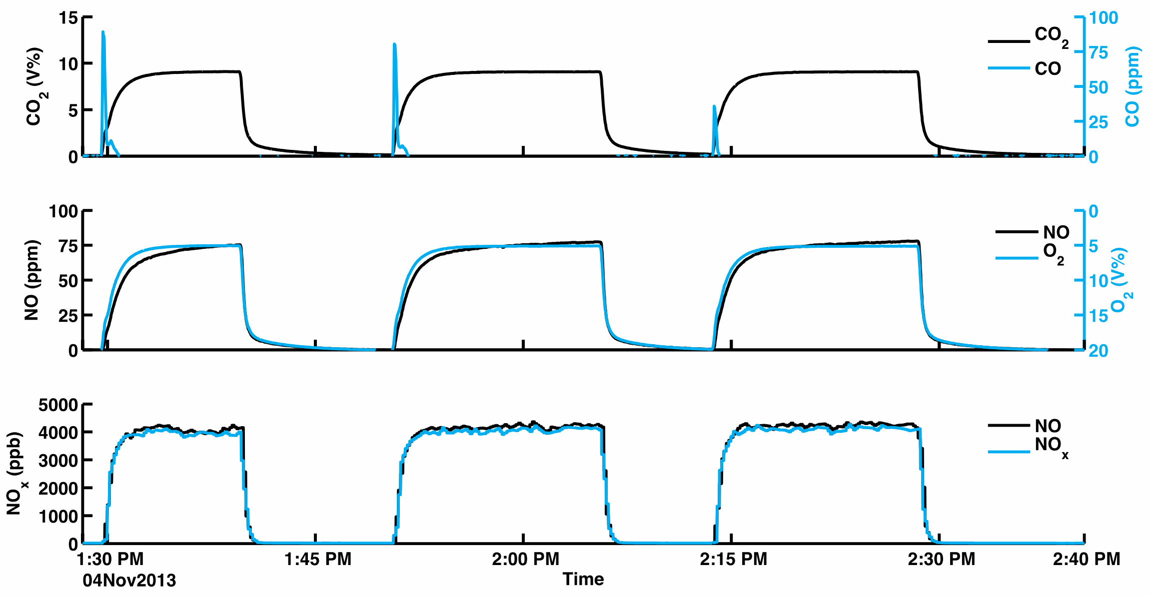

Figure 50. **Measured analyte concentrations for storage water heater AW06 with fuel 1C (F001). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn.**

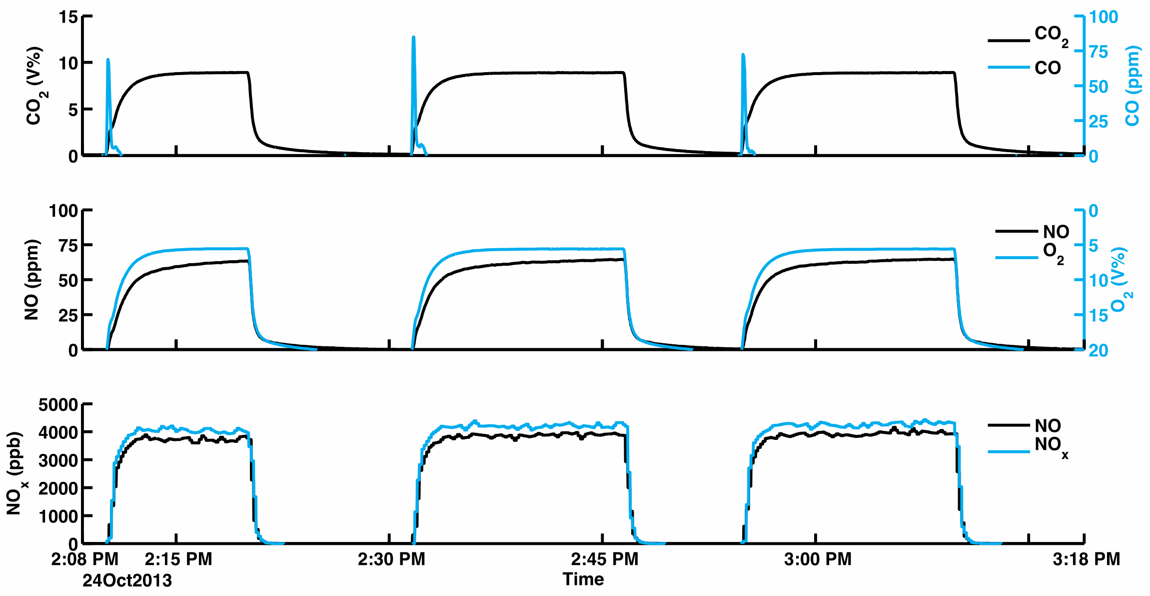

Figure 51. **Measured analyte concentrations for storage water heater AW06 with fuel 1N (F002). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system(Thermo 42i). The first large, steady peak is the purge burn.**

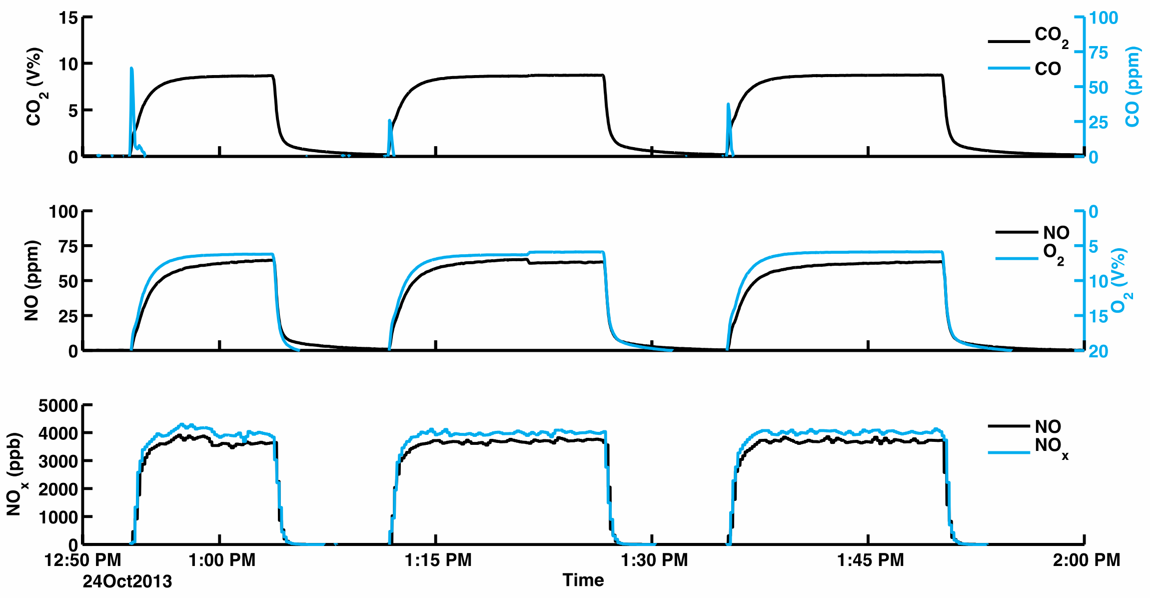

Figure 52. Measured analyte concentrations for storage water heater AW06 with PG&E gas (F003). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn.

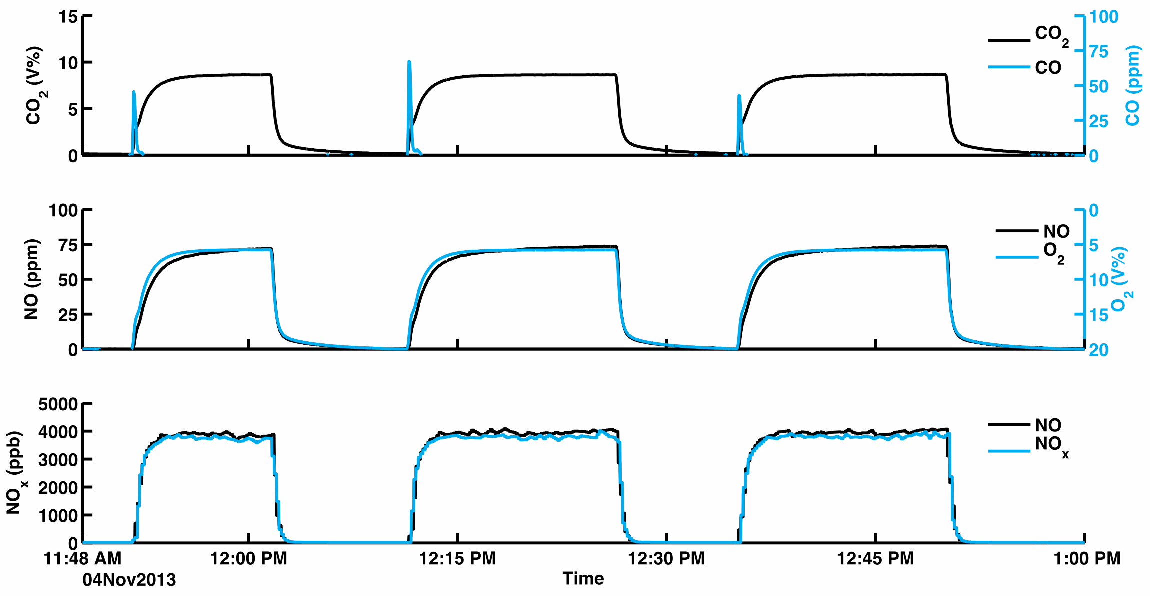

Figure 53. Measured analyte concentrations for storage water heater AW06 with fuel PG&E, repeat (F004). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn.

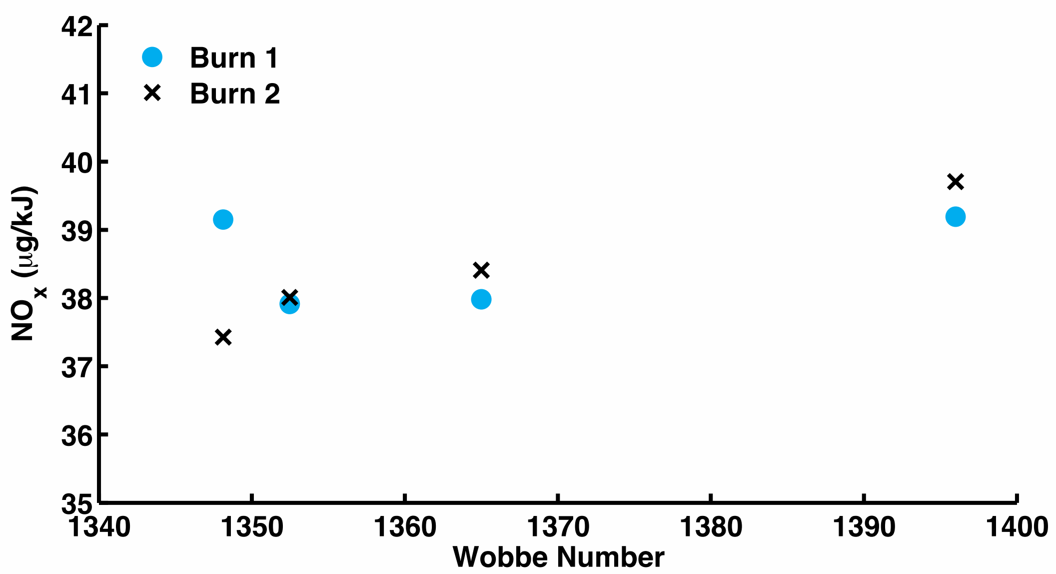

Figure 54. **NO_x as a function of Wobbe Number for storage water heater AW06. NO_x concentrations increase slightly with Wobbe Number. NO_x shows little variation between Burn 1 and Burn 2 except for the first burn of the lowest Wobbe Number fuel (PG&E line gas).**

3.7 Results for AW07

3.7.1 Summary of Experiments. This induced draft, water heater (not compliant with SCAQMD rule 1121) was donated new and installed in the test facilities at LBNL used for LNG interchangeability and energy efficiency experiments (see Figure 55). This water heater was tested for comparing fuel sensitivity of previously compliant technology with newer, ultra-low NO_X compliant technology. Table 59 provides a summary of the burner information. The fan (or intake blower) is located on the side of the water heater and is used to pull combustion air into the chamber, as shown in Figure 56. The combustion system is pressurized using the intake blower in order to achieve higher efficiency (Energy Factor = 0.70).

In November of 2013, five experiments were conducted on this unit. Two experiments were conducted on November 7, 2013 using the PG&E line gas (WN=1349) and fuel mixture 1C (WN=1396). On November 14, 2013, three experiments were conducted using fuel mixture 1N (WN =1365), fuel mixture 3C (WN=1426), and the PG&E line gas (WN=1348). Composition and properties of each fuel are presented in Table 60. For all experiments, water was not drawn from the water heater when the burner was operated. Instead, water was drawn prior to each burn and then shut-off before the burner was operated. The thermostat was set to the hottest temperature setting during burner operation. The burner was turned on and off by switching the dial between the hottest temperature setting and pilot. Environmental conditions were similar on both days. Pressure at the dry gas meter was 7 inches of water for all fuels tested. The two thermocouples were installed 12-inches into the central flue prior to the draft diverter. Emissions were also sampled 12-inches into the central flue (see Figure 58).

3.7.2 Summary of Results. Tables and figures that follow provide detailed results from the LNG interchangeability experiments for storage water heater AW07. For all experiments, the Horiba gas analyzer overcompensated for CO_2 interference in the CO signal, resulting in negative CO emission measurements. In order to correct for this overcompensation, the surface fit equations described in Section 2.2.4 were used to adjust the measured CO and reported in the tables that follow. At the beginning of each burn, the CO spiked and then dropped to lower concentrations after the first minute of operation. For all experiments, between 87% and 90% of NO_X was in the form of NO. Full burn emission rates, shown in Table 66, ranged from 0.8 to 1.6 ng/J for CO and 34.0 to 38.9 ng/J for NO_X, 0.03-0.08 ng/J for formaldehyde, and 0.04-0.10 ng/J for acetaldehyde. NO_X increased slightly with Wobbe Number and did not vary much between burns of each fuel mixture (see Figure 64), with the exception of the first burn of the PG&E line gas on November 7, 2013.

Figure 55. **Experimental apparatus installed for storage water heater AW07. Dilution sampling tube is located behind the water heater and sampled before the fan. The Thermo 42i and house-air line are located behind the water heater (not shown).**

Figure 56. **Air intake for water heater AW07. Temperature and relative humidity were measured in front of the air intake.**

Figure 57. **Dilution tube and emissions sampling setup for storage water heater AW07. Dilution tube, emissions, and temperature were sampled 12-inches into the flue prior to the draft diverter.**

Figure 58. **Detailed image of dilution tube and emissions sampling setup for storage water heater AW07. Turbulator was bent slightly to accommodate exhaust lines and thermocouples.**

Table 59. **Published information for water heater AW07.**

Burner ID	AW07
Burner category	Energy Star qualified, induced draft storage water heater
Technology	"Pancake" burner; with hot surface ignitor (no pilot); NOT compliant with SCAQMD rule 1121, does not comply with 10 ng/J NO_x emissions
Appliance manufacturer	A.O. Smith
Model	Effex® (Model GAHH-40 102)
Serial number	1231A002000
Capacity	40.0 gal.
Recovery rating	46.55 gal per hr
Energy factor rating	0.7
Design manifold Press	4.0 in. H_2O
Burner ratings (Btu/h)	40,000

Table 60. **Composition of fuels for interchangeability experiments for storage water heater AW07.**

Exp.	Fuel	Date	N_2 (%)	CO_2 (%)	HHV (Btu/scf)	Wobbe Number
G001	1C$^+$	11/07/13	0.00	0.00	1076	1396
G002	1N$^+$	11/14/13	1.70	0.00	1058	1365
G003	3C$^+$	11/14/13	0.00	0.00	1131	1426
G004	PG&E*	11/07/13	0.48**	0.71**	1027	1349
G005	PG&E*	11/14/13	0.54**	0.72**	1027	1348

$^+$ All information provided by Praxair.
* Gas quality information provided by PG&E online pipeline data, line J01 (downloaded 11/14/2013).
** Values are given in mol % not volume %.

Table 61. **Burner operating parameters for experiments with storage water heater AW07.**

Exp.	Burn times		Fuel flowrate (ft^3 h^{-1})		Firing rate (kBtu/h)	
	Burn 1	Burn 2	B1	B2	B1	B2
G001	13:55:11-14:10:14	14:18:31-14:33:30	33.5	33.2	36.0	35.7
G002	12:01:53-12:16:54	12:25:33-12:40:35	33.1	33.0	35.1	34.9
G003	13:29:22-13:44:21	13:52:32-14:08:34	32.3	30.2	36.6	34.2
G004	12:28:17-12:43:15	12:43:15-13:06:14	33.5	33.6	34.4	34.5
G005	10:34:06-10:49:08	10:57:44-11:12:42	33.4	33.3	34.3	34.2

Table 62. Aldehyde measurement times with storage water heater AW07[*].

Fuel	Experiment	Date	Aldehyde Start Time	Aldehyde Stop Time	Total Liters Sampled
Lab Air[**]	-	11/07/2013	11:48	13:50	122.5
Lab Air[**]	-	11/14/2013	9:53	11:53	125.5
1C	G001	11/07/2013	13:43	14:44	65.7
			13:43	14:44	70.1
1N	G002	11/14/2013	11:57	12:48	57.4
			11:57	12:48	56.9
3C	G003	11/14/2013	13:23	14:15	57.9
			13:23	14:15	62.6
PG&E	G004	11/07/2013	12:23	13:15	56.3
			12:23	13:15	59.4
PG&E	G005	11/14/2013	10:25	11:20	57.9
			10:25	11:20	45.7

[*] Two Aldehyde measurements were taken on the dilution tube for each experiment.

[**] Aldehyde was measured directly from the lab air supply.

Table 63. **Combustion air conditions[1] for experiments with water heater AW07.**

Exp.	T, burn 1 (°C)	T, burn 2 (°C)	RH, burn 1 (%)	RH, burn 2 (%)
G001	21.3 ± 0.1	21.1 ± 0.1	35.2 ± 0.3	34.4 ± 0.2
G002	19.5 ± <0.1	19.8 ± <0.1	60.0 ± 0.2	59.2 ± 0.2
G003	19.9 ± 0.1	19.7 ± 0.1	56.9 ± 0.3	55.4 ± 0.2
G004	21.0 ± 0.1	21.2 ± 0.1	38.5 ± 0.2	38.1 ± 0.4
G005	18.9 ± 0.1	19.0 ± 0.1	62.5 ± 0.3	61.7 ± 0.3

[1] Mean ± standard deviation measured over period of two sampling burns, measured next to the water heater near the air intake.

Table 64. Sampling system conditions for experiments with water heater AW07.

Exp.	Flue Temperature 1 (°C)[1]		Flue Temperature 2 (°C)[2]		Dilution Ratio[3]	
	Burn 1	Burn 2	Burn 1	Burn 2	Burn 1	Burn 2
C001	194 ± 1	195 ± 0.6	174 ± 0.7	178 ± 0.7	16	17
C002	199 ± 0.9	199 ± 2.1	181 ± 0.6	180 ± 0.7	13	13
C003	203 ± 0.6	206 ± 0.9	186 ± 0.6	186 ± 0.6	13	13
C004	193 ± 0.8	180 ± 0.8	176 ± 0.6	164 ± 0.3	16	16
C005	196 ± 0.9	198 ± 0.9	181 ± 0.5	181 ± 0.5	12	12
C006	194 ± 1.0	195 ± 0.6	174 ± 0.7	178 ± 0.7	16	17

[1] Measured in flue (PVC-piping) 12-inches below elbow prior to blower; mean over last 5 min of each burn.

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

Table 65. Calculated air-free concentrations (using O_2) over last 5 min of each burn, water heater AW07.

Exp	Fuel	Wobbe	CO[1] (ppm)		NO_2[2] (ppm)		NO_X[2] (ppm)	
			B1	B2	B1	B2	B1	B2
G001	1C	1396	2	2	10	10	93	101
G002	1N	1365	3	3	11	11	93	93
G003	3C	1426	3	3	11	11	96	96
G004	PG&E	1349	2	3	10	9	93	89
G005	PG&E	1348	3	3	12	12	95	95

[1] CO emissions adjusted using surface fit given by Equation (1).

[2] Emissions measured from Thermo 42i.

Table 66. Calculated emission rates over entirety of each burn, water heater AW07.

Exp	Fuel	Wobbe	CO[1] (ng/J)		NO_2[2] (ng/J)		NO_X[2] (ng/J)		HCHO (ng/J)	Acetaldehyde (ng/J)
			B1	B2	B1	B2	B1	B2		
G001	1C	1396	0.8	0.9	4.3	4.2	37.5	38.9	0.04	0.10
G002	1N	1365	1.3	1.3	4.9	4.8	37.7	37.6	0.04	0.05
G003	3C	1426	1.0	1.1	4.7	4.8	38.7	38.9	0.03	0.05
G004	PG&E	1349	1.2	1.6	4.2	3.9	36.3	34.0	0.08	0.12
G005	PG&E	1348	1.4	1.6	5.0	4.8	37.1	37.1	0.05	0.04

[1] CO emissions calculated using adjusted ppm CO from surface fit given by Equation (1).

[2] Calculation assumes molecular mass of NO_2 for NO_x (46 g/mol). Emissions measured from Thermo 42i.

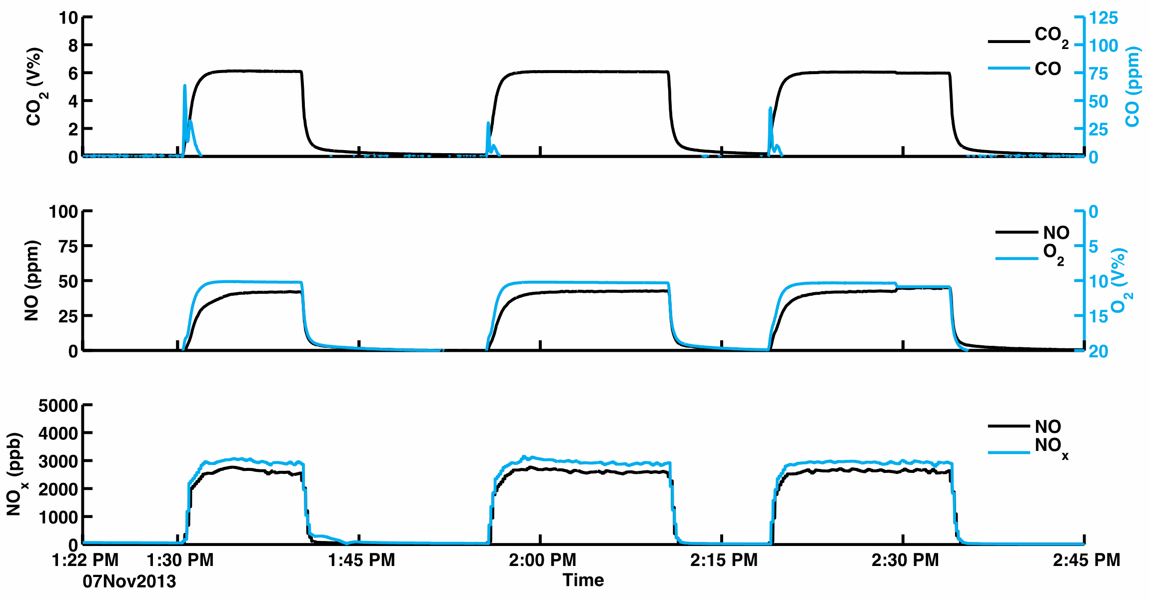

Figure 59. **Measured analyte concentrations for storage water heater AW07 with fuel 1C (G001). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn.**

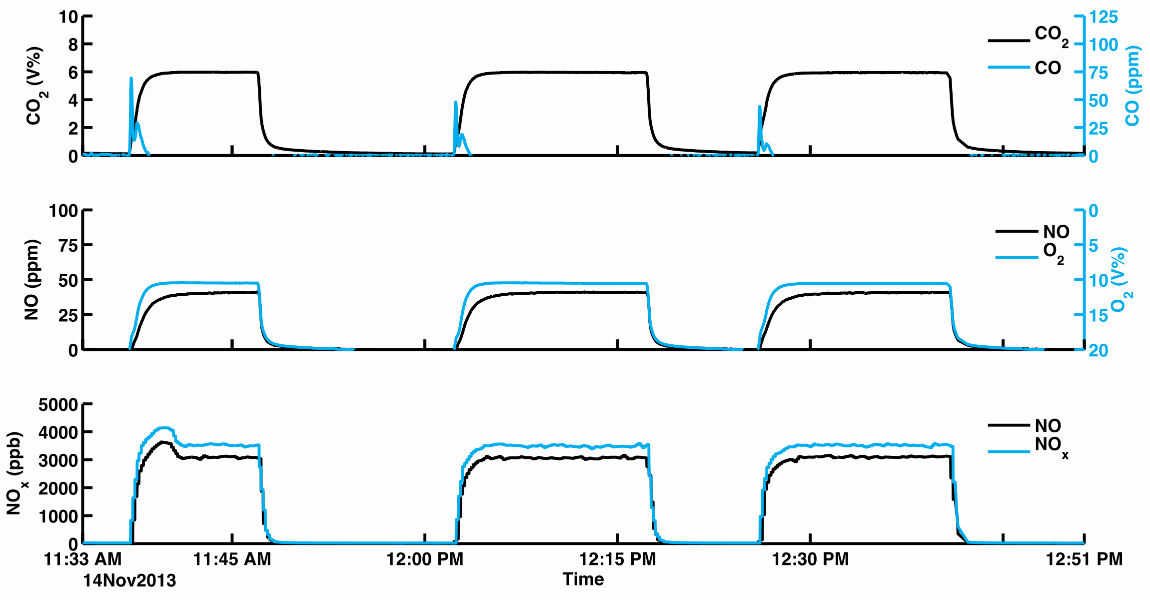

Figure 60. **Measured analyte concentrations for storage water heater AW07 with fuel 1N (G002). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn.**

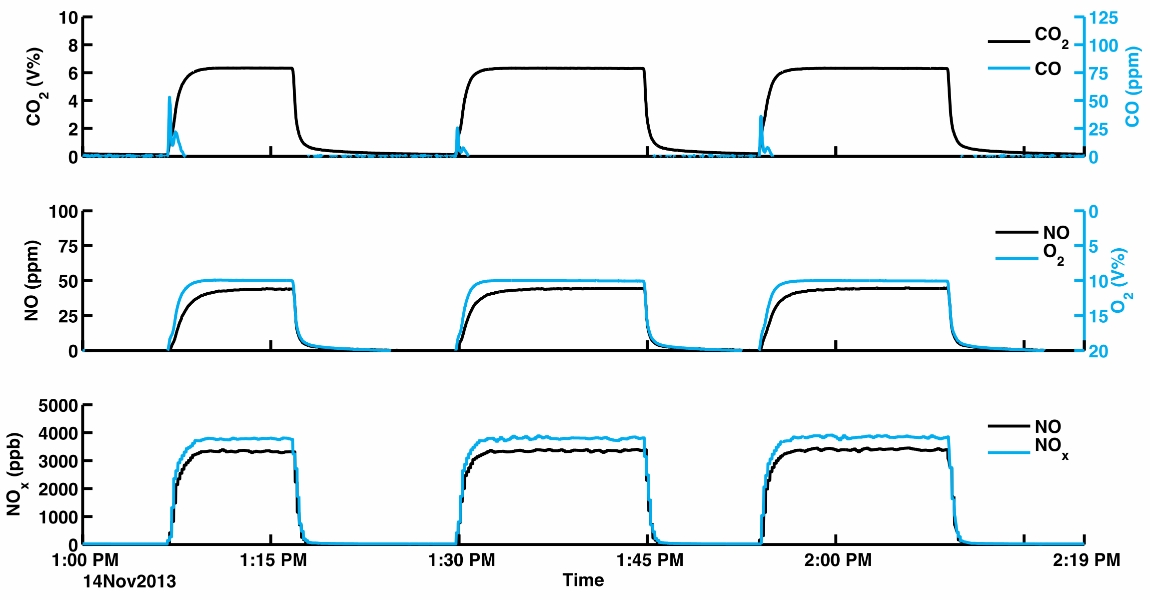

Figure 61. Measured analyte concentrations for storage water heater AW07 with fuel 3C (G003). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn.

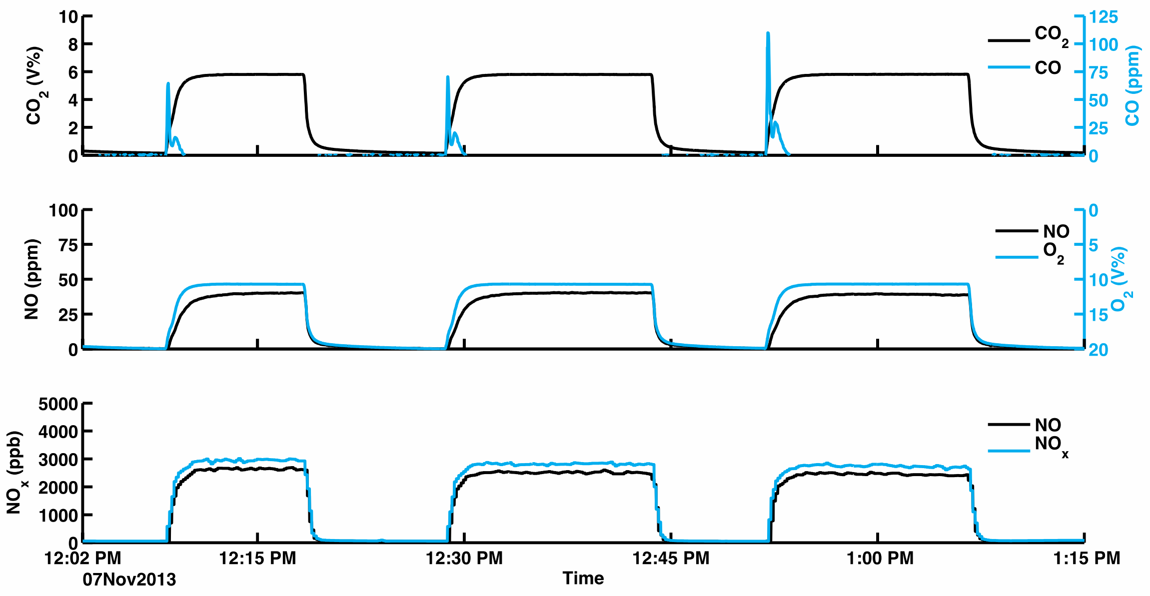

Figure 62. Measured analyte concentrations for storage water heater AW07 with PG&E gas (G004). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn.

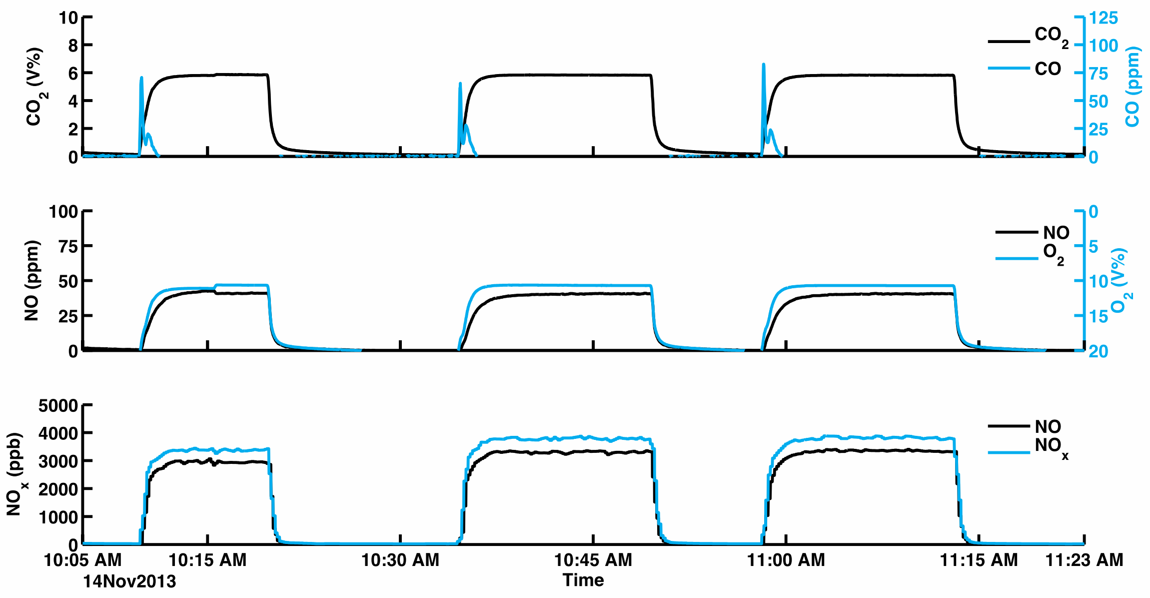

Figure 63. Measured analyte concentrations for storage water heater AW07 with fuel PG&E, repeat (G005). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn.

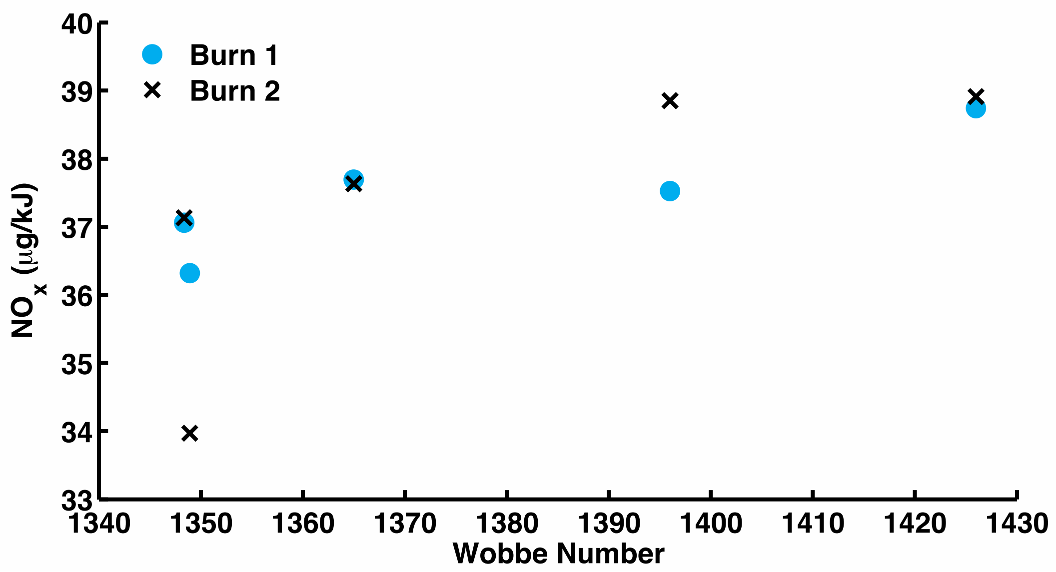

Figure 64. NO$_x$ as a function of Wobbe Number for storage water heater AW07. NO$_x$ concentrations increase slightly with Wobbe Number. NO$_x$ does not vary much between Burn 1 and Burn 2 except for the first PG&E line gas experiment (WN=1349).

3.8 Results for AW08

3.8.1 Summary of Experiments. This condensing, ultra-low NO_X water heater was donated new and installed in the test facilities at LBNL used for LNG interchangeability and energy efficiency experiments (see Figure 65). Table 67 provides a summary of the burner information. This advanced technology water heater has a separate combustion air intake located on the top of the water heater, shown in Figure 66. The water heater has a thermal efficiency of 96% and contains a helical internal heat exchanger with a cylindrical burner located in the center of the tank.

In November of 2013, five experiments were conducted on this unit over two consecutive days. Three experiments were conducted on November 26, 2013 using the PG&E line gas (WN=1348), fuel mixture 1N (WN =1365), and fuel mixture 3C (WN=1426). On the following day, November 27, 2013, two experiments were conducted using, fuel mixture 1C (WN=1396) and the PG&E line gas (WN=1349). Composition and properties of each fuel are presented in Table 68. For all experiments, water was not drawn from the water heater when the burner was operated. Instead, water was drawn prior to each burn and then shut-off before the burner was operated. The thermostat was set to the hottest temperature setting during burner operation. The burner was turned on and off by switching the water heater on and off.

Environmental conditions were similar on both days. Pressure at the dry gas meter was 7 inches of water for all fuels tested. Two thermocouples were installed 12-inches into the exhaust vent (see Figure 67); however, one of the thermocouples failed when operating the water heater prior to the fuel interchangeability experiments. Emissions were also sampled 12-inches into the exhaust vent.

3.8.2 Summary of Results. Tables and figures that follow provide detailed results from the LNG interchangeability experiments for storage water heater AW08. For all experiments, the Horiba gas analyzer overcompensated for CO_2 interference in the CO signal, resulting in negative CO emission measurements. In order to correct for this overcompensation, the surface fit equations described in Section 2.2.4 were used to adjust the measured CO and reported in the tables that follow. At the beginning of each burn, the CO spiked and then dropped to lower concentrations after the first minute of operation. For all experiments, 80% to 92% of the NO_X was in the form of NO. Full burn emission rates, shown in Table 74, ranged from 0.6 to 1.0 ng/J of CO and 12.0.0 to 20.9 ng/J for NO_X. The exhaust contained almost no formaldehyde (less than 0.01 ng/J) and very little acetaldehyde (less than 0.04 ng/J). NO_X increased linearly with Wobbe Number and did not vary much between burns of each fuel mixture (see Figure 73). NO_X emissions from this water heater are more sensitive to fuel composition than other storage water heaters investigated in this study.

Figure 65. **Experimental apparatus installed for storage water heater AW08. Dilution sampling tube is located behind the water heater and sampled before the fan. The Thermo 42i and house-air line are located behind the water heater (not shown).**

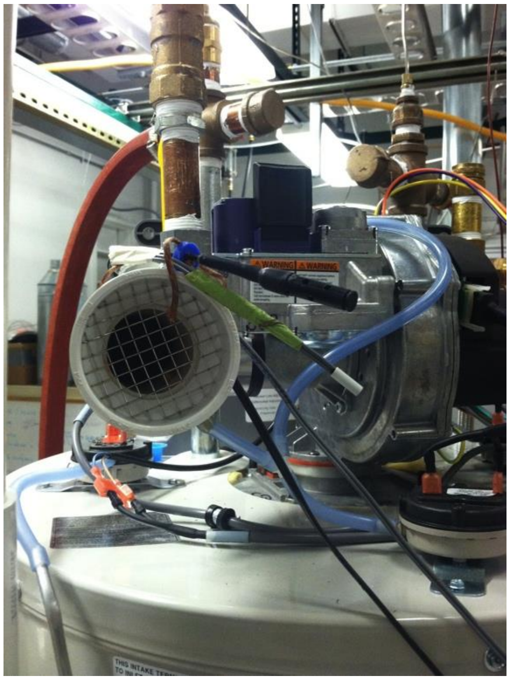

Figure 66. **Air intake for water heater AW08. Temperature and relative humidity were measured in front of the air intake.**

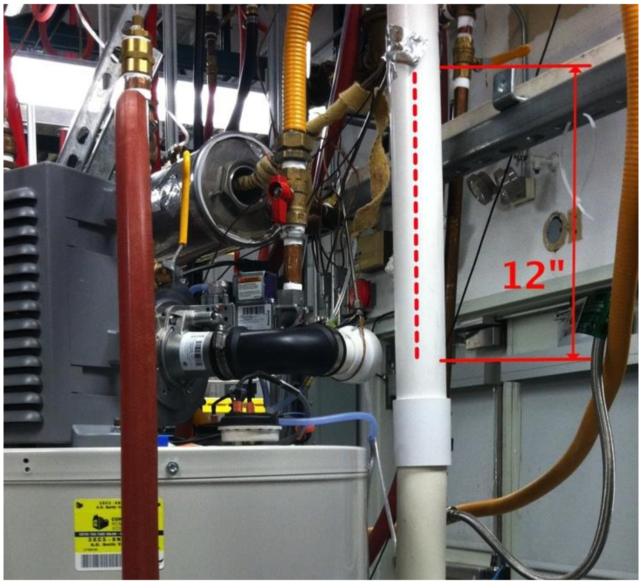

Figure 67. **Dilution tube and emissions sampling setup for storage water heater AW08. Dilution tube, emissions, and temperature were sampled 12-inches into the exhaust vent.**

Table 67. **Published information for water heater AW08.**

Burner ID	AW08
Burner category	Condensing, ultra-low NO_X storage water heater
Technology	Cylindrical burner positioned in the center of the tank with hot surface ignitor (no pilot); SCAQMD rule 1146.2 compliant, complies with 14 ng/J NO_x emissions; power vent; condensing
Appliance manufacturer	A.O. Smith
Model	Vertex (Model GDHE 50 124)
Serial number	1237M001769
Capacity	50 gal.
Recovery rating	129.29 gal per h
Thermal Efficiency	0.96
Design manifold Press	4 in. H_2O
Burner ratings (Btu/h)	100,000

Table 68. **Composition of fuels for interchangeability experiments for storage water heater AW08.**

Exp.	Fuel	Date	N_2 (%)	CO_2 (%)	HHV (Btu/scf)	Wobbe Number
H001	1C$^+$	11/27/13	0.00	0.00	1076	1396
H002	1N$^+$	11/26/13	1.70	0.00	1058	1365
H003	3C$^+$	11/26/13	0.00	0.00	1131	1426
H004	PG&E*	11/26/13	0.59**	0.70**	1028	1348
H005	PG&E*	11/27/13	0.57**	0.72**	1029	1349

$^+$ All information provided by Praxair.
* Gas quality information provided by PG&E online pipeline data, line J01 (downloaded 11/27/2013).
** Values are given in mol % not volume %.

Table 69. Aldehyde measurement times with storage water heater AW08*.

Fuel	Experiment	Date	Aldehyde Start Time	Aldehyde Stop Time	Total Liters Sampled
Lab Air**	-	11/26/13	9:45	11:45	128.35
Lab Air**	-	11/27/13	10:15	12:15	135.5
1C	H001	11/27/13	12:03	12:58	59.6
			12:03	12:58	60.9
1N	H002	11/26/13	13:16	14:12	58.7
			13:16	14:12	46.5
3C	H003	11/26/13	11:37	12:37	65.0
			11:37	12:37	69.3
PG&E	H004	11/26/13	10:16	11:09	56.29
			10:16	11:09	59.04
PG&E	H005	11/27/13	10:45	11:38	58.7
			10:45	11:38	57.9

*Two Aldehyde measurements were taken on the dilution tube for each experiment.
**Aldehyde was measured directly from the lab air supply.

Table 70. Burner operating parameters for experiments with storage water heater AW08.

Exp.	Burn times		Fuel flowrate (ft^3 h^{-1})		Firing rate (kBtu/h)	
	Burn 1	Burn 2	B1	B2	B1	B2
H001	12:13:29-12:28:18	12:36:50-12:51:50	90.0	89.6	96.9	96.4
H002	13:27:29-13:41:45	13:50:51-14:05:51	88.8	89.3	93.9	94.5
H003	11:49:34-12:04:03	12:13:20-12:28:20	86.0	86.1	97.3	97.4
H004	10:20:36-10:35:35	10:35:35-10:59:31	90.8	89.5	92.8	91.9
H005	10:50:29-11:05:28	11:14:02-11:29:01	90.8	90.7	93.4	93.3

Table 71. Combustion air conditions[1] for experiments with water heater AW08.

Exp.	T, burn 1 (°C)	T, burn 2 (°C)	RH, burn 1 (%)	RH, burn 2 (%)
H001	21.9 ± 0.4	22.1 ± 0.2	39.3 ± 0.7	38.0 ± 0.8
H002	21.5 ± 0.3	21.8 ± 0.2	33.6 ± 0.4	33.1 ± 0.2
H003	21.7 ± 0.4	22.0 ± 0.2	35.6 ± 0.5	35.1 ± 0.4
H004	21.1 ± 0.4	21.6 ± 0.3	38.0 ± 0.7	36.3 ± 0.5
H005	22.1 ± 0.4	22.5 ± 0.3	38.9 ± 1.1	37.4 ± 1.0

[1] Mean ± standard deviation measured over period of two sampling burns, measured next to the water heater near the air intake.

Table 72. Sampling system conditions for experiments with water heater AW08.

Exp.	Flue Temperature 1 (°C)[*]		Dilution Ratio[**]	
	Burn 1	Burn 2	Burn 1	Burn 2
H001	49 ± 1.8	47 ± 1.8	14	14
H002	49 ± 2.0	47 ± 1.8	13	14
H003	48 ± 1.8	46 ± 1.8	12	12
H004	49 ± 1.7	47 ± 1.7	12	12
H005	49 ± 1.7	48 ± 1.6	14	14
H006	49 ± 1.8	47 ± 1.8	14	14

[*] Measured in flue (PVC-piping) 12-inches below elbow prior to blower; mean over last 5 min of each burn.

[**] Calculated by comparing NO measured in gas manifold (PG-250) and dilution sampler (Thermo 42i) over last 5 min of each burn.

Table 73. Calculated air-free concentrations (using O_2) over last 5 min of each burn, water heater AW08.

Exp	Fuel	Wobbe	CO[1] (ppm)		NO_2[2] (ppm)		NO_X[2] (ppm)	
			B1	B2	B1	B2	B1	B2
H001	1C	1396	3	4	7	7	43	44
H002	1N	1365	2	2	4	4	33	32
H003	3C	1426	3	3	4	4	50	50
H004	PG&E	1348	1	1	4	4	28	28
H005	PG&E	1350	2	2	6	6	31	31

[1] CO emissions adjusted using surface fit given by Equation (1).

[2] Emissions measured from Thermo 42i.

Table 74. Calculated emission rates over entirety of each burn, water heater AW08.

Exp	Fuel	Wobbe	CO[1] (ng/J)		NO_2[2] (ng/J)		NO_X[2] (ng/J)		HCHO (ng/J)	Acetaldehyde (ng/J)
			B1	B2	B1	B2	B1	B2		
H001	1C	1396	1.0	1.0	2.7	2.7	17.3	17.4	0.01	0.03
H002	1N	1365	0.6	0.6	1.5	1.5	13.4	13.1	0.01	0.04
H003	3C	1426	1.0	1.0	1.8	1.7	20.9	20.1	0.01	0.03
H004	PG&E	1348	0.5	0.4	1.4	1.3	11.5	10.8	0.01	0.03
H005	PG&E	1350	0.7	0.7	2.2	2.2	12.1	12.0	0.01	0.03

[1] CO emissions calculated using adjusted ppm CO from surface fit given by Equation (1).

[2] Calculation assumes molecular mass of NO_2 for NO_x (46 g/mol). Emissions measured from Thermo 42i.

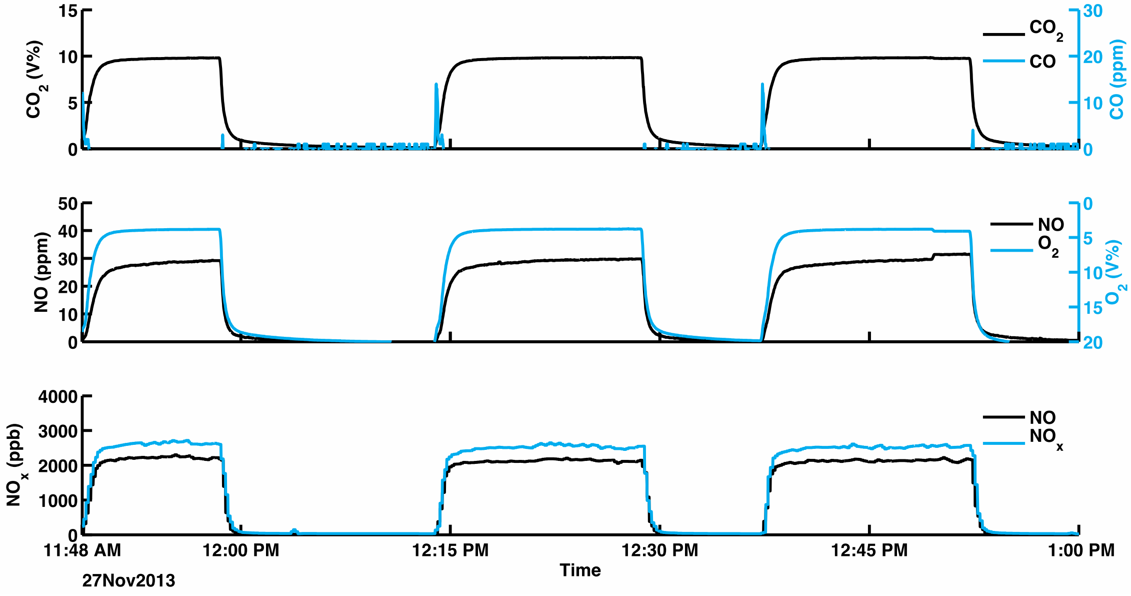

Figure 68. **Measured analyte concentrations for storage water heater AW08 with fuel 1C (H001). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn.**

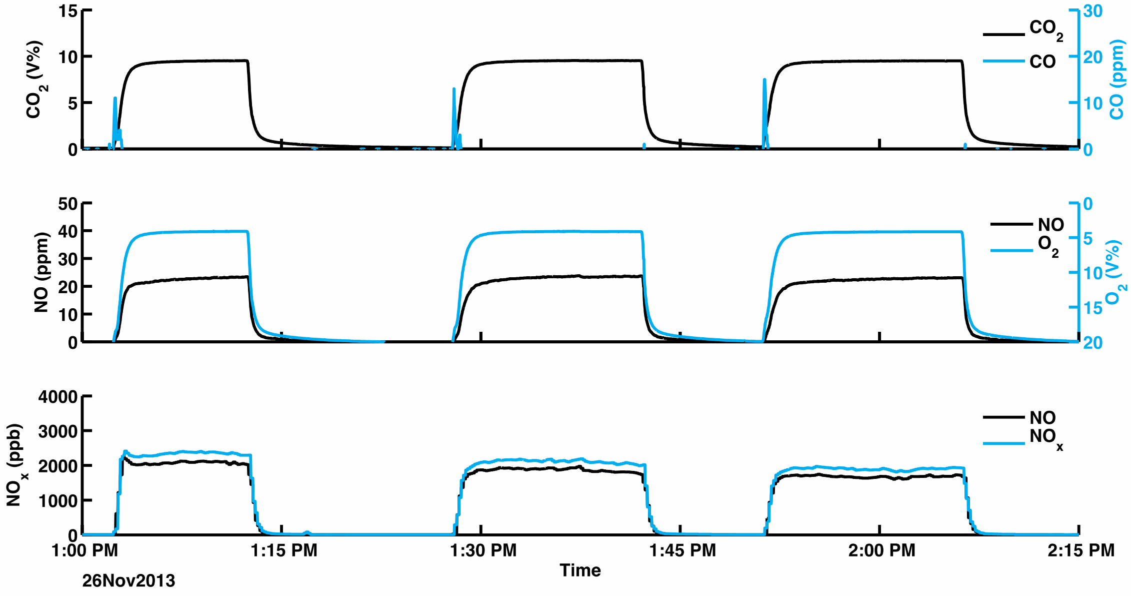

Figure 69. **Measured analyte concentrations for storage water heater AW08 with fuel 1N (H002). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn.**

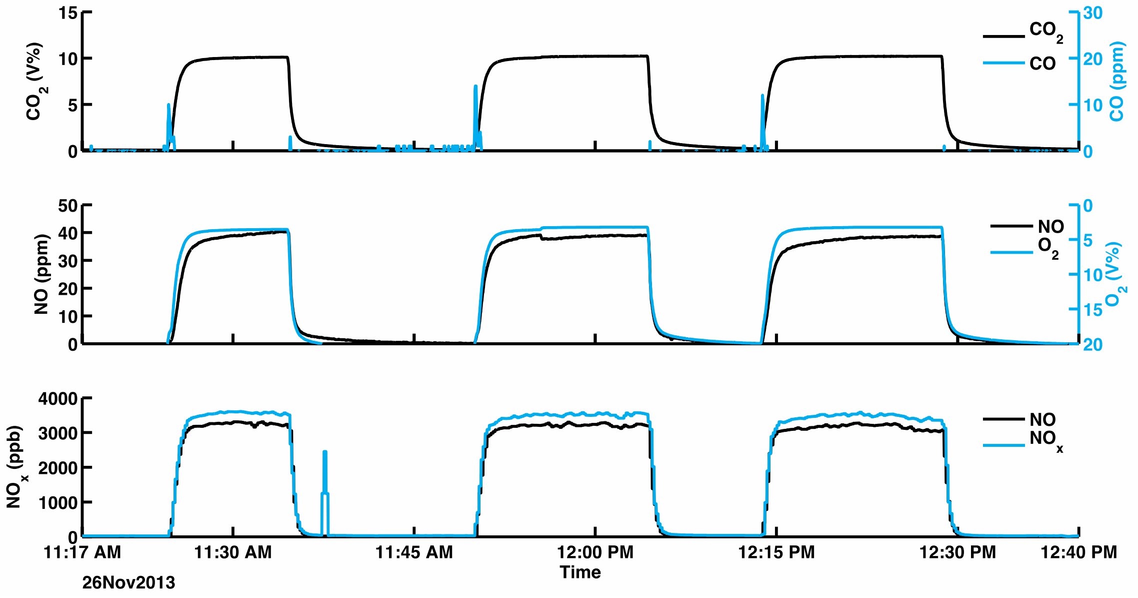

Figure 70. **Measured analyte concentrations for storage water heater AW08 with fuel 3C (H003). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn. The spike in NO$_x$ prior to the first burn was a communication error between the computer and the Thermo 42i.**

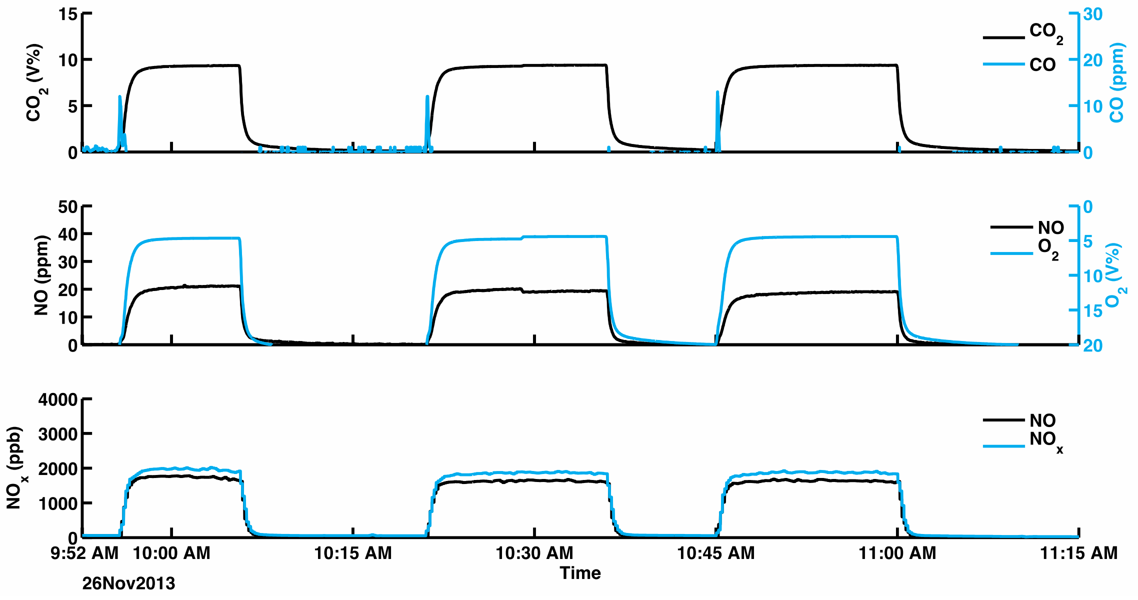

Figure 71. **Measured analyte concentrations for storage water heater AW08 with PG&E gas (H004). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn.**

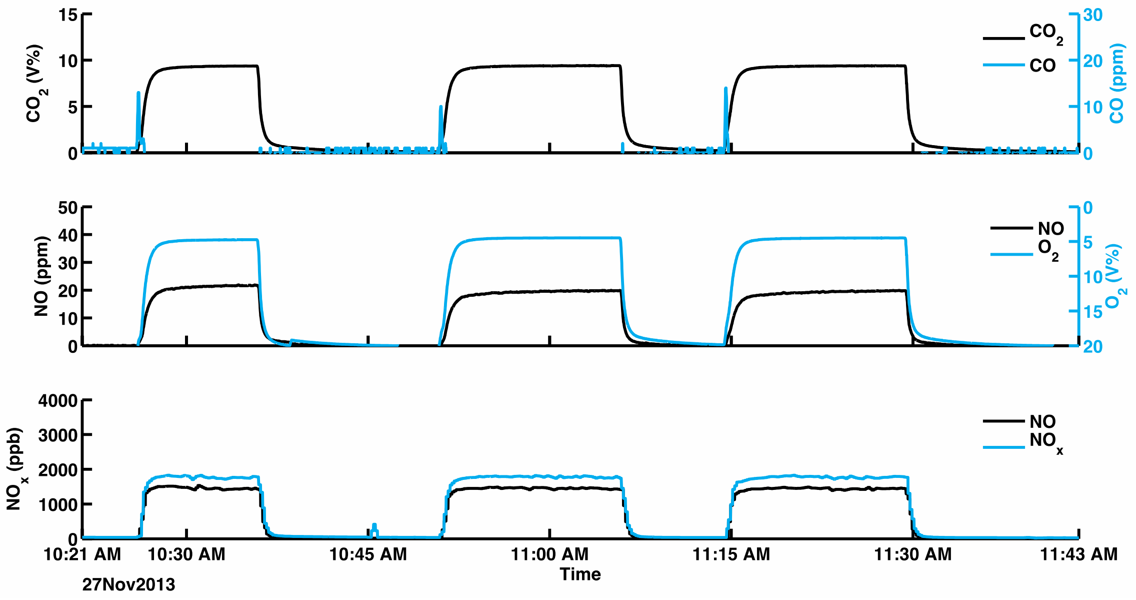

Figure 72. Measured analyte concentrations for storage water heater AW08 with fuel PG&E, repeat (H005). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system (Thermo 42i). The first large, steady peak is the purge burn. The small spike in NO$_x$ prior to the first burn was a communication error between the computer and the Thermo 42i.

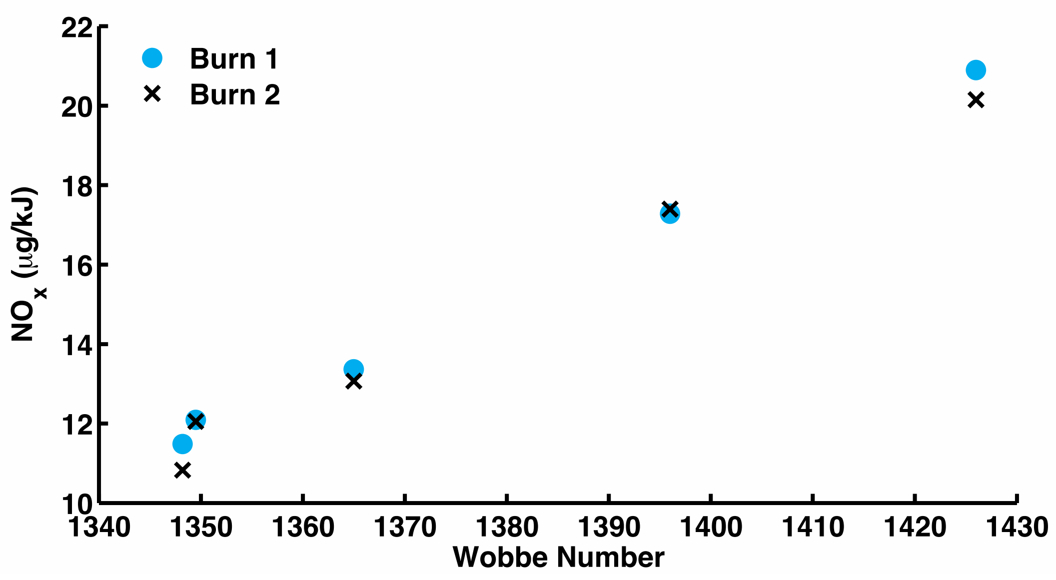

Figure 73. NO$_x$ as a function of Wobbe Number for storage water heater AW08. NO$_x$ concentrations increase linearly with Wobbe Number. Additionally, NO$_x$ shows almost no variation between Burn 1 and Burn 2.

4.0 On-Demand Water Heater Results

Four on-demand water heaters were used for the LNG interchangeability experiments. The following table provides a summary of the on-demand water heaters tested and key aspects of their respective technologies. Published information and results for each on-demand water heater are provided in the following sections.

Table 75. Tankless water heaters evaluated experimentally for fuel interchangeability

ID	Technology[1]	Manufacturer & Model	Serial Number	Rating (Btu/h)	Fuels Evaluated[2]
AT01	Ultra-low NO_X, non-condensing	Rheem RTG-84DVLN	RHUNM421211336	11,000-180,000	PG&E (2), 1C, 1N, 3C
AT02	Ultra-low NO_X, non-condensing	Rheem RTG-64DVLN	RHUNM161311132	11,000-150,000	PG&E (2), 1C, 1N, 3C
AT03	Ultra-low NO_X, condensing, dual stage burner	Navien NR-180(A)	9543-20100412-3081	15,000-150,000	PG&E (2), 1C, 1N, 3C
AT04	Ultra-low NO_X, hybrid	Eternal GU100	G1204853	16,000-100,000	PG&E (2), 1C, 1N, 3C

[1] Ultra-low NO_X implies the water heater meets SCAQMD rule 1146.2 for on-demand water heaters.
[2] One experiment per fuel, except as indicated in parentheses.

4.1 Results for AT01

<u>4.1.1 Summary of Experiments.</u> This direct vent, ultra-low NO_x (SCAQMD rule 1146.2 compliant) on-demand (tankless) water heater was donated new and installed in the test facilities at LBNL used for LNG interchangeability and energy efficiency experiments (see Figure 74). Table 76 provides a summary of the water heater information. Because the water heater is direct, power-vented, and uses concentric venting, the emissions sample lines and flue thermocouples were installed into the exit of the exhaust vent, shown in Figure 75 and Figure 76. Temperature was sampled 14-inches into the exhaust vent and emissions were sampled 12-inches into the exhaust vent. During each experiment, less than 100 mL of water condensed from the vent.

In April and May of 2013, five experiments were conducted on this unit over two consecutive days. The first experiment was conducted on April 30, 2013 using the PG&E line gas (WN=1349). During this experiment, the water heater temperature was set to 118°F and water was drawn at three flow rates, 1GPM, 2GPM, and 4GPM. After the third draw, the water heater temperature was set to the maximum temperature, 120°F, and water was drawn again at 4GPM. Emissions measurements for this burn were similar to the emissions at 118°F and 4 GPM, so the lower temperature setting was chosen to reduce risk of damage to the in-line hot water flow meter. On the following day, May 1, 2013, four experiments were conducted using fuel mixture 1C (WN =1396), fuel mixture 1N (WN=1365), fuel mixture 3C (WN=1426), and the PG&E line gas (WN=1348). For each of these experiments, the water heater temperature was set to 118°F and water was drawn at three flow rates, 1GPM, 2GPM, and 4 GPM. Composition and properties of each fuel are presented in Table 77. Environmental conditions were similar on both days. Pressure at the dry gas meter was 7 inches of water for all fuels tested.

<u>4.1.2 Summary of Results.</u> Ambient temperature was similar on both testing days. However, relative humidity was about 20% lower in the early afternoon than in the late afternoon/evening on May 01, 2013. The second thermocouple inside the vent consistently measured lower temperatures than the first vent thermocouple. The measurements suggest that the second thermocouple was touching the sidewall of the vent, thus lowering its temperature shown in Table 81. Therefore, measurements from the first thermocouple provide a more accurate representation of the exhaust temperature. CO emission rates increased with hot water flow.

For all experiments, the Horiba gas analyzer overcompensated for CO_2 interference in the CO signal, resulting in negative CO emission measurements. In order to correct for this overcompensation, the surface fit equations described in Section 2.2.4 were used to adjust the measured CO and reported in the tables that follow.

On Apr. 30, 2013, a fourth burn was conducted at a flow rate of 4 GPM when the water heater was set to 120°F. After the third draw, the water heater temperature was set to the maximum temperature, 120°F, and water was drawn again at 4GPM. Emissions measurements for this burn were similar to the emissions at 118°F and 4 GPM (see Table 83), so the lower temperature setting was chosen to reduce risk of damage to the in-line hot water flow meter. It should be noted that the line-gas pressure dropped to 6 inches of water when the water heater was operated at 120°F.

For experiment TA005, a false start occurred prior to the first burn. The water heater was turned on for about 20 seconds and then shut off. After this false start, the water heater remained off for 4 minutes before starting the first burn of experiment TA005. The formaldehyde and acetaldehyde samples include emissions from the false start. For each burn, a little over half (52%-68%) of the NO_X was in the form of NO. Full burn emission rates, shown in Table 83, ranged from 26.6-70.6 ng/J for CO, 7.6-26.4 ng/J for NO_X, 0.50-0.65 ng/J for formaldehyde, and 0.23-0.26 ng/J for acetaldehyde. As the hot water flow from the water heater increased, CO and NO_x decreased for almost every burn. In Figure 83, NO_x emissions increased with Wobbe Number for hot water flows of 2 and 4 GPM. For 1 GPM hot water flows, NO_X showed no obvious correlation with Wobbe Number. Tables and figures that follow provide detailed results from the LNG interchangeability experiments for storage water heater AT01.

Figure 74. Experimental apparatus installed for on-demand water heater AT01. Exhaust temperature, emissions, and dilution sampling tube are located at water heater vent exit. The Thermo 42i and house-air line are located behind the drywall (not shown).

Figure 75. Dilution tube and emissions sampling setup for on-demand water heater AT01. Dilution and emissions sampling tubes are located at the vent exit and sampled 12-inches into the exhaust vent.

Figure 76. Detailed image of temperature, dilution tube, and emissions sampling setup for on-demand water heater AT01. Dilution tube and emissions were sampled 12-inches into the exhaust vent. Exhaust temperature was measured 14-inches into the exhaust vent in two locations.

Table 76. Published information for water heater AT01.

Burner ID	AT01
Burner category	Ultra-low NO_x, non-condensing on-demand water heater
Technology	Indoor, direct vent, SCAQMD rule 1146.2 compliant; contains an integrated condensate collector for vent, but is NOT considered a condensing unit
Appliance manufacturer	Rheem
Model	RTG-84DVLN
Serial number	RHUNM421211336
Capacity	8.4 GPM @ 35°F rise 6.7 GPM @ 45°F rise 3.9 GPM @ 77°F rise
Recovery rating	184 Gallons/hr
Energy factor rating	0.82
Max inlet gas pressure	10.5 in. w.c.
Min inlet gas pressure	4.0 in. w.c.
Manifold Pressure	2.8 in. w.c. (for max burner input)
Electrical rating	120 V, 60 Hz, < 2 Amps
Max burner input	180,000 Btu/hr
Min burner input	11,000 Btu/hr

Table 77. **Composition of fuels for interchangeability experiments for on-demand water heater AT01.**

Exp.	Fuel	Date	N_2 (%)	CO_2 (%)	HHV (Btu/scf)	Wobbe number
TA001	1C[+]	05/01/13	0.00	0.00	1076	1396
TA002	1N[+]	05/01/13	1.70	0.00	1058	1365
TA003	3C[+]	05/01/13	0.00	0.00	1131	1426
TA004	PG&E[*]	04/30/13	0.59[**]	0.78[**]	1031	1349
TA005	PG&E[*]	05/01/13	0.59[**]	0.80[**]	1030	1348

[+] All information provided by Praxair.

[*] Gas quality information provided by PG&E online pipeline data, BTU area J01 (downloaded 05/01/2013).

[**] Values are given in mol % not volume %.

Table 78. Aldehyde measurement times with on-demand water heater AT01[*].

Fuel	Experiment	Date	Aldehyde Start Time	Aldehyde Stop Time	Total Liters Sampled
Lab Air[**]	-	04/30/13	12:18	14:25	124.9
Lab Air[**]	-	05/01/13	11:10	13:18	120.0
1C	TA001	05/01/13	15:05	16:06	52.9
			15:05	16:06	66.4
1N	TA002	05/01/13	13:37	14:37	50.3
			13:37	14:37	65.0
3C	TA003	05/01/13	11:50	12:52	52.0
			11:50	12:52	63.8
PG&E	TA004	04/30/13	14:58	16:14	75.4
			14:58	16:14	83.0
PG&E	TA005	05/01/13	16:27	17:30	55.40
			16:27	17:30	70.5

[*] Two Aldehyde measurements were taken on the dilution tube for each experiment.

[**] Aldehyde was measured directly from the lab air supply.

Table 79. **Burner operating times, fuel flow, and firing rate for experiments with on-demand water heater AT01.**

Exp.	Burn	Burn Time	Fuel Flow ($ft^3\ h^{-1}$)	Firing Rate[3] (kBtu/h)
TA001	1	15:10:32-15:18:35	31.1	33.5
	2	15:28:56-15:37:17	53.4	57.4
	3	15:48:09-15:56:10	100.6	108.2
TA002	1	13:43:03-13:51:07	32.8	34.7
	2	14:01:16-14:09:20	54.8	58
	3	14:19:35-14:27:39	100.8	106.6
TA003	1	11:56:21-12:04:24	31.5	35.6
	2	12:14:47-12:22:49	52.6	59.5
	3	12:33:16-12:41:16	96.6	109.2
TA004	1	15:00:47-15:08:50	34.1	35.1
	2	15:19:15-15:27:17	54.4	56.1
	3	15:37:58-15:46:03	110	113.4
	4*	15:56:26-16:04:29	114.5	118.1
TA005	1	16:34:25-16:42:27	33.4	34.4
	2	16:52:37-17:00:40	56.5	58.2
	3	17:10:57-17:19:00	105.4	108.6

* Experiment was conducted with the thermostat set to 120°F. This set-point was only conducted for experiment TA004 (PG&E line gas). All other experiments were conducted at a thermostat setting of 118°F.

Table 80. Combustion air conditions and measured water flow* for experiments with on-demand water heater AT01.

Exp.	Fuel	Burn	Air Temp (°C)	RH (%)	Water Draw (GPM)
TA001	1C	1	23.8 ± 0.1	35.6 ± 0.2	1.2 ± <0.1
		2	23.8 ± 0.1	35.6 ± 0.1	2.2 ± <0.1
		3	23.8 ± 0.1	36.3 ± 0.1	4.2 ± 0.2
TA002	1N	1	23.6 ± 0.1	24.5 ± 0.8	1.2 ± <0.1
		2	23.6 ± <0.1	29.9 ± 0.7	2.2 ± <0.1
		3	23.7 ± 0.1	32.7 ± 0.4	4.2 ± 0.2
TA003	3C	1	23.0 ± 0.1	18.5 ± 0.3	1.2 ± <0.1
		2	23.0 ± <0.1	18.0 ± 0.2	2.2 ± 0.1
		3	23.2 ± 0.1	18.3 ± 0.4	4.3 ± 0.1
TA004	PG&E	1	22.8 ± 0.2	39.9 ± 1.1	1.2 ± <0.1
		2	22.5 ± <0.1	38.4 ± 0.2	2.1 ± <0.1
		3	22.6 ± <0.1	38.4 ± 0.4	4.3 ± 0.2
		4**	22.6 ± 0.1	37.9 ± 0.4	4.2 ± 0.1
TA005	PG&E	1	23.9 ± 0.2	38.5 ± 0.4	1.2 ± <0.1
		2	23.7 ± 0.1	38.6 ± 0.2	2.2 ± 0.1
		3	23.6 ± 0.1	38.9 ± 0.3	4.2 ± 0.2

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

** Experiment was conducted with the thermostat set to 120°F. This set-point was only conducted for experiment TA004 (PG&E line gas). All other experiments were conducted at a thermostat setting of 118°F.

Table 81. Sampling system conditions for experiments with on-demand water heater AT01.

Exp.	Fuel	Burn	Vent Temp 1[1] (°C)	Vent Temp 2[1] (°C)	Dilution[2] Ratio
TA001	1C	1	62 ± 0.1	56 ± 0.2	12
		2	66 ± 0.2	60 ± 0.2	13
		3	76 ± 0.8	68 ± 0.3	14
TA002	1N	1	62 ± 0.1	57 ± 0.2	12
		2	66 ± 0.1	60 ± 0.2	13
		3	76 ± 0.6	68 ± 1.7	14
TA003	3C	1	63 ± 0.1	56 ± 0.1	13
		2	65 ± 0.1	59 ± 0.2	13
		3	75 ± 0.2	67 ± 0.3	14
TA004	PG&E	1	61 ± 0.1	55 ± 0.2	13
		2	65 ± 0.3	58 ± 0.3	13
		3	79 ± 0.3	69 ± 0.4	14
		4[3]	81 ± 1.3	71 ± 0.5	14
TA005	PG&E	1	64 ± 0.1	58 ± 0.1	12
		2	67 ± 0.1	61 ± 0.2	13
		3	78 ± 0.2	65 ± 5.8	13

[1] Measured in flue 12-inches below top of vent opening; mean over last 5 min of each burn.

[2] Calculated by dividing mean NO measured in gas manifold (PG-250) by dilution sampler (Thermo 42i) over last 5 min of each burn.

[3] Experiment was conducted with the thermostat set to 120°F. This set-point was only conducted for experiment TA004 (PG&E line gas). All other experiments were conducted at a thermostat setting of 118°F.

Table 82. Emission concentrations over last 5 min of each burn, water heater AT01.

Exp.	Wobbe	Burn[4]	CO[2] (ppm)	CO_2[2] (%)	O_2[2] (%)	NO[3] (ppm)	NO_2[3] (ppm)	NO_X[3] (ppm)
TA001	1396	1	157	1	18	21	15	35
		2	159	3	16	21	15	36
		3	115	6	11	13	10	22
TA002	1365	1	239	1	19	29	22	52
		2	151	3	16	19	15	34
		3	103	6	10	10	10	20
TA003	1426	1	257	2	18	38	24	62
		2	192	3	16	30	20	49
		3	113	6	10	15	12	27
TA004	1349	1	213	1	19	23	17	40
		2	144	3	16	17	12	29
		3	115	6	11	11	9	21
		4[1]	118	6	10	12	10	21
TA005	1348	1	161	1	18	17	13	30
		2	144	3	16	16	13	28
		3	117	6	11	10	9	18

[1] Experiment was conducted with the thermostat set to 120°F. This set-point was only conducted for experiment TA004 (PG&E line gas). All other experiments were conducted at a thermostat setting of 118°F. CO, NO_2, and NOx are Calculated air-free concentrations using O_2.

[2] Measurement from PG250 Horiba gas analyzer. CO emissions adjusted using surface fit given by Equation (2).

[3] Measurement from Thermo 42i.

[4] Burns correspond to water draws of approximately 1, 2, and 4 GPM, respectively.

Table 83. Calculated emission rates over entirety of each burn, water heater AT01.

Exp.	Wobbe	Burn[5]	CO[2] (ng/J)	NO[3,4] (ng/J)	NO_2[3,4] (ng/J)	NO_X[3,4] (ng/J)	HCHO (ng/J)	Acetaldehyde (ng/J)
TA001	1396	1	40.5	8.3	6.0	14.3	0.52	0.26
		2	41.3	8.7	6.2	14.9		
		3	30.1	5.3	3.5	7.8		
TA002	1365	1	63.4	12.1	9.2	21.3	0.58	0.26
		2	40.3	8.1	6.3	14.4		
		3	26.6	4.2	3.8	8.0		
TA003	1426	1	70.6	16.0	10.4	26.4	0.50	0.25
		2	50.7	12.4	7.6	19.0		
		3	30.2	6.4	5.0	11.4		
TA004	1349	1	55	9.1	7.0	16.1	0.65	0.23
		2	35.5	6.5	4.7	11.2		
		3	29.2	4.7	3.7	8.3		
		4[1]	29.5	4.8	3.9	8.6		
TA005	1348	1	39.7	6.5	5.1	11.6	0.55	0.23
		2	34.5	6.0	4.7	10.7		
		3	29.8	4.3	3.7	7.6		

[1] Experiment was conducted with the thermostat set to 120°F. This set-point was only conducted for experiment TA004 (PG&E line gas). All other experiments were conducted at a thermostat setting of 118°F.

[2] Measurement from PG250 Horiba gas analyzer. CO emissions calculated using adjusted ppm CO from surface fit given by Equation (2).

[3] Measurement from Thermo 42i.

[4] Calculation assumes molecular mass of NO_2 for NO and NO_x (46 g/mol).

[5] Burns correspond to water draws of approximately 1, 2, and 4 GPM, respectively.

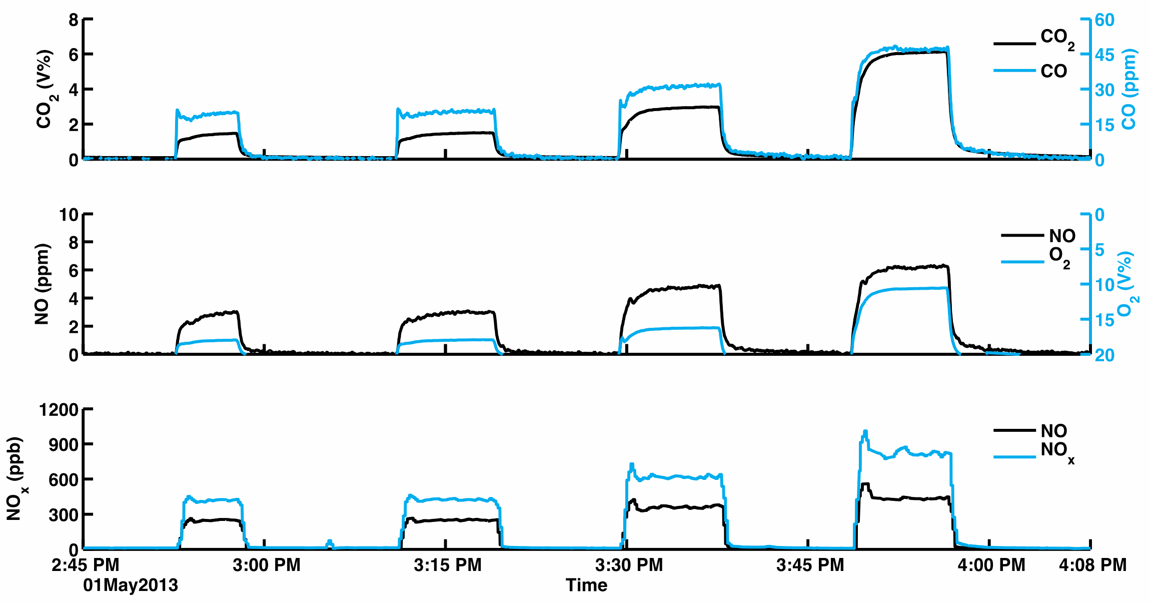

Figure 77. Measured analyte concentrations for on-demand water heater AT01 with fuel 1C (TA001). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn.

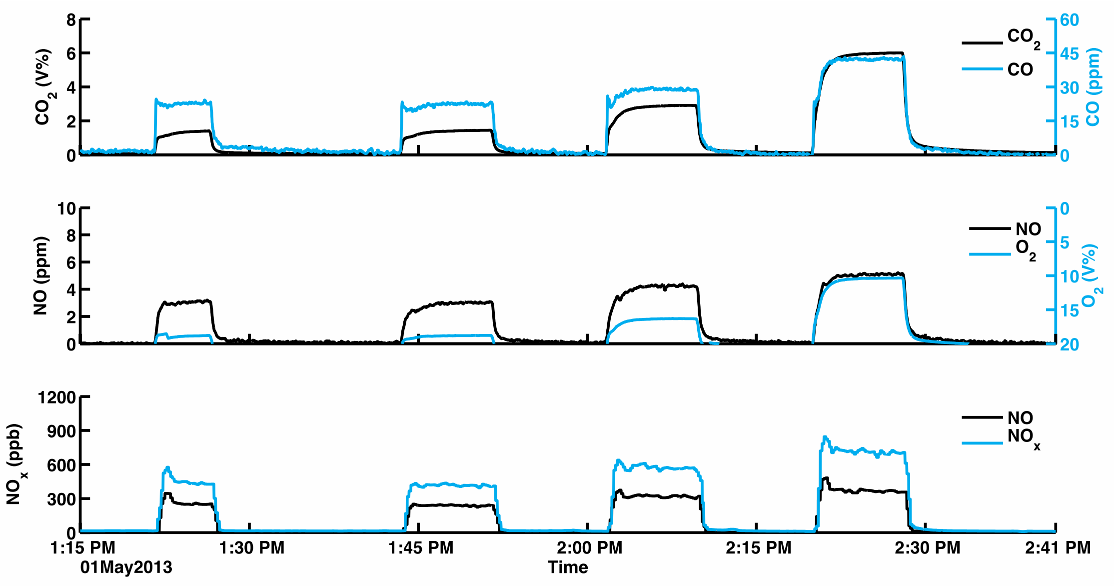

Figure 78. Measured analyte concentrations for on-demand water heater AT01 with fuel 1N (TA002). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn.

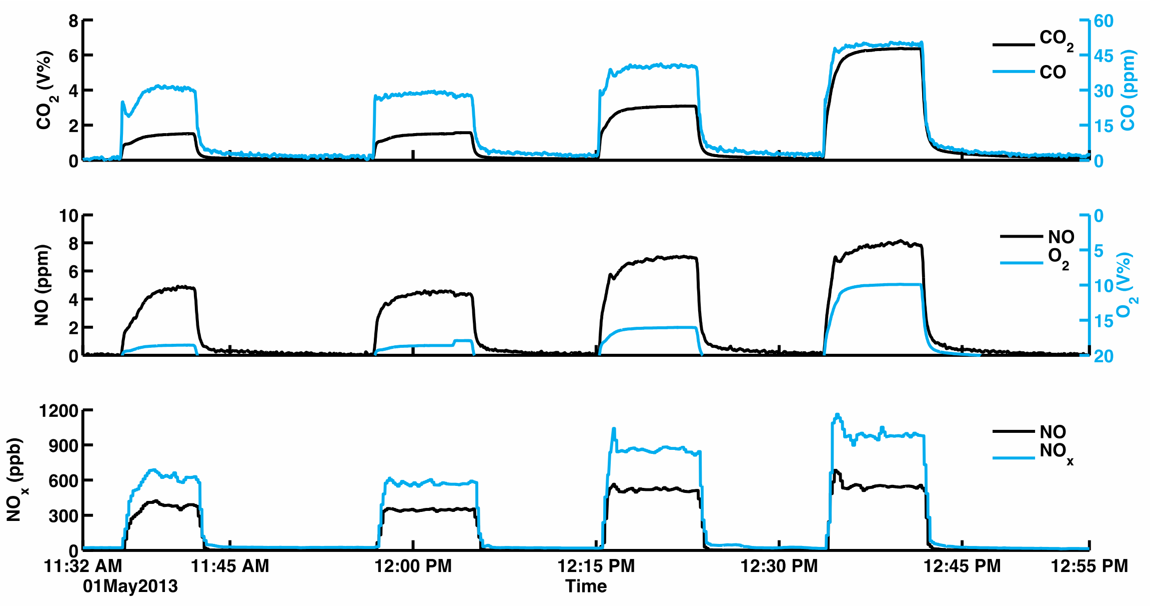

Figure 79. Measured analyte concentrations for on-demand water heater AT01 with fuel 3C (TA003). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first peak is the purge burn.

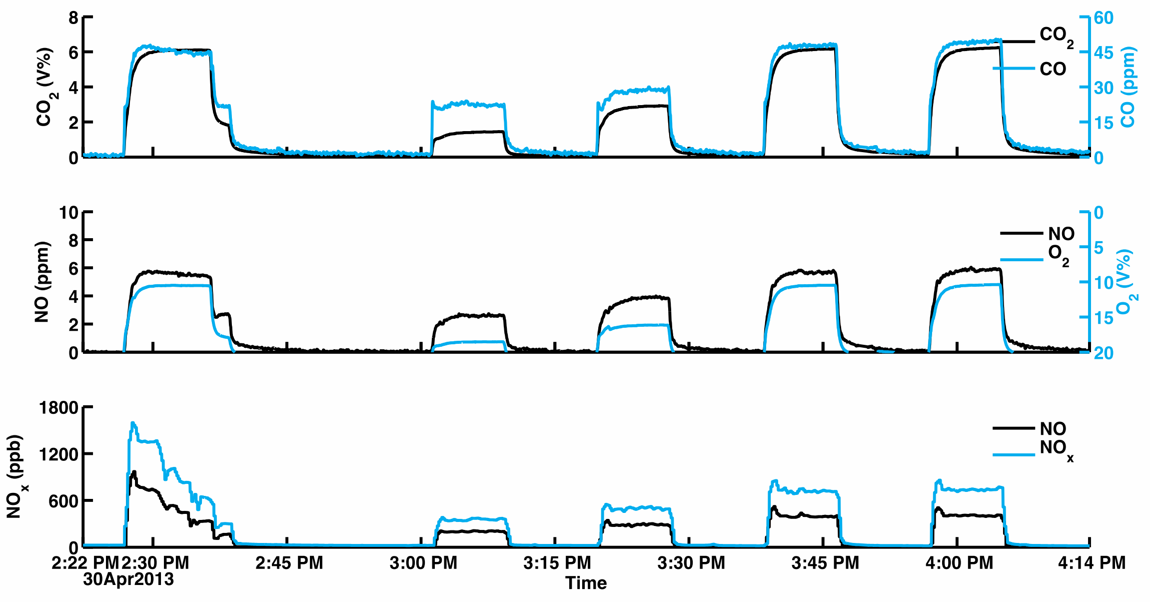

Figure 80. Measured analyte concentrations for on-demand water heater AT01 with PG&E gas (TA004). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first peak shown is the purge burn.

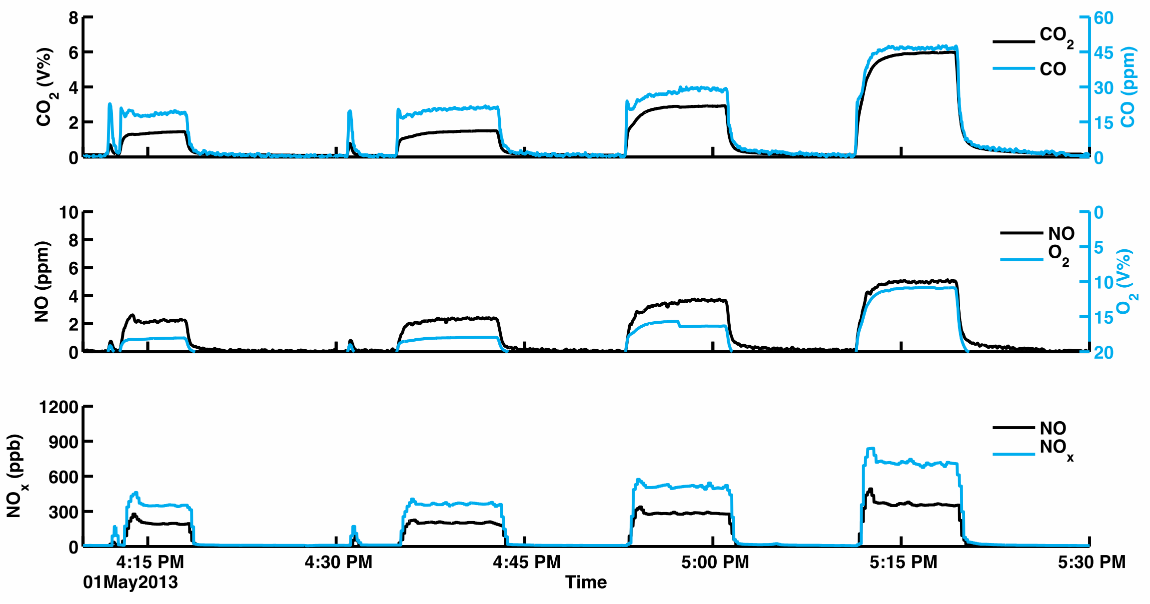

Figure 81. **Measured analyte concentrations for on-demand water heater AT01 with fuel PG&E, repeat (TA005). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first peak shown is the purge burn. Prior to the first test, the water heater operated for about 20 seconds before it shut off. After four minutes, the experiment was restarted. Formaldehyde and acetaldehyde was recorded over this period.**

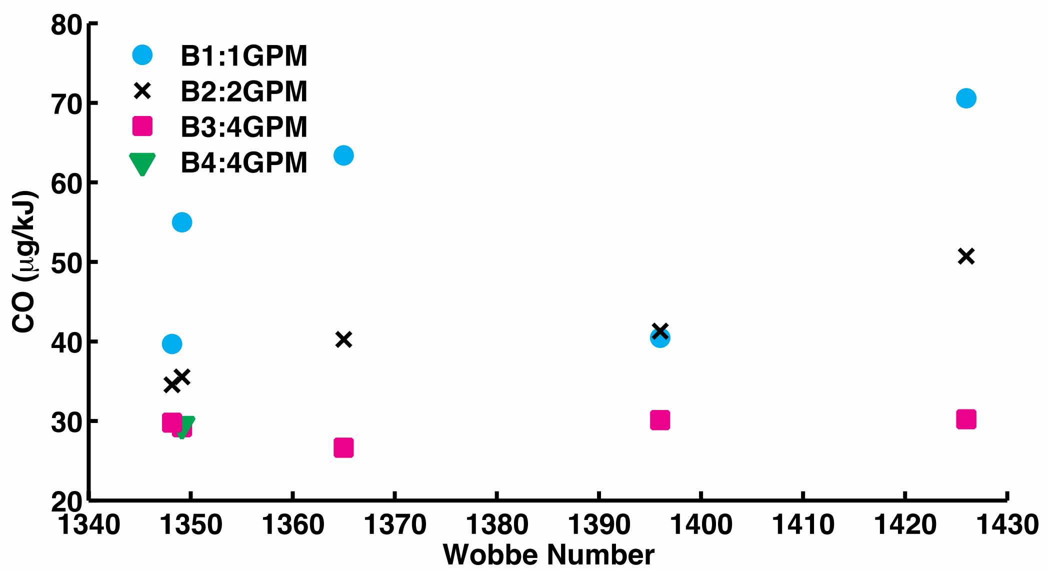

Figure 82. **CO as a function of Wobbe Number for on-demand water heater AT01. The fuels show slight increase in CO for a large increase in Wobbe Number for hot water flows of 2 GPM and 4 GPM. Lower water flows (1 GPM) generally produced more CO.**

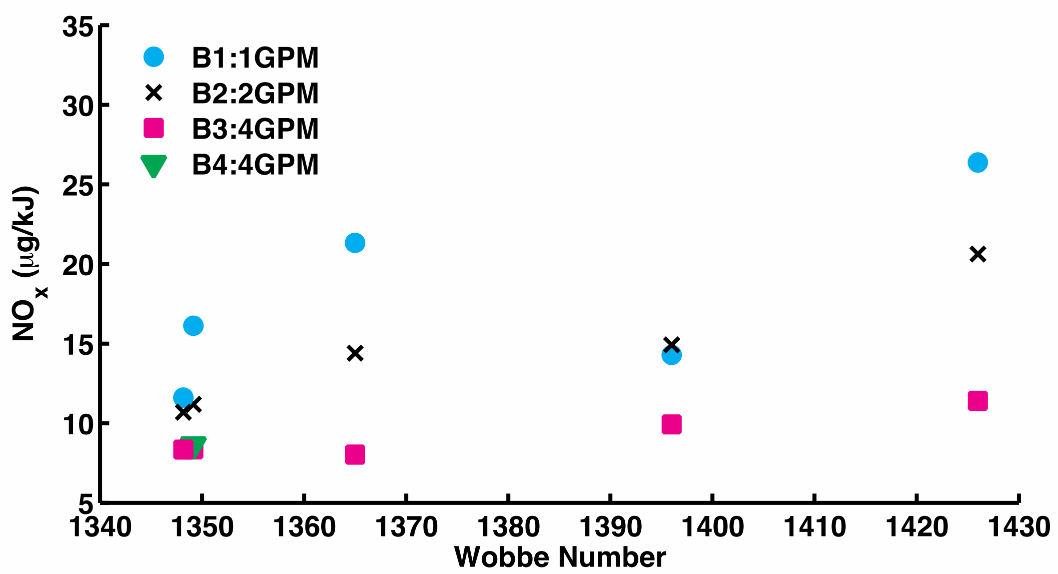

Figure 83. **NO_x as a function of Wobbe Number for on-demand water heater AT01. The fuels show slight increase in NO_x with increasing Wobbe Number for hot water flows of 2 GPM and 4 GPM. Lower water flows (1 GPM) produced more NO_x.**

4.2 Results for AT02

4.2.1 Summary of Experiments. The Rheem, direct vent, ultra-low NO_x (SCAQMD rule 1146.2 compliant) on-demand (tankless) water heater was donated new and installed in the test facilities at LBNL used for LNG interchangeability and energy efficiency experiments (see Figure 84). Table 84 provides a summary of the water heater information. Because the water heater is direct, power-vented, and uses concentric venting, the emissions sample lines and flue thermocouples were installed into the exit of the exhaust vent, shown in Figure 85 and Figure 86. Temperature was sampled 14-inches into the exhaust vent and emissions were sampled 12-inches into the exhaust vent. During each experiment, less than 100 mL of water condensed from the vent.

In June of 2013, five experiments were conducted on this unit over two consecutive days. Two experiments were conducted on June 10, 2013 using the PG&E line gas (WN=1365) and fuel mixture 1C (WN =1396). During this experiment, the water heater temperature was set to 118°F and water was drawn at three flow rates, 1 GPM, 2 GPM, and 4 GPM. This temperature setting was chosen to reduce risk of damage to the in-line hot water flow meter. On the following day, June 11, 2013, three experiments were conducted using fuel mixture 1N (WN=1365), fuel mixture 3C (WN=1426), and the PG&E line gas (WN=1362). The same temperature setting and flow rates were used. Composition and properties of each fuel are presented in Table 85. Environmental conditions were similar on both days. Pressure at the dry gas meter was 7 inches of water for all fuels tested.

4.2.2 Summary of Results. On June 10, 2013 and June 11, 2013, ambient temperature ranged from 21.0°C to 23.5°C and relative humidity ranged from 51% to 54%. During the purge burn of each experiment, three valves used to control the hot water flow rate were adjusted for flows of 1 GPM, 2 GPM, and 4 GPM. Prior to each burn, the hot water flow rate fluctuated and required small adjustments to match the desired rate. The average flow rate for each burn is shown in Table 88. Adjustment to the water flow was made within the first 30 seconds of each burn. Fluctuations in the flow could be due to high water demand in other areas of the building. Overall, this problem was expected to have minimal effect on the emissions since water flow rates were stable for the majority of each burn.

For all experiments, the Horiba gas analyzer overcompensated for CO_2 interference in the CO signal, resulting in negative CO emission measurements. In order to correct for this overcompensation, the surface fit equations described in Section 2.2.4 were used to adjust the measured CO and reported in the tables that follow.

Although two vent temperatures were measured, the first thermocouple (Vent Temp 1) consistently measured lower temperatures than the second thermocouple (Vent Temp 2). The readings suggest that the first thermocouple was touching the sidewall of the vent, thus lowering its temperature (see Table 89). Therefore, measurements from the second thermocouple provide a more accurate representation of the exhaust temperature.

A false start occurred prior to the main burn (after the purge burn) during experiment TB004, but formaldehyde was not sampled during this period. The water heater was allowed to cool at least 10 minutes after the false start before starting the test for the main burns. For each burn, about half (45–54%) of the NO_X was in the form of NO_2. Full burn emission rates, shown in **Table 91**, ranged from 23.7-58.6 ng/J for CO, 6.1–18.9 ng/J for NO_X, 0.44-0.51 ng/J for formaldehyde, and 0.13-0.16 ng/J for acetaldehyde. Experiments TB004 and TB002, which were the first experiments conducted on each day of testing, produced higher CO emissions than the other experiments. Fuel mixture 1N (WN=1365) produced the highest emissions. As the hot water flow from the water heater increased, CO and NO_x emissions decreased (see **Table 91**). One possible explanation for the decreased CO with increase water flow is more complete combustion at higher burn rates. In **Figure 93**, NO_x emissions increase slightly with Wobbe Number for hot water flows of 2 and 4 GPM. For 1 GPM hot water flows, NO_X showed no obvious correlation with Wobbe Number. Tables and figures that follow provide detailed results from the LNG interchangeability experiments for storage water heater AT02.

Figure 84. **Experimental apparatus installed for on-demand water heater AT02. Exhaust temperature, emissions, and dilution sampling tube are located at water heater vent exit. The Thermo 42i and house-air line are located behind the drywall (not shown).**

Figure 85. **Dilution tube and emissions sampling setup for on-demand water heater AT02. Dilution and emissions sampling tubes are located at the vent exit and sampled 12-inches into the exhaust vent.**

Figure 86. **Detailed image of temperature, dilution tube, and emissions sampling setup for on-demand water heater AT02. Dilution tube and emissions were sampled 12-inches into the exhaust vent. Exhaust temperature was measured 14-inches into the exhaust vent in two locations.**

Table 84. **Published information for water heater AT02.**

Burner ID	AT02
Burner category	Ultra-low NO_x, non-condensing on-demand water heater
Technology	Indoor, direct vent, SCAQMD rule 1146.2 compliant; contains an integrated condensate collector for vent, but is NOT considered a condensing unit
Appliance manufacturer	Rheem
Model	RTG-64DVLN
Serial number	RHUNM161311132
Capacity	6.4 GPM @ 35°F rise 5.6 GPM @ 45°F rise 3.3 GPM @ 77°F rise
Activation flow	0.4 GPM
Recovery rating	155 Gallons/hr
Energy factor rating	0.82
Max inlet gas pressure	10.5 in. w.c.
Min inlet gas pressure	4.0 in. w.c.
Manifold Pressure	2.0 in. w.c. (for max burner input)
Electrical rating	120 V, 60 Hz, < 2 Amps
Max burner input	150,000 Btu/hr
Min burner input	11,000 Btu/hr

Table 85. **Composition of fuels for interchangeability experiments for on-demand water heater AT02.**

Exp.	Fuel	Date	N_2 (%)	CO_2 (%)	HHV (Btu/scf)	Wobbe number
TB001	1C[+]	06/10/13	0.00	0.00	1076	1396
TB002	1N[+]	06/11/13	1.70	0.00	1058	1365
TB003	3C[+]	06/11/13	0.00	0.00	1131	1426
TB004	PG&E[*]	06/10/13	0.72[**]	0.79[**]	1062	1365
TB005	PG&E[*]	06/11/13	0.75[**]	0.78[**]	1058	1362

[+] All information provided by Praxair.
[*] Gas quality information provided by PG&E online pipeline data, BTU area J01 (downloaded 06/11/2013).
[**] Values are given in mol % not volume %.

Table 86. Aldehyde measurement times with on-demand water heater AT02[*].

Fuel	Experiment	Date	Aldehyde Start Time	Aldehyde Stop Time	Total Liters Sampled
Lab Air[**]	-	06/10/13	13:54	15:55	116.4
Lab Air[**]	-	06/11/13	11:21	13:54	154.0
1C	TB001	06/10/13	16:29	17:29	61.0
			16:29	17:29	70.9
1N	TB002	06/11/13	12:13	13:12	59.3
			12:13	13:12	69.7
3C	TB003	06/11/13	13:51	14:52	60.8
			13:51	14:52	66.1
PG&E	TB004	06/10/13	14:48	15:48	57.4
			14:48	15:48	70.8
PG&E	TB005	06/11/13	15:12	16:12	61.3
			15:12	16:12	72.8

[*] Two Aldehyde measurements were taken on the dilution tube for each experiment.
[**] Aldehyde was measured directly from the lab air supply.

Table 87. **Burner operating times, fuel flow, and firing rate for experiments with on-demand water heater AT02.**

Exp.	Burn	Burn Time	Fuel Flow (ft^3 h^{-1})	Firing Rate (kBtu/h)
TB001	1	16:33:40-16:41:38	31.2	33.6
	2	16:52:16-17:00:17	52.9	56.9
	3	17:10:30-17:18:33	101.9	109.6
TB002	1	12:16:57-12:24:59	35.2	37.2
	2	12:35:15-12:43:17	56.5	59.8
	3	12:53:27-13:01:30	101.7	107.6
TB003	1	13:56:23-14:04:25	30.1	34.0
	2	14:14:33-14:22:35	51.4	58.1
	3	14:32:42-14:40:46	99.5	112.5
TB004	1	14:53:20-15:01:23	33.1	35.2
	2	15:11:32-15:19:35	53.0	56.3
	3	15:29:45-15:37:47	101.6	108.0
TB005	1	15:15:42-15:23:45	31.7	33.5
	2	15:33:50-15:41:51	53.6	56.8
	3	15:42:03-16:00:05	105.4	111.5

Table 88. **Combustion air conditions and measured water flow[1] for experiments with on-demand water heater AT02.**

Exp.	Fuel	Burn	Air Temp (°C)	RH (%)	Water Draw[2] (GPM)
TB001	1C	1	22.7 ± 0.7	52.9 ± 1.7	1.1 ± <0.1
		2	21.0 ± 0.1	52.7 ± 0.4	1.9 ± <0.1
		3	21.0 ± 0.1	52.9 ± 0.2	3.9 ± 0.1
TB002	1N	1	23.6 ± 1.1	55.9 ± 2.5	1.1 ± <0.1
		2	21.6 ± 0.1	53.9 ± 0.4	2.0 ± <0.1
		3	21.7 ± 0.1	53.1 ± 0.2	3.8 ± 0.1
TB003	3C	1	22.0 ± 0.6	52.5 ± 1.2	1.0 ± <0.1
		2	21.3 ± 0.1	51.5 ± 0.3	1.9 ± <0.1
		3	21.4 ± 0.1	51.2 ± 0.1	3.8 ± 0.1
TB004	PG&E	1	23.5 ± 1.0	54.2 ± 2.5	1.1 ± <0.1
		2	21.2 ± 0.2	52.7 ± 1.0	1.9 ± 0.1
		3	21.1 ± 0.1	52.6 ± 0.3	3.8 ± 0.1
TB005	PG&E	1	22.2 ± 0.5	51.8 ± 1.1	1.0 ± <0.1
		2	21.4 ± 0.1	51.6 ± 0.4	1.9 ± <0.1
		3	21.5 ± 0.1	51.4 ± 0.2	3.9 ± 0.1

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

[2] Measured by Omega in-line water flow pulse meter.

Table 89. Sampling system conditions for experiments with on-demand water heater AT02.

Exp.	Fuel	Burn	Vent Temp 1[1] (°C)	Vent Temp 2[1] (°C)	Dilution[2] Ratio
TB001	1C	1	59 ± 0.1	61 ± 0.2	12
		2	64 ± 0.2	66 ± 0.1	13
		3	71 ± 2.0	80 ± 0.2	14
TB002	1N	1	60 ± 0.1	63 ± 0.1	12
		2	65 ± 0.2	68 ± 0.2	12
		3	73 ± 1.8	81 ± 0.6	13
TB003	3C	1	59 ± 0.1	62 ± 0.1	11
		2	64 ± 0.1	68 ± 0.1	12
		3	76 ± 1.6	82 ± 0.5	13
TB004	PG&E	1	59 ± 0.2	61 ± 0.2	13
		2	63 ± 0.1	66 ± 0.1	14
		3	76 ± 0.2	79 ± 0.2	14
TB005	PG&E	1	60 ± 0.1	63 ± 0.1	11
		2	65 ± 0.1	68 ± 0.1	11
		3	78 ± 1.8	84 ± 0.4	13

[1] Measured in flue 12-inches below top of vent opening; mean over last 5 min of each burn.

[2] Calculated by dividing mean NO measured in gas manifold (PG-250) by dilution sampler (Thermo 42i) over last 5 min of each burn.

Table 90. Emission concentrations over last 5 min of each burn, water heater AT02.

Exp.	Wobbe	Burn[3]	CO[1] (ppm)	CO_2[1] (%)	O_2[1] (%)	NO[2] (ppm)	NO_2[2] (ppm)	NO_X[2] (ppm)
TB001	1396	1	150	1	18	18	15	33
		2	123	3	16	14	12	26
		3	106	6	11	10	9	19
TB002	1365	1	219	1	18	23	21	45
		2	119	3	15	12	12	25
		3	94	6	10	8	9	17
TB003	1426	1	148	2	18	19	16	35
		2	128	3	15	15	14	29
		3	99	6	10	10	10	20
TB004	1365	1	224	1	19	23	24	46
		2	144	3	16	13	14	28
		3	97	6	11	7	9	17
TB005	1362	1	134	1	18	13	13	26
		2	114	3	15	10	11	21
		3	97	6	10	7	9	16

[1] Measurement from PG250 Horiba gas analyzer. CO emissions adjusted using surface fit given by Equation (2). CO, NO_2, and NOx are Calculated air-free concentrations using O_2.
[2] Measurement from Thermo 42i.
[3] Burns correspond to water draws of approximately 1, 2, and 4 GPM, respectively.

Table 91. Calculated emission rates over entirety of each burn, water heater AT02.

Exp.	Wobbe	Burn[4]	CO[1] (ng/J)	NO[2,3] (ng/J)	NO_2[2,3] (ng/J)	NO_X[2,3] (ng/J)	HCHO (ng/J)	Acetaldehyde (ng/J)
TB001	1396	1	38.7	7	6.2	13.2	0.45	0.13
		2	31.7	5.6	4.9	10.5		
		3	27.8	4.3	3.8	8		
TB002	1365	1	58.6	9.8	9.2	18.9	0.51	0.13
		2	30.9	5.1	5.1	10.2		
		3	24.4	3.3	3.7	7.1		
TB003	1426	1	37.1	7.7	6.3	14	0.44	0.14
		2	32.9	6.2	5.6	11.9		
		3	25.7	4.3	4.2	8.5		
TB004	1365	1	49.1	7.7	8.0	15.7	0.51	0.16
		2	36.3	5.4	5.8	11.2		
		3	23.7	2.9	3.5	6.5		
TB005	1362	1	32	5	4.8	9.8	0.50	0.13
		2	27.5	3.9	4.1	8		
		3	23.7	2.8	3.3	6.1		

[1] Measurement from PG250 Horiba gas analyzer. CO emissions calculated using adjusted ppm CO from surface fit given by Equation (2).
[2] Measurement from Thermo 42i.
[3] Calculation assumes molecular mass of NO_2 for NO and NO_x (46 g/mol).
[4] Burns correspond to water draws of approximately 1, 2, and 4 GPM, respectively.

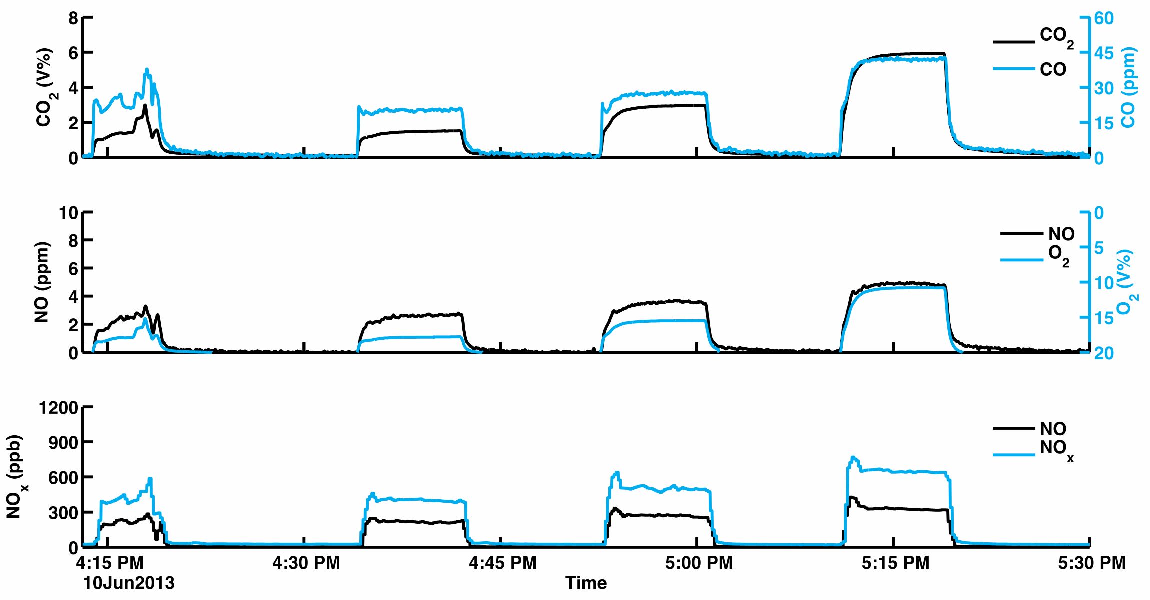

Figure 87. Measured analyte concentrations for on-demand water heater AT02 with fuel 1C (TB001). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn.

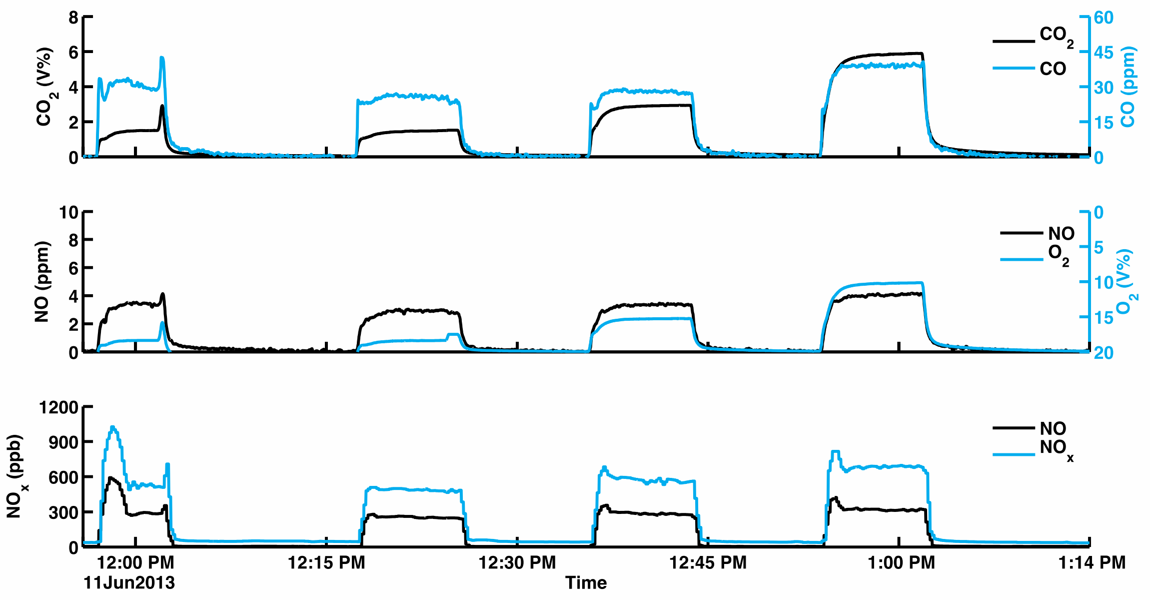

Figure 88. Measured analyte concentrations for on-demand water heater AT02 with fuel 1N (TB002). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn.

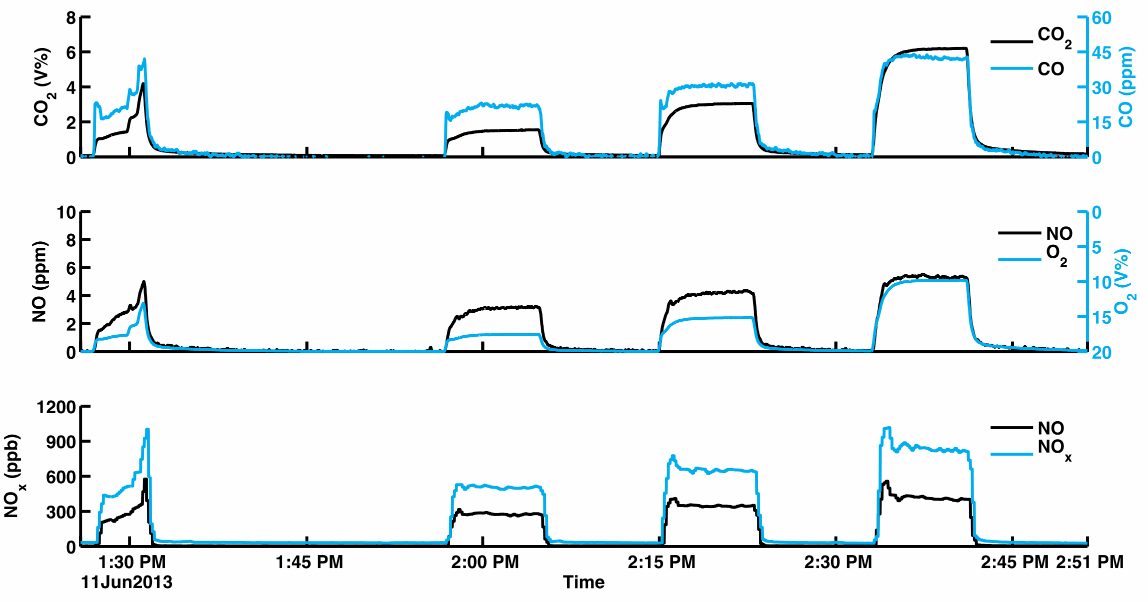

Figure 89. **Measured analyte concentrations for on-demand water heater AT02 with fuel 3C (TB003). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn.**

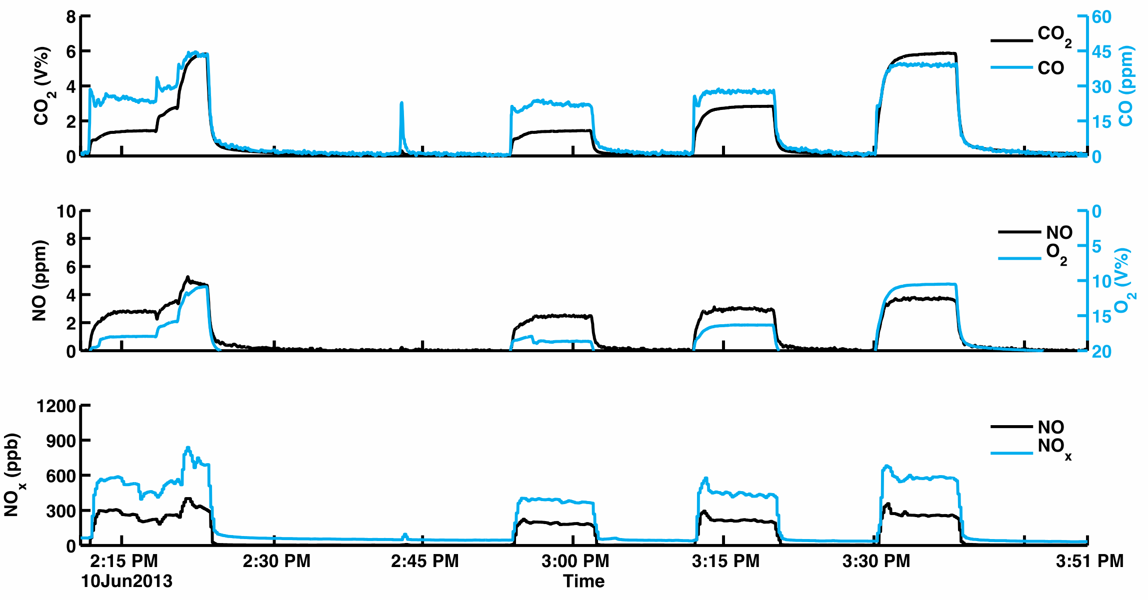

Figure 90. **Measured analyte concentrations for on-demand water heater AT02 with PG&E gas (TB004). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first peak is the purge burn. A false start occurred prior to the first burn, but formaldehyde was not sampled. The water heater was left off for at least 10 minutes before conducting the first experiment.**

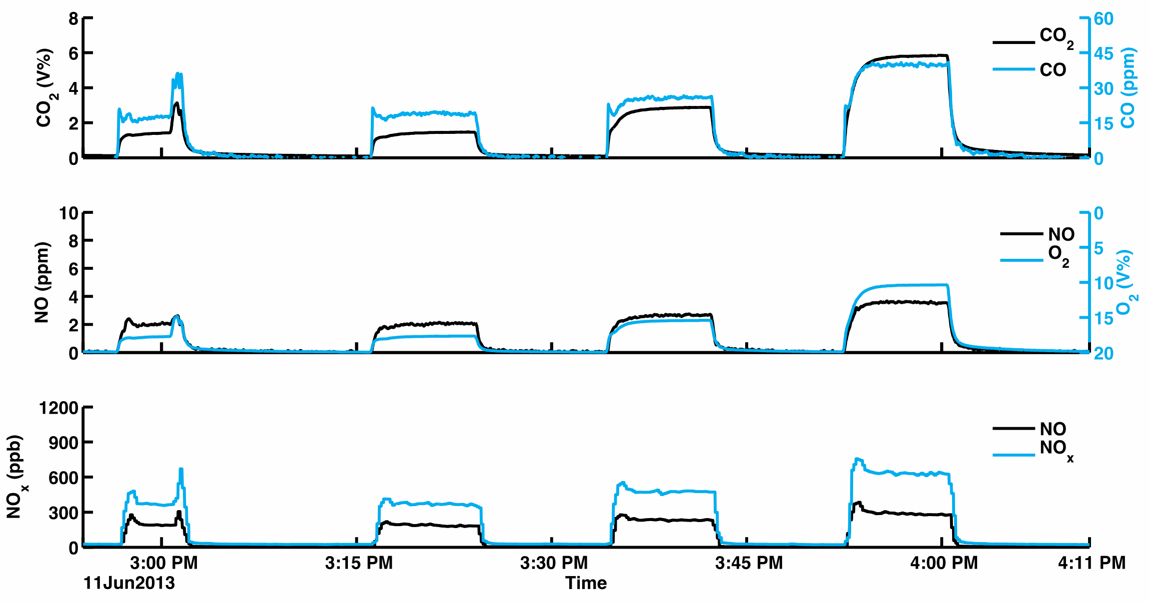

Figure 91. Measured analyte concentrations for on-demand water heater AT02 with fuel PG&E, repeat (TB005). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first peak shown is the purge burn.

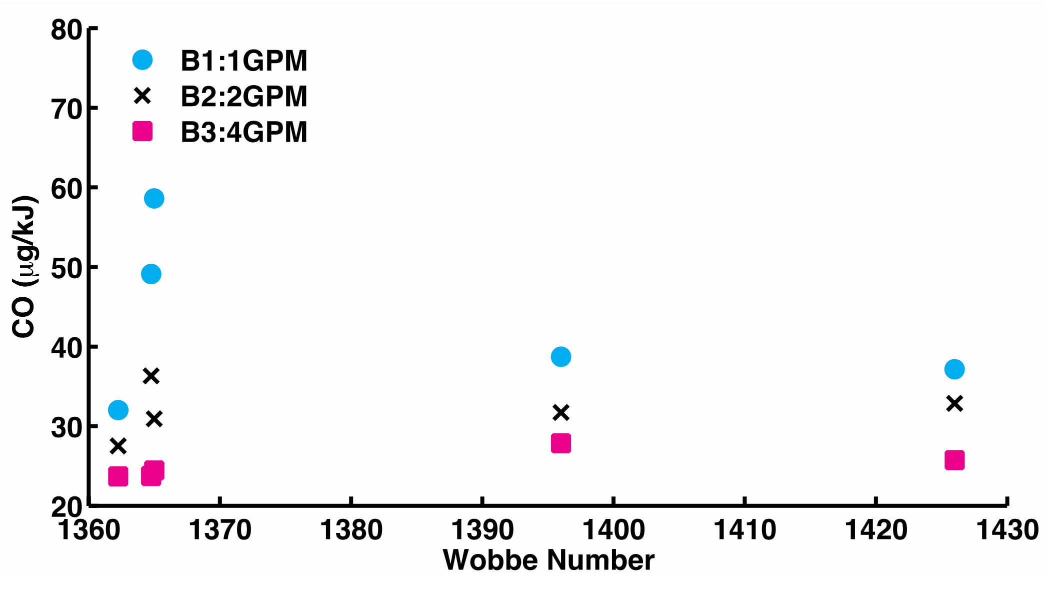

Figure 92. CO as a function of Wobbe Number for on-demand water heater AT02. The fuels show slight decrease in CO with a significant increase in Wobbe Number for hot water flows of 2 GPM and 4 GPM, while lower water flows (1 GPM) produced more CO.

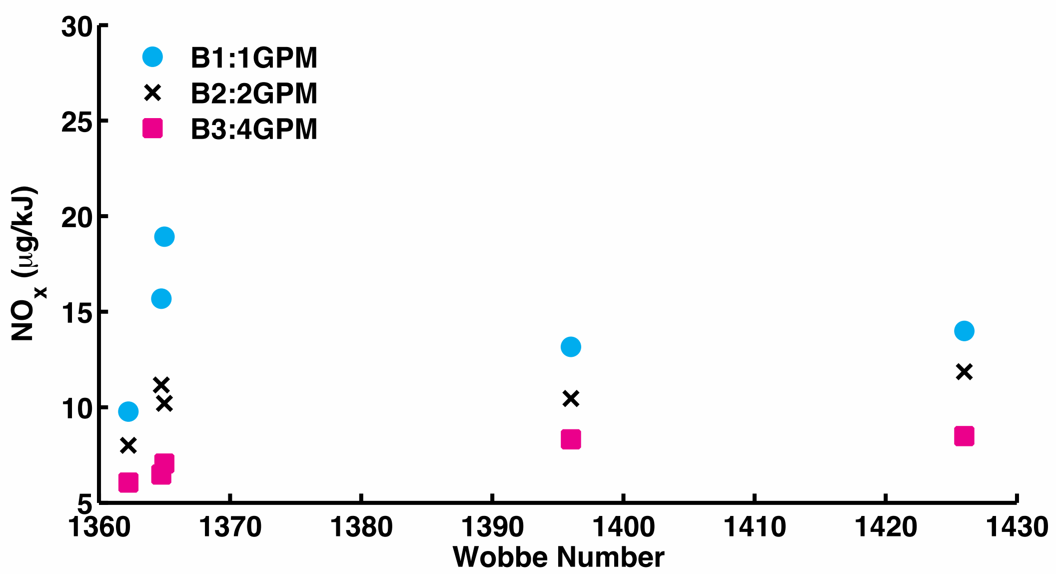

Figure 93. **NO$_x$ as a function of Wobbe Number for on-demand water heater AT02. The fuels show slight increase in NO$_x$ with increasing Wobbe Number for hot water flows of 2 GPM and 4 GPM. Lower water flows (1 GPM) produced more NO$_x$.**

4.3 Results for AT03

4.3.1 Summary of Experiments. The Navien condensing, ultra-low NO_x (SCAQMD rule 1146.2 compliant) on-demand (tankless) water heater was a donated display model. The water heater was installed in the test facilities at LBNL used for LNG interchangeability and energy efficiency experiments (see Figure 94). This water heater is unique in that it contains a dual stage burner and a small, internal buffer tank, shown in Figure 95. The water heater also has separate venting for the intake combustion air and the exhaust gases. Further details on the water heater are presented in Table 92.

Figure 96 and Figure 97 show the detailed exhaust pollutant and temperature sampling configuration. The emissions sample lines and flue thermocouples were installed about 32 inches above the water heater in the exhaust venting (see Figure 96). Two thermocouples were used to ensure accuracy when measuring exhaust temperature. The thermocouples were installed 12-inches into the exhaust.

In August of 2013, five experiments were conducted on this unit over two consecutive days. Two experiments were conducted on August 05, 2013 using the PG&E line gas (WN=1347) and fuel mixture 3C (WN=1426). During this experiment, the water heater temperature was set to 118°F and water was drawn at three flow rates, 1GPM, 2GPM, and 4GPM. This temperature setting was chosen to reduce risk of damage to the in-line hot water flow meter. On the following day, August, 06, 2013, three experiments were conducted using fuel mixture 1C (WN=1396), fuel mixture 1N (WN=1365), and the PG&E line gas (WN=1344). Composition and properties of each fuel are presented in Table 93. Environmental conditions were similar on both days. Pressure at the dry gas meter was 7 inches of water for fuel mixtures 1C, 1N, and 3C. The pressure at the dry gas meter was 7 inches of water for the PG&E line gas when the water heater pulled 1GPM and 2 GPM, but was 6 inches of water at 4 GPM.

4.3.2 Summary of Results. On August 5, 2013 and August 6, 2013, ambient temperature ranged from 20.2°C to 21.3°C and relative humidity ranged from 52.1% to 56.8%. Across burns, NO_2 constituted 16% to 47% of the NO_X. CO and NO_X emissions tended to vary throughout each burn, regardless of flow rate. One possible explanation is that this water heater contains a variable speed fan that could be adjusting the air supplied to the combustion chamber; the change in combustion air would then change the equivalence ratio and thus the CO and NO_X emissions. Another possible explanation for the variance in emissions is the burner design and staging of each burner bank.

For all experiments, the Horiba gas analyzer overcompensated for CO_2 interference in the CO signal, resulting in negative CO emission measurements. In order to correct for this overcompensation, the surface fit equations described in Section 2.2.4 were used to adjust the measured CO and reported in the tables that follow.

Full burn emission rates, shown in Table 99, ranged from 34–214 ng/J for CO, 9.5–37 ng/J for NO_X, 0.24–0.28 ng/J for formaldehyde, and 0.08–0.09 mg/J for acetaldehyde. Experiments conducted for hot water flows of 2 GPM produced the highest CO and NO_X emissions, while 4 GPM produced the lowest emissions. As shown in Figure 104, NO_x emissions appear to increase for fuels with a Wobbe Number greater than 1365 at two of the flow rates. Tables and figures that follow provide detailed results from the LNG interchangeability experiments for storage water heater AT03.

Figure 94. Experimental apparatus installed for on-demand water heater AT03. Vent thermocouples, emission sampling tube, and dilution sampling tube are located about 32-inches above the water heater in the exhaust vent. The Thermo 42i and house-air line are not shown in this picture, but are located behind the drywall.

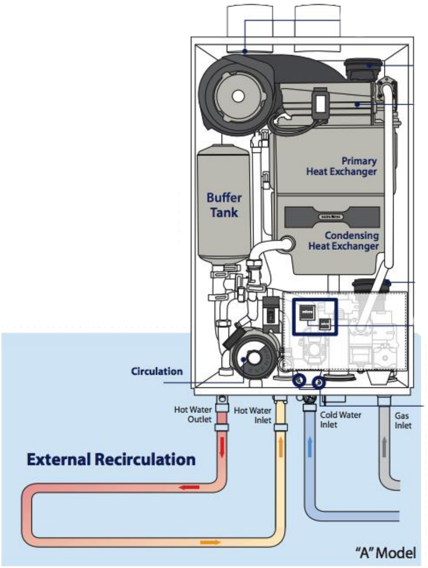

Figure 95. Internal schematic of on-demand water heater AT03 shows the small buffer tank located inside the water heater (schematic taken from Navien NR-180A Brochure).

Figure 96. Dilution tube and emissions sampling setup for on-demand water heater AT03. Dilution and emissions sampling tubes are located at the about 32-inches from the water heater and sampled 12-inches into the exhaust vent.

Figure 97. Detailed image of temperature, dilution tube, and emissions sampling setup for on-demand water heater AT03. Emissions and temperature were sampled 12-inches into the exhaust vent.

Table 92. Published information for water heater AT03.

Burner ID	AT03
Burner category	Ultra-low NO_x, condensing, on-demand water heater
Technology	Indoor, dual stage burner, SCAQMD rule 1146.2 compliant; condensing on-demand water heater; contains a small internal tank to allow for no minimum flow rate requirement
Appliance manufacturer	Navien
Model	NR-180A NG
Serial number	9543-20100412-3081
Activation flow	None
Recovery rating	227 Gallons/hr
Hot water flow rates	4.0 GPM @ 35°F 4.7 GPM @ 4.7°F 8.0 GPM @ 70°F
Energy factor rating	0.94
Max inlet gas pressure	10.5 in. w.c.
Min inlet gas pressure	6.0 in. w.c.
Manifold Pressure	4.9 in. w.c.
Electrical rating	120 V, 60 Hz, < 2 Amps
Max burner input	150,000 Btu/hr
Min burner input	15,000 Btu/hr

Table 93. Composition of fuels for interchangeability experiments for on-demand water heater AT03.

Exp.	Fuel	Date	N_2 (%)	CO_2 (%)	HHV (Btu/scf)	Wobbe number
TC001	1C[+]	08/06/13	0.00	0.00	1076	1396
TC002	1N[+]	08/06/13	1.70	0.00	1058	1365
TC003	3C[+]	08/05/13	0.00	0.00	1131	1426
TC004	PG&E[*]	08/05/13	0.74[**]	0.78[**]	1030	1347
TC005	PG&E[*]	08/06/13	0.86[**]	0.77[**]	1028	1344

[+] All information provided by Praxair.

[*] Gas quality information provided by PG&E online pipeline data, BTU area J01 (downloaded 08/06/2013).

[**] Values are given in mol % not volume %.

Table 94. Aldehyde measurement times with on-demand water heater AT03[*].

Fuel	Experiment	Date	Aldehyde Start Time	Aldehyde Stop Time	Total Liters Sampled
Lab Air[**]	-	08/05/13	10:23	12:43	137.9
Lab Air[**]	-	08/06/13	13:58	16:03	128.0
1C	TC001	08/06/13	17:35	18:37	62.5
			17:35	18:37	73.7
1N	TC002	08/06/13	16:01	17:06	60.8
			16:01	17:06	79.3
3C	TC003	08/05/13	17:22	18:22	61.4
			17:22	18:22	73.23
PG&E	TC004	08/05/13	11:43	12:43	60.3
			11:43	12:43	72.8
PG&E	TC005	08/06/13	14:36	15:38	62.8
			14:36	15:38	73.6

[*] Two Aldehyde measurements were taken on the dilution tube for each experiment.

[**] Aldehyde was measured directly from the lab air supply.

Table 95. Burner operating times, fuel flow, and firing rate for experiments with on-demand water heater AT03. Double check the highlighted values

Exp.	Burn	Burn Time	Fuel Flow (ft^3 h^{-1})	Firing Rate (kBtu/h)
TC001	1	17:41:29-17:49:30	24.4	26.2
	2	17:59:40-18:07:41	45.0	48.4
	3	18:17:47-18:25:49	85.0	91.5
TC002	1	16:09:49-16:17:50	25.4	26.8
	2	16:28:12-16:36:14	44.1	46.7
	3	16:46:21-16:54:23	88.3	93.4
TC003	1	17:26:58-17:35:00	24.1	27.2
	2	17:45:18-17:53:20	42.6	48.2
	3	18:03:28-18:11:29	78.1	88.4
TC004	1	11:46:51-11:54:54	26.7	27.5
	2	12:05:07-12:13:09	48.9	50.4
	3	12:23:27-12:31:29	92.1	94.9
TC005	1	14:42:18-14:50:20	25.6	26.3
	2	15:00:34-15:08:36	45.8	47.1
	3	15:18:43-15:26:46	88.7	91.2

Table 96. Combustion air conditions and measured water flow[1] for experiments with on-demand water heater AT03.

Exp.	Fuel	Burn	Air Temp (°C)			RH (%)			Water Draw[2] (GPM)		
TC001	1C	1	20.8	±	0.1	53.6	±	0.1	1.1	±	<0.1
		2	20.8	±	0.1	53.6	±	0.1	2.1	±	<0.1
		3	20.9	±	0.1	53.5	±	0.2	4.1	±	0.1
TC002	1N	1	21.1	±	0.1	52.8	±	0.1	1.1	±	<0.1
		2	21.1	±	<0.1	52.4	±	0.1	2.0	±	<0.1
		3	21.1	±	0.1	52.1	±	0.1	4.1	±	0.1
TC003	3C	1	20.7	±	0.1	53.1	±	0.3	1.1	±	<0.1
		2	20.7	±	0.1	52.5	±	0.1	2.1	±	<0.1
		3	20.8	±	0.1	52.3	±	0.1	4.1	±	0.1
TC004	PG&E	1	20.2	±	0.1	56.8	±	0.2	1.1	±	<0.1
		2	20.3	±	<0.1	56.2	±	0.1	2.2	±	0.1
		3	20.5	±	0.1	55.5	±	0.1	4.2	±	0.1
TC005	PG&E	1	21.1	±	0.1	52.9	±	0.2	1.1	±	<0.1
		2	21.2	±	0.1	52.8	±	0.1	2.1	±	<0.1
		3	21.3	±	0.1	52.6	±	0.1	4.1	±	0.2

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

[2] Measured by Omega in-line water flow pulse meter.

Table 97. Sampling system conditions for experiments with on-demand water heater AT03.

Exp.	Fuel	Burn	Vent Temp 1[1] (°C)			Vent Temp 2[1] (°C)			Dilution[2] Ratio
TC001	1C	1	26	±	<0.1	26	±	<0.1	15
		2	26	±	0.1	27	±	0.2	15
		3	30	±	0.2	30	±	0.2	14
TC002	1N	1	27	±	<0.1	27	±	<0.1	13
		2	26	±	0.1	26	±	0.1	14
		3	30	±	0.2	30	±	0.2	15
TC003	3C	1	25	±	0.2	26	±	0.2	12
		2	26	±	0.3	27	±	0.3	13
		3	30	±	0.3	30	±	0.3	14
TC004	PG&E	1	26	±	0.1	27	±	0.1	13
		2	27	±	0.2	27	±	0.2	14
		3	30	±	0.4	30	±	0.4	14
TC005	PG&E	1	26	±	0.2	27	±	0.2	13
		2	27	±	0.2	27	±	0.2	14
		3	30	±	0.2	30	±	0.2	14

[1] Measured in flue 12-inches below top of vent opening; mean over last 5 min of each burn.

[2] Calculated by dividing mean NO measured in gas manifold (PG-250) by dilution sampler (Thermo 42i) over last 5 min of each burn.

Table 98. Emission concentrations over last 5 min of each burn, water heater AT03.

Exp.	Wobbe	Burn[3]	CO[1] (ppm)	CO_2[1] (%)	O_2[1] (%)	NO[2] (ppm)	NO_2[2] (ppm)	NO_X[2] (ppm)
TC001	1396	1	290	3	16	36	19	55
		2	625	5	11	58	11	69
		3	122	9	5	16	7	23
TC002	1365	1	215	3	16	20	15	35
		2	354	5	12	47	12	59
		3	193	10	4	26	9	35
TC003	1426	1	361	3	16	41	32	73
		2	902	6	12	69	26	95
		3	213	10	4	32	17	49
TC004	1347	1	313	3	17	33	29	62
		2	371	5	12	45	23	68
		3	188	10	4	24	14	38
TC005	1344	1	234	3	16	27	17	45
		2	303	5	12	43	12	55
		3	220	10	4	31	10	41

[1] Measurement from PG250 Horiba gas analyzer. CO emissions adjusted using surface fit given by Equation (2). CO, NO_2, and NOx are Calculated air-free concentrations using O_2.

[2] Measurement from Thermo 42i.

[3] Burns correspond to water draws of approximately 1, 2, and 4 GPM, respectively.

Table 99. Calculated emission rates over entirety of each burn, water heater AT03.

Exp.	Wobbe	Burn[4]	CO[1] (ng/J)	NO[2,3] (ng/J)	NO_2[2,3] (ng/J)	NO_X[2,3] (ng/J)	HCHO (ng/J)	Acetaldehyde (ng/J)
TC001	1396	1	71.7	13.8	7.3	21.1	0.28	0.09
		2	144.9	22.3	4.5	26.8		
		3	33.6	6.6	2.9	9.5		
TC002	1365	1	54.1	7.9	5.8	13.6	0.30	0.09
		2	84.6	18.0	4.7	22.7		
		3	47.4	10.1	3.5	13.6		
TC003	1426	1	95.8	16.2	12.9	29.1	0.24	0.08
		2	213.7	26.9	10.3	37.2		
		3	58.4	13.2	7.0	20.2		
TC004	1344	1	77.3	12.4	11.0	23.4	0.25	0.08
		2	87.1	16.8	8.4	25.2		
		3	44.8	9.0	5.2	14.2		
TC005	1347	1	57.8	10.2	6.6	16.8	0.27	0.08
		2	69.4	15.5	4.7	20.2		
		3	50.9	11.3	3.8	15.1		

[1] Measurement from PG250 Horiba gas analyzer. CO emissions calculated using adjusted ppm CO from surface fit given by Equation (2).

[2] Measurement from Thermo 42i.

[3] Calculation assumes molecular mass of NO_2 for NO and NO_x (46 g/mol).

[4] Burns correspond to water draws of approximately 1, 2, and 4 GPM, respectively.

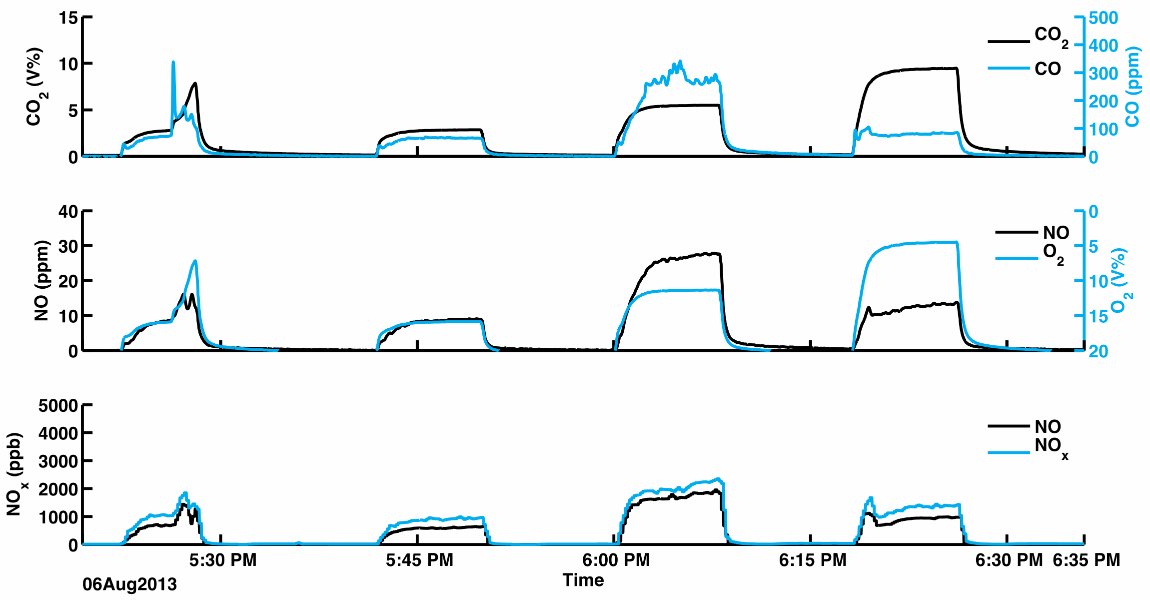

Figure 98. **Measured analyte concentrations for on-demand water heater AT03 with fuel 1C (TC001). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn.**

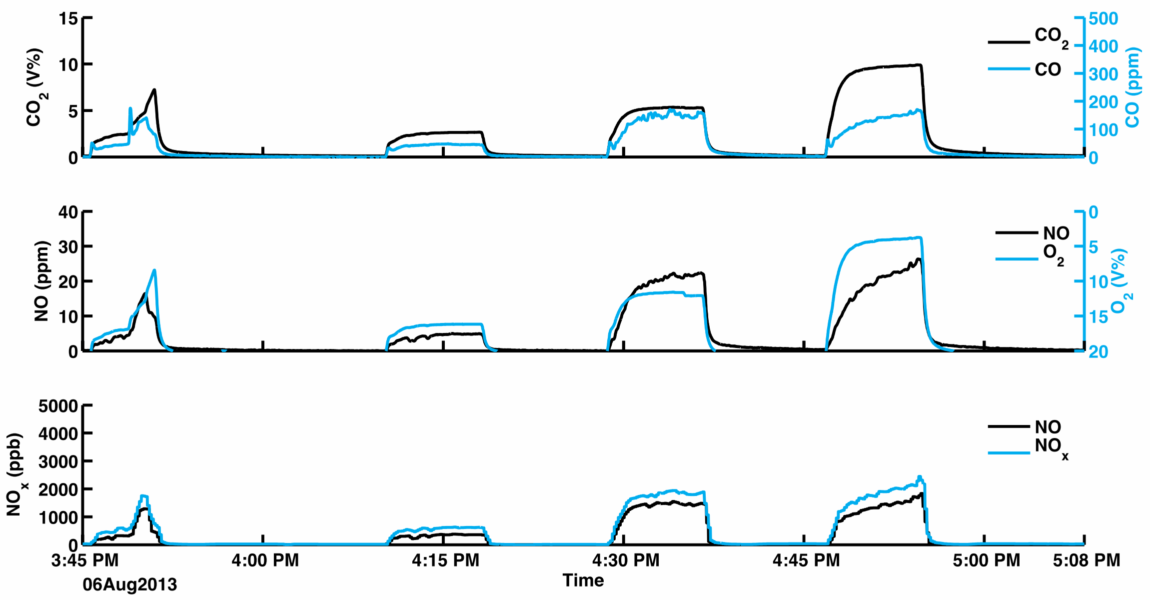

Figure 99. **Measured analyte concentrations for on-demand water heater AT03 with fuel 1N (TC002). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn.**

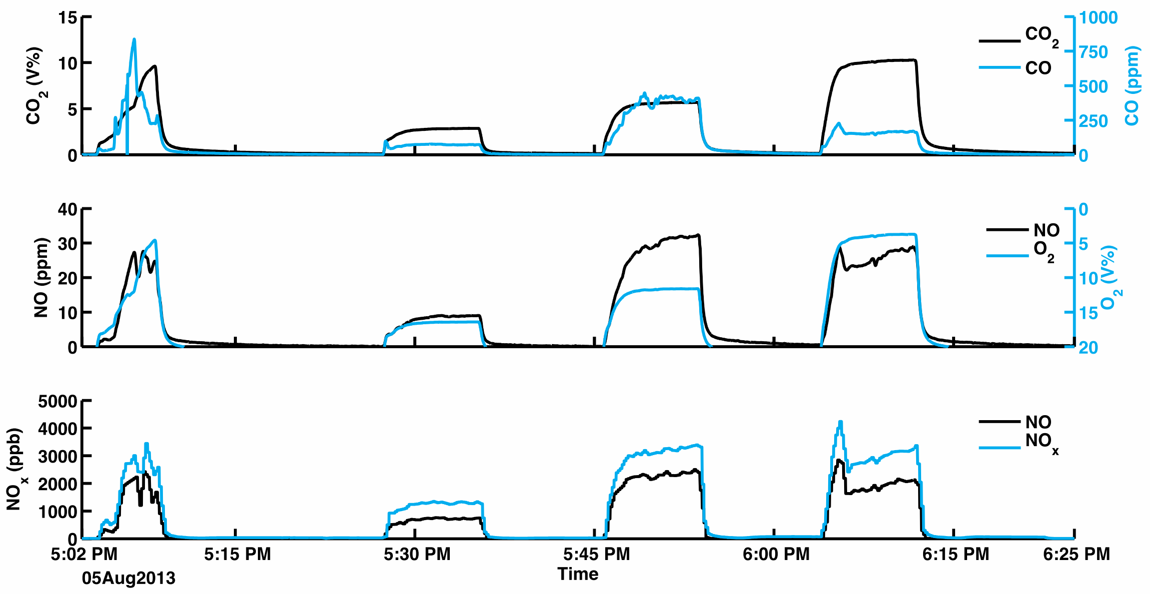

Figure 100. Measured analyte concentrations for on-demand water heater AT03 with fuel 3C (TC003). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn.

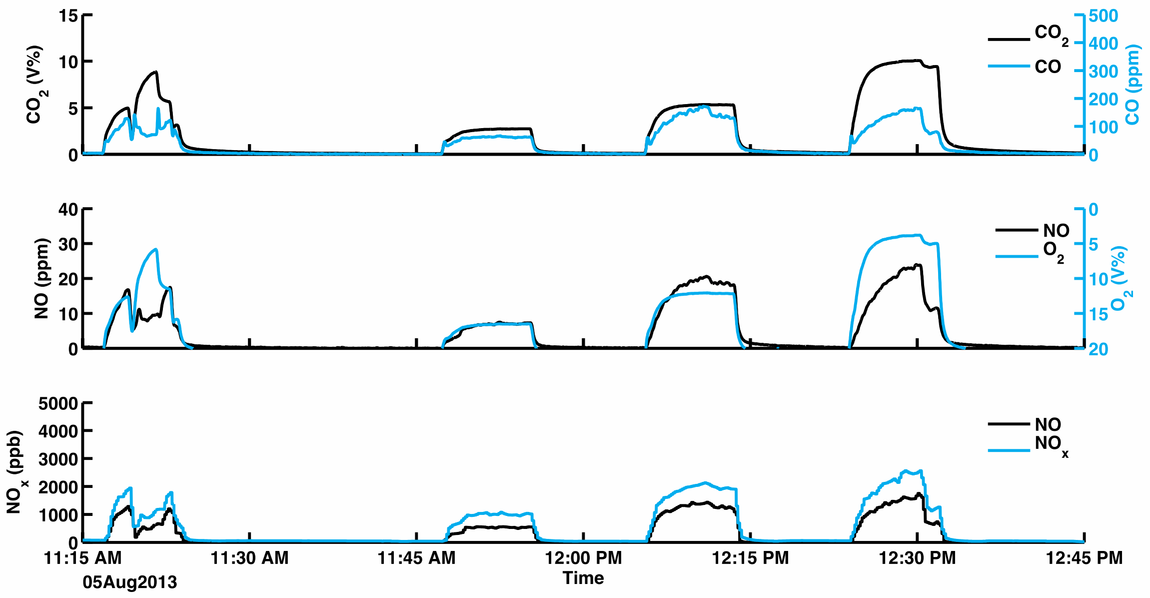

Figure 101. Measured analyte concentrations for on-demand water heater AT03 with PG&E gas (TC004). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first large, steady peak is the purge burn.

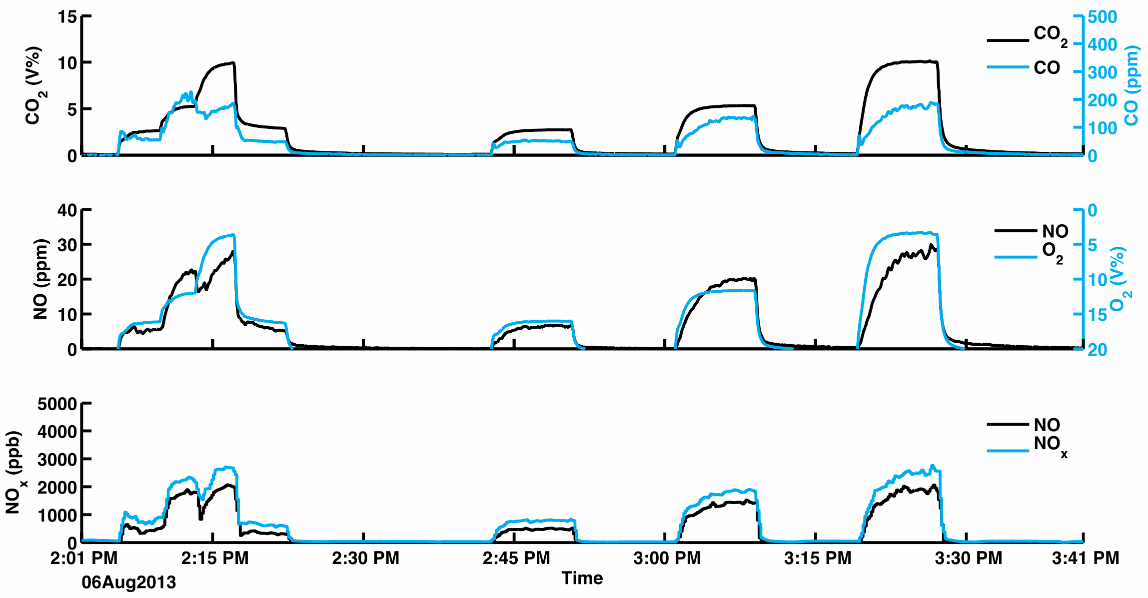

Figure 102. Measured analyte concentrations for on-demand water heater AT03 with fuel PG&E, repeat (TC005). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system. The first peak shown is the purge burn.

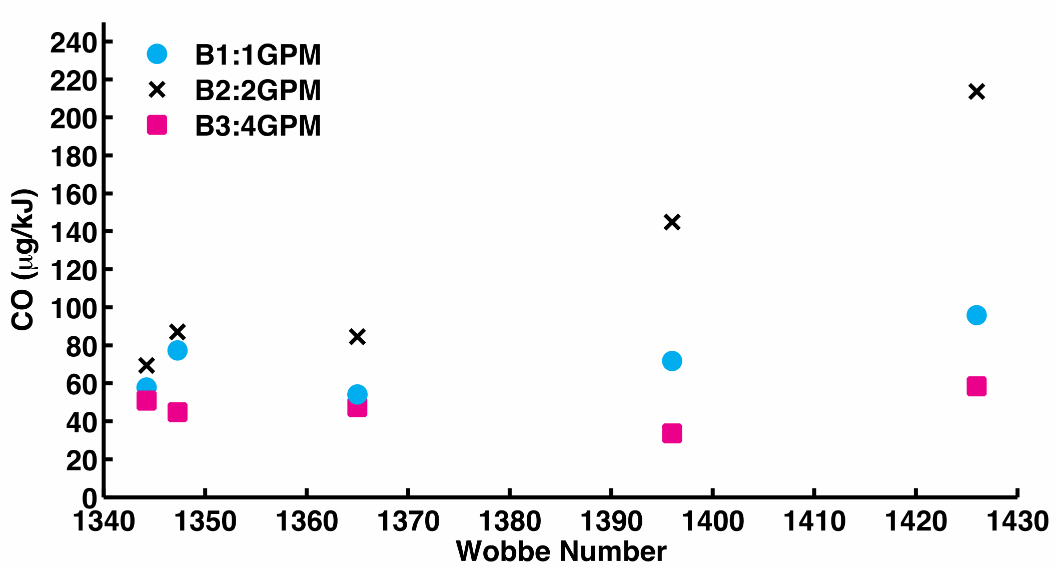

Figure 103. CO as a function of Wobbe Number for on-demand water heater AT03. The results show CO increases with Wobbe Number. For all experiments, Burn 2 (2 GPM hot water flow) produced the most CO.

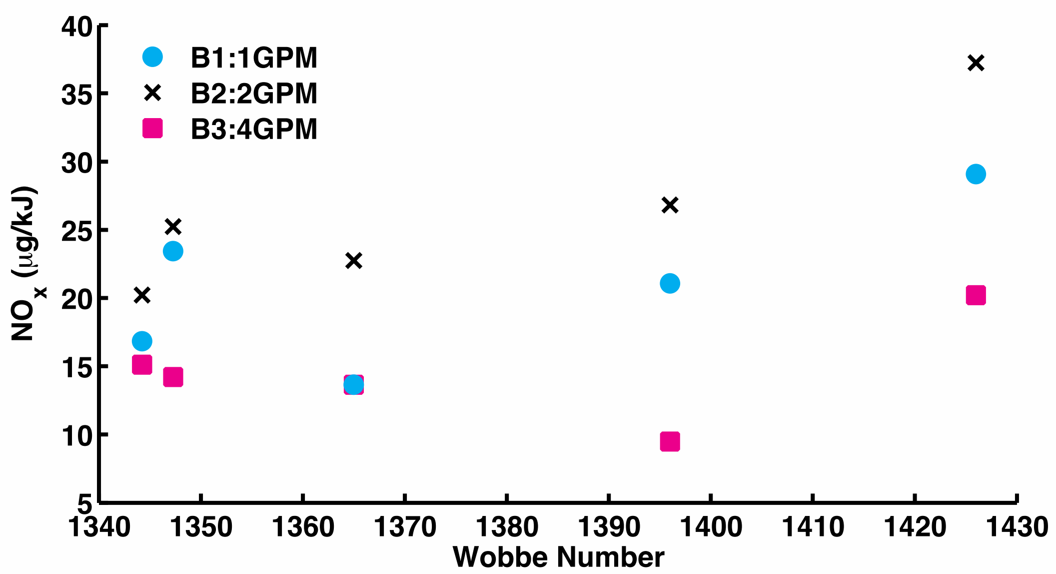

Figure 104. **NO$_x$ as a function of Wobbe Number for on-demand water heater AT03. The fuels show no obvious correlation between NO$_x$ and Wobbe Number for WN less than 1365. At higher Wobbe Numbers (greater than 1365), NO$_x$ increases with Wobbe Number. For all experiments, Burn 2 (2 GPM hot water flow) produced the most amount of NO$_X$.**

4.4 Results for AT04

4.4.1 Summary of Experiments. The Eternal ultra-low NO_x (SCAQMD rule 1146.2 compliant) hybrid water heater was purchased new. The water heater was installed in the test facilities at LBNL used for LNG interchangeability and energy efficiency experiments (see Figure 105). This hybrid water heater contains a reserve tank (less than 2 gallons) that surrounds a cylindrical burner element. The water heater also has separate venting for the intake combustion air and the exhaust gases. Further details on the water heater are presented in Table 100.

Figure 106 shows the detailed exhaust pollutant and temperature sampling configuration. The emissions sample lines and flue thermocouples were installed about 4-feet above the water heater in the exhaust venting (see Figure 105). Two thermocouples were used to ensure accuracy when measuring exhaust temperature. The thermocouples were installed 12-inches into the exhaust vent. Emissions were also sampled 12-inches into the exhaust vent.

In September of 2013, five experiments were conducted on this unit over two consecutive days. Three experiments were conducted on September 11, 2013 using the PG&E line gas (WN=1346), fuel mixture 1C (WN=1396), and fuel mixture 1N (WN=1365). During this experiment, the water heater temperature was set to 115°F and water was drawn at three flow rates, 1GPM, 2GPM, and 4GPM. This temperature setting was chosen to reduce risk of damage to the in-line hot water flow meter. On the following day, September 12, 2013, two experiments were conducted using fuel mixture 3C (WN=1426) and the PG&E line gas (WN=1349). Composition and properties of each fuel are presented in Table 101.

Environmental conditions were similar on both days. Pressure at the dry gas meter was 7 inches of water for fuel mixtures 1C, 1N, and 3C. The pressure at the dry gas meter was 7 inches of water for the PG&E line gas when the water heater pulled 1GPM and 2 GPM, but was 6 inches of water at 4 GPM. Additionally, the water heater would randomly turn on the burner (likely to heat up the small tank) when no water was being drawn. In order to prevent the water heater from turning on the burner in between burns, the water heater was manually turned on and off using the power switch.

4.4.2 Summary of Results. On September 11, 2013 and September 12, 2013, ambient temperature ranged from 20.8°C to 21.9°C and relative humidity ranged from 55.0% to 61.3%. For each burn, 20% to 39% of the NO_X was in the form of NO_2. During Experiment TD003, just prior to Burn 2 (2 GPM), the water heater automatically turned itself on about 20 seconds early. In order to keep the burner on, water was immediately drawn from the water heater. The extra 20-seconds of on-time did not significantly affect the emission results. We suspect the water inside the small tank dropped below a set point temperature, triggering the burner to come on.

For all experiments, the Horiba gas analyzer overcompensated for CO_2 interference in the CO signal, resulting in negative CO emission measurements. In order to correct for this overcompensation, the surface fit equations described in Section 2.2.4 were used to adjust the measured CO and reported in the tables that follow.

Full burn emission rates, shown in Table 107, ranged from 6.8–47 ng/J for CO and 3.0–29 ng/J for NO_X, 0.04–0.06 ng/J for formaldehyde, and 0.07–0.13 ng/J for acetaldehyde. Experiments conducted for hot water flows of 4 GPM produced the highest CO and NO_X emissions, while 1 GPM produced the lowest emissions. In Figure 113, NO_x increases linearly with Wobbe Number for each burn. NO_x also increases with hot water flow rate. Tables and figures that follow provide detailed results from the LNG interchangeability experiments for storage water heater AT04.

Figure 105. **Experimental apparatus installed for on-demand water heater AT04. Vent thermocouples, emission sampling tube, and dilution sampling tube are located in the exhaust vent about 4-feet above the water heater. The Thermo 42i and house-air line are not shown in this picture, but are located behind the drywall.**

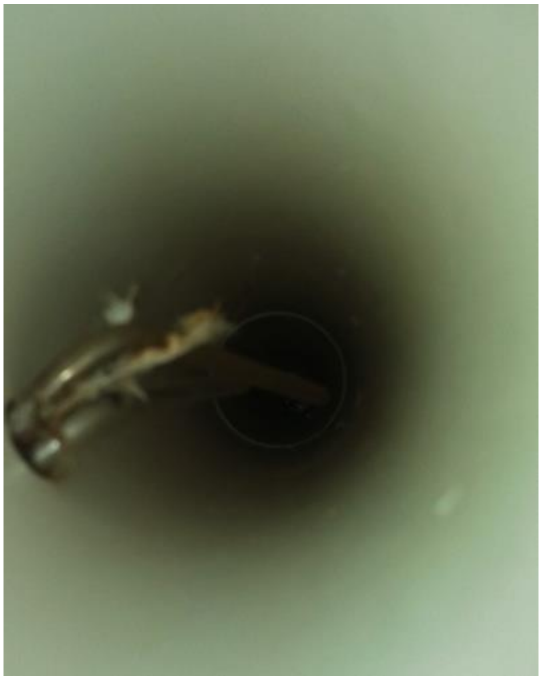

Figure 106. **Dilution tube and emissions sampling setup for on-demand water heater AT04. Dilution and emissions sampling tubes are located in the exhaust vent and sampled 12-inches into the exhaust vent. Exhaust temperature was measured in two locations 12-inches into the exhaust vent.**

Table 100. **Published information for water heater AT04.**

Burner ID	AT04
Burner category	Ultra-low NO_x, hybrid water heater
Technology	Hybrid condensing water heater; SCAQMD rule 1146.2 compliant; Contains a 1.7 Gallon tank; Burner system is a single orifice premixed fuel injection metal fiber infrared; Gas valve system is dual stage negative pressure full modulation air ratio
Appliance manufacturer	Eternal
Model	GU100/508(11,12,21,22)1100
Serial number	G1204853
Water Flow Rate Capacity	4.4 GPM @ 45°F rise 2.5 GPM @ 80°F rise
GPM Capacity Range	0.1 to 10 GPM
Water Holding Capacity	1.7 Gallons
Energy factor rating	0.94
Max inlet gas pressure	10.5 in. w.c.
Min inlet gas pressure	3.5 in. w.c.
Manifold Pressure	-0.04 in. w.c.
Electrical rating	120 V, 60 Hz, < 5 Amps
Max burner input	100,000 Btu/hr
Min burner input	16,000 Btu/hr

Table 101. **Composition of fuels for interchangeability experiments for on-demand water heater AT04.**

Exp.	Fuel	Date	N_2 (%)	CO_2 (%)	HHV (Btu/scf)	Wobbe number
TD001	1C$^+$	09/11/13	0.00	0.00	1076	1396
TD002	1N$^+$	09/11/13	1.70	0.00	1058	1365
TD003	3C$^+$	09/12/13	0.00	0.00	1131	1426
TD004	PG&E*	09/11/13	0.79**	0.77**	1029	1346
TD005	PG&E*	09/12/13	0.76**	0.80**	1035	1349

$^+$ All information provided by Praxair.

* Gas quality information provided by PG&E online pipeline data, BTU area J01 (downloaded 09/15/2013).

** Values are given in mol % not volume %.

Table 102. Aldehyde measurement times with on-demand water heater AT04*.

Fuel	Experiment	Date	Aldehyde Start Time	Aldehyde Stop Time	Total Liters Sampled
Lab Air**	-	09/11/13	11:02	13:21	138.8
Lab Air**	-	09/12/13	10:25	12:27	132.8
1C	TD001	09/11/13	13:53	14:58	78.6
			13:53	14:58	68.5
1N	TD002	09/11/13	15:32	16:33	73.7
			15:32	16:33	65.2
3C	TD003	09/12/13	12:35	13:36	63.7
			12:35	13:36	72.3
PG&E	TD004	09/11/13	12:12	13:19	71.0
			12:12	13:19	81.4
PG&E	TD005	09/11/13	10:46	11:46	63.7
			10:46	11:46	72.0

*Two Aldehyde measurements were taken on the dilution tube for each experiment.
**Aldehyde was measured directly from the lab air supply.

Table 103. Burner operating times, fuel flow, and firing rate for experiments with on-demand water heater AT04.

Exp.	Burn	Burn Time	Fuel Flow ($ft^3 h^{-1}$)	Firing Rate (kBtu/h)
TD001	1	14:00:18-14:08:21	18.7	20.1
	2	14:21:26-14:29:27	20.8	47.3
	3	14:39:57-14:48:01	41.1	93.7
TD002	1	15:39:26-15:47:32	19.4	20.6
	2	15:58:32-16:06:33	43.6	46.1
	3	16:16:44-16:24:44	86.1	91.0
TD003	1	12:39:09-12:47:17	18.0	20.4
	2	12:57:42-13:05:43	41.8	47.2
	3	13:17:04-13:25:08	84.2	95.2
TD004	1	12:20:35-12:28:38	20.3	20.9
	2	12:40:20-12:48:25	45.5	46.8
	3	12:58:51-13:06:56	92.2	94.9
TD005	1	10:49:43-10:57:47	19.5	20.2
	2	11:08:16-11:16:19	48.5	48.1
	3	11:26:45-11:34:48	93.0	96.3

Table 104. **Combustion air conditions and measured water flow[1] for experiments with on-demand water heater AT04.**

Exp.	Fuel	Burn	Air Temp (°C)			RH (%)			Water Draw[2] (GPM)		
TD001	1C	1	21.8	±	0.1	55.4	±	0.1	1.1	±	<0.1
		2	21.6	±	0.1	56.4	±	0.1	2.1	±	<0.1
		3	21.7	±	0.2	56.1	±	0.2	4.3	±	0.1
TD002	1N	1	21.9	±	0.1	55.0	±	0.1	1.1	±	<0.1
		2	21.7	±	0.1	55.7	±	0.1	2.1	±	<0.1
		3	21.9	±	0.1	55.0	±	0.2	4.2	±	0.1
TD003	3C	1	21.2	±	0.1	60.1	±	0.2	1.1	±	<0.1
		2	21.1	±	<0.1	61.1	±	0.1	2.1	±	<0.1
		3	21.3	±	0.1	60.9	±	0.1	4.3	±	0.1
TD004	PG&E	1	21.1	±	0.1	56.8	±	0.2	1.2	±	<0.1
		2	21.2	±	0.1	56.7	±	0.2	2.1	±	<0.1
		3	21.3	±	0.1	56.3	±	0.3	4.2	±	0.1
TD005	PG&E	1	21.0	±	0.1	60.9	±	0.2	1.1	±	<0.1
		2	20.8	±	0.1	61.3	±	0.1	2.1	±	<0.1
		3	21.1	±	0.1	60.6	±	0.2	4.3	±	0.1

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

[2] Measured by Omega in-line water flow pulse meter.

Table 105. Sampling system conditions for experiments with on-demand water heater AT04.

Exp.	Fuel	Burn	Vent Temp 1[1] (°C)			Vent Temp 2[1] (°C)			Dilution[2] Ratio
TD001	1C	1	27	±	0.2	28	±	0.2	14
		2	33	±	0.4	34	±	0.4	14
		3	48	±	0.6	49	±	0.6	14
TD002	1N	1	27	±	0.1	27	±	0.1	14
		2	33	±	0.4	34	±	0.4	14
		3	48	±	0.8	48	±	0.7	14
TD003	3C	1	27	±	0.1	27	±	0.1	13
		2	33	±	0.4	34	±	0.4	13
		3	48	±	1.1	49	±	1.0	13
TD004	PG&E	1	26	±	0.1	27	±	0.1	14
		2	33	±	0.5	34	±	0.4	14
		3	49	±	0.8	50	±	0.7	14
TD005	PG&E	1	27	±	0.1	27	±	0.1	13
		2	34	±	0.4	34	±	0.4	13
		3	49	±	0.8	49	±	0.7	13

[1] Measured in flue 12-inches below top of vent opening; mean over last 5 min of each burn.

[2] Calculated by dividing mean NO measured in gas manifold (PG-250) by dilution sampler (Thermo 42i) over last 5 min of each burn.

Table 106. Emission concentrations over last 5 min of each burn, water heater AT04.

Exp.	Wobbe	Burn[3]	CO[1] (ppm)	CO_2[1] (%)	O_2[1] (%)	NO[2] (ppm)	NO_2[2] (ppm)	NO_X[2] (ppm)
TD001	1396	1	3	8	7	7	2	9
		2	26	9	5	15	7	22
		3	35	10	3	39	18	57
TD002	1365	1	3	8	7	6	2	8
		2	18	9	6	13	6	19
		3	27	10	4	30	16	46
TD003	1426	1	5	8	7	7	2	9
		2	6	9	5	18	8	26
		3	48	10	3	51	22	73
TD004	1346	1	2	8	8	5	2	7
		2	3	9	6	11	6	17
		3	28	10	4	27	15	42
TD005	1349	1	3	8	8	5	2	7
		2	4	9	6	12	7	18
		3	29	10	4	26	15	41

[1] Measurement from PG250 Horiba gas analyzer; CO emissions adjusted using surface fit given by Equations (1) and (2). CO, NO_2, and NOx are Calculated air-free concentrations using O_2.

[2] Measurement from Thermo 42i.

[3] Burns correspond to water draws of approximately 1, 2, and 4 GPM, respectively.

Table 107. Calculated emission rates over entirety of each burn, water heater AT04.

Exp.	Wobbe	Burn[4]	CO[1] (ng/J)	NO[2,3] (ng/J)	NO_2[2,3] (ng/J)	NO_X[2,3] (ng/J)	HCHO (ng/J)	Acetaldehyde (ng/J)
TD001	1396	1	9.6	3	0.9	3.9	0.1	0.1
		2	39.5	6.6	2.9	9.5		
		3	21.9	16	7.3	23.3		
TD002	1365	1	10.9	2.8	0.7	3.5	0.1	0.1
		2	46.8	5.5	2.5	8		
		3	16.0	12.4	6.3	18.7		
TD003	1426	1	25.5	3.2	0.9	4.1	0.1	0.1
		2	14.8	7.8	3.2	11		
		3	26.5	20.7	8.6	29.4		
TD004	1346	1	7.7	2.2	0.8	3	0.1	0.1
		2	7.3	4.4	2.4	6.8		
		3	16.1	10.4	5.9	16.3		
TD005	1349	1	11.2	2.3	0.8	3.1	<0.1	0.1
		2	6.8	4.6	2.7	7.3		
		3	16.5	10	5.8	15.8		

[1] Measurement from PG250 Horiba gas analyzer; CO emissions calculated using adjusted ppm CO from surface fit given by Equations (1) and (2).

[2] Measurement from Thermo 42i

[3] Calculation assumes molecular mass of NO_2 for NO and NO_x (46 g/mol)

[4] Burns correspond to water draws of approximately 1, 2, and 4 GPM, respectively

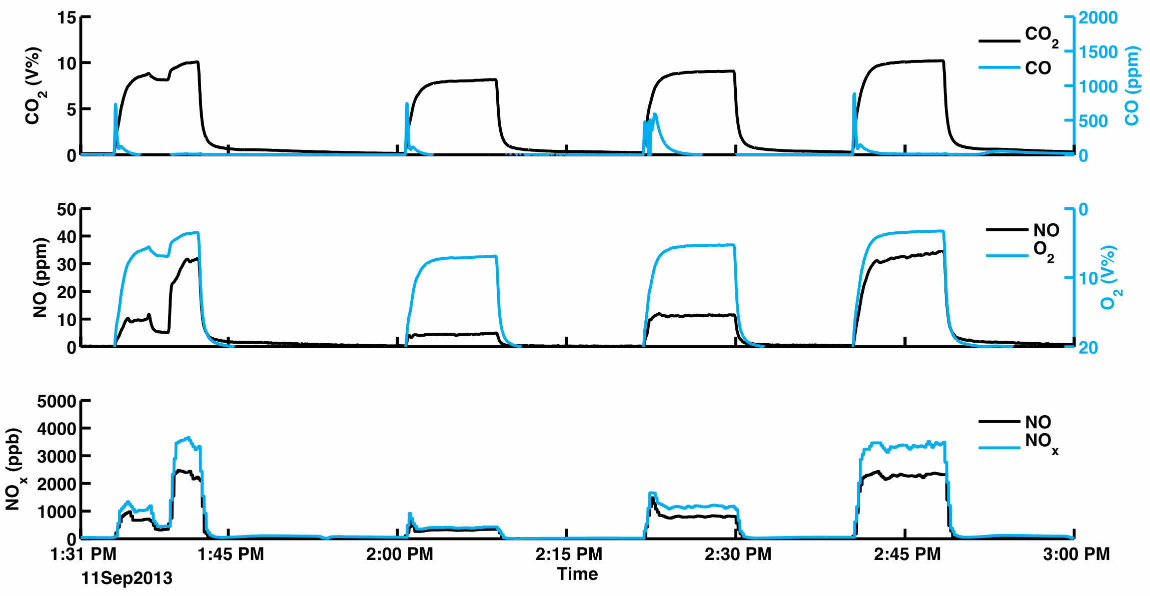

Figure 107. Measured analyte concentrations for on-demand water heater AT04 with fuel 1C (TD001). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system.

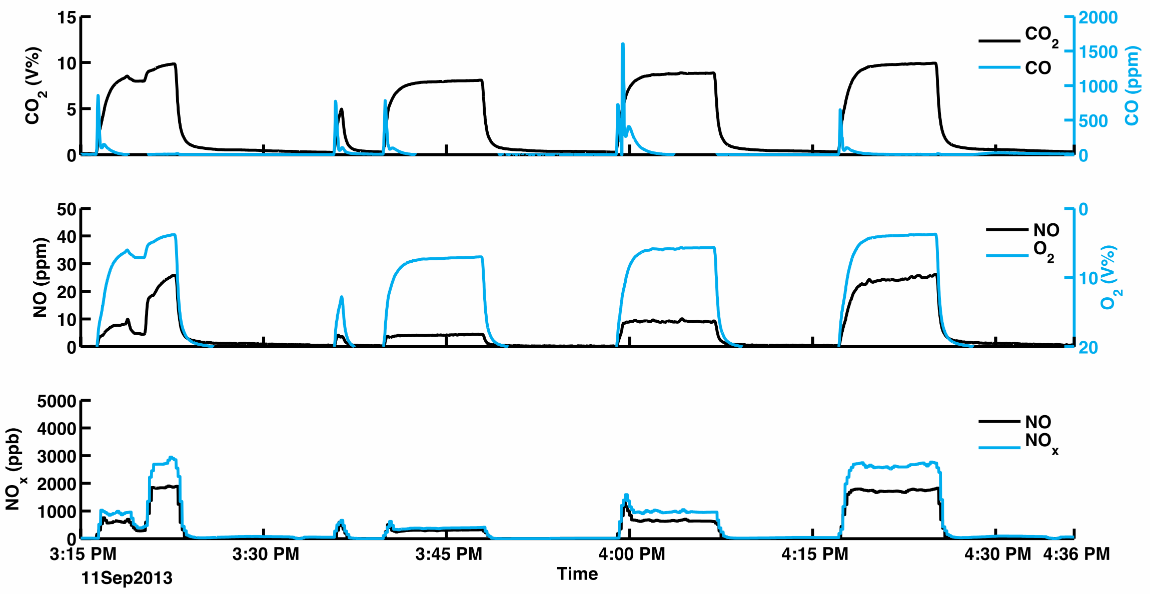

Figure 108. Measured analyte concentrations for on-demand water heater AT04 with fuel 1N (TD002). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system.

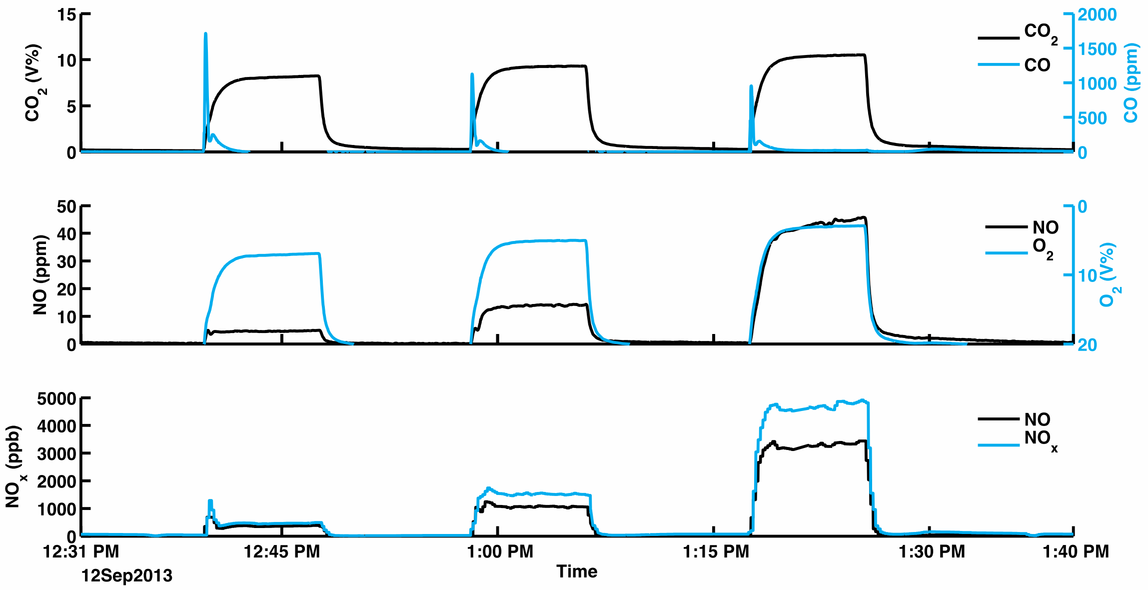

Figure 109. Measured analyte concentrations for on-demand water heater AT04 with fuel 3C (TD003). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system.

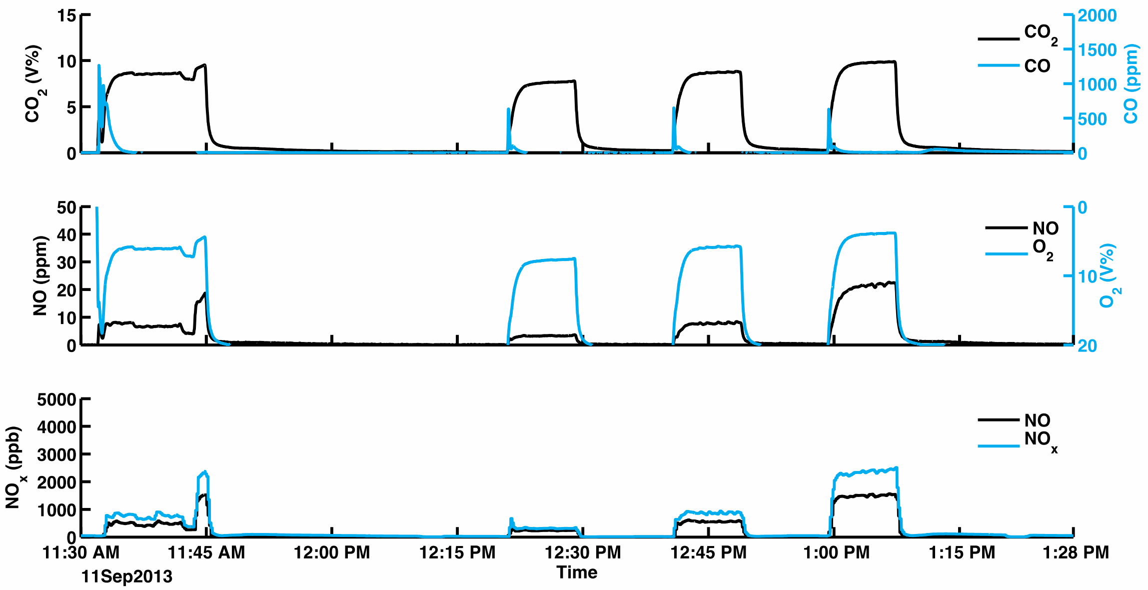

Figure 110. Measured analyte concentrations for on-demand water heater AT04 with PG&E gas (TD004). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system.

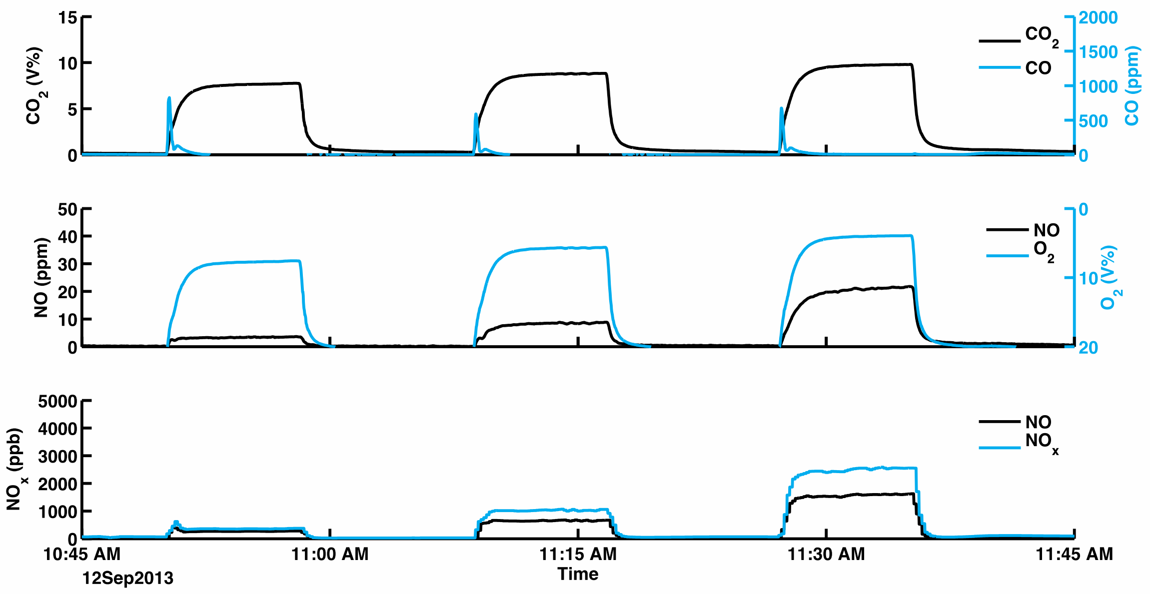

Figure 111. Measured analyte concentrations for on-demand water heater AT04 with fuel PG&E, repeat (TD005). The top two panels present data measured with the Horiba PG-250 analyzer in the gas manifold; the bottom panel presents measurements from the dilution system.

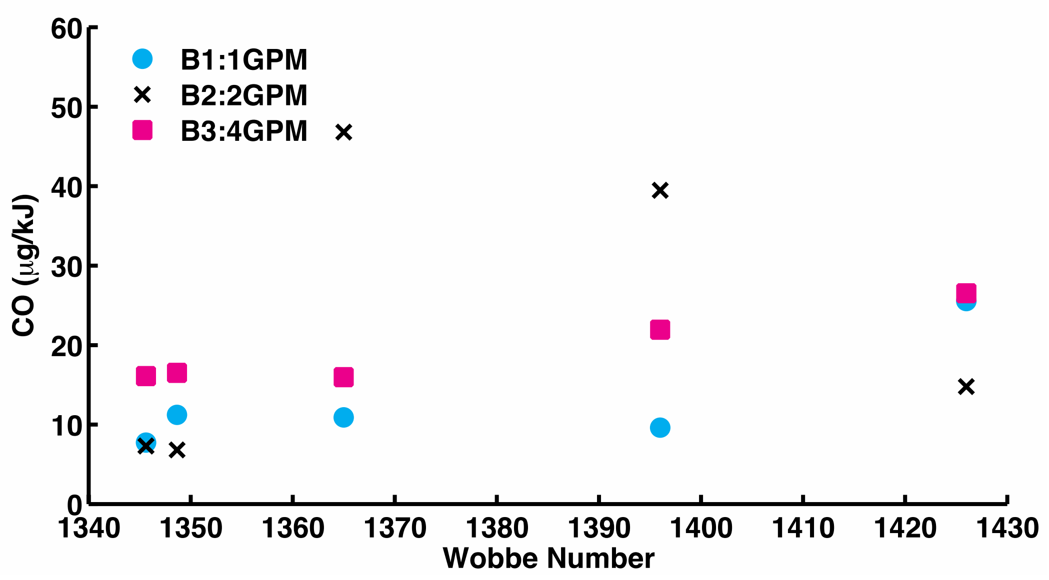

Figure 112. CO as a function of Wobbe Number for on-demand water heater AT04. CO increases slightly with a large increase in Wobbe Number. For most experiments, Burn 2 (2 GPM hot water flow) produced the most CO.

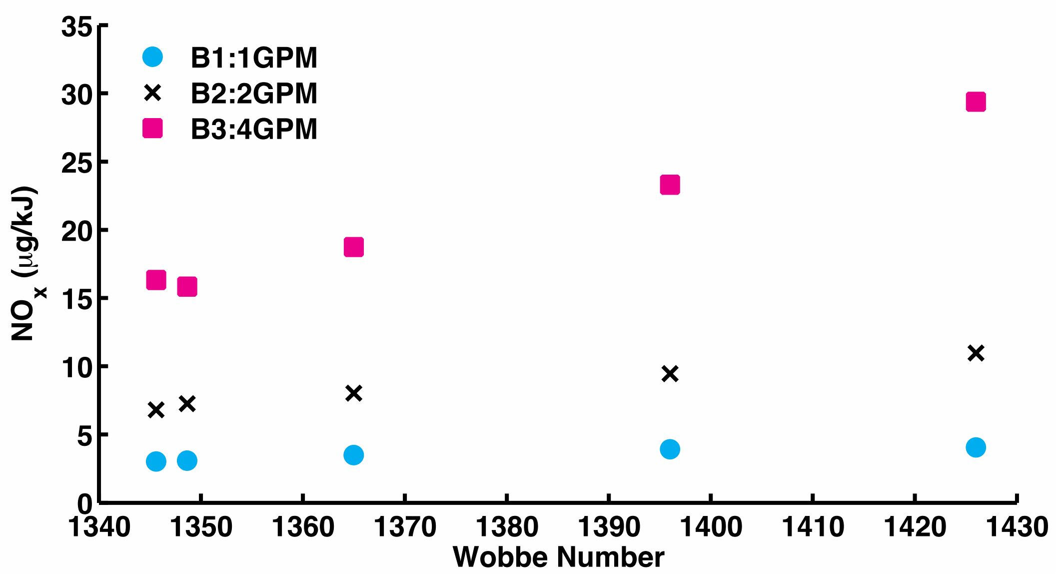

Figure 113. NO_x as a function of Wobbe Number for on-demand water heater AT04. NO_x increases linearly with Wobbe Number for each burn. NO_x also increases with hot water flow rate.

4.5 Emission Statistics from On-Demand Water Heaters

Table 108. Gaseous emission p-values of individual burns from tested on-demand water heaters.

Water Heater ID	Burn[1]	CO (ng/J)	NO_2 (ng/J)	NO_X (ng/J)
AT01	1	0.447	0.300	0.210
	2	0.010	0.019	0.010
	3	0.494	0.018	0.011
AT02	1	0.507	0.663	0.856
	2	0.761	0.535	0.252
	3	0.226	0.037	0.035
AT03	1	0.167	0.399	0.226
	2	0.005	0.434	0.036
	3	0.760	0.448	0.572
AT04	1	0.098	0.370	0.008
	2	0.717	0.016	0.000
	3	0.006	0.001	0.000

[1] Burns correspond to water draws of approximately 1, 2, and 4 GPM, respectively

5.0 Summary and Conclusions

The tables below provide summary results in terms of pollutant emission factors for each water heater using the average results from the PG&E line gas experiments. The tables also present the statistically discernible trends of emission factors changing with increasing fuel Wobbe number. The impact of Wobbe number is provided for a change of 50 Wobbe number.

Table 109 shows that the three water heaters that were <u>not</u> rated as ultra low-NO_X – AW04, AW06 and AW07 – had NO_X emissions of 36–38 ng/J with PG&E fuel. Those emission factors are higher than the NO_X emissions measured for conventional technology devices in the recent LBNL study (Singer et al. 2010). These three water heaters use conventional burner technologies but utilize enhancements in venting and heat transfer to extract more energy from the combustion process to improve energy efficiency. Increasing Wobbe number caused small increases in NO_X emissions of these devices, estimated at 2-5% for a 50 Wobbe number change.

Table 109. Summary of experiments and results for storage water heaters[1,2]

ID	Description	Rating (Btu/h)	PG&E[3] WN	CO (ng/J)	NO_2 (ng/J)	NO_X (ng/J)	HCHO (ng/J)	Acetald. (ng/J)
AW01	Ultra-low NO_X; natural draft; “round” burner; 38 gal	38,000	1350 1348	0.0 (ns)	1.2 (ns)	*7.5* *2.0*	0.06 (ns)	0.04 (ns)
AW02	Ultra-low NO_X; natural draft; “cake-pan” burner; 40 gal	40,000	1347 1346	-0.9[4] (ns)	1.4 (ns)	*6.3* *1.3*	0.04 (ns)	0.04 (ns)
AW03	Ultra-low NO_X; power vent; “cake-pan” burner; 40 gal	42,000	1348[5]	2.1 (ns)	2.5 (ns)	6.2 1.4	0.15 (ns)	0.11 (ns)
AW04	Condensing; “pancake” burner; 50 gal	76,000	1347 1353	11.3 (ns)	5.2 (ns)	35.2 (ns)	0.02 (ns)	0.07 (ns)
AW05	Ultra-low NO_X; power vent; “round” burner; 40 gal	36,000	1348 1349	1.2 (ns)	1.2 (ns)	9.9 1.5	0.12 (ns)	0.1 (ns)
AW06	Energy Star, induced draft; “pancake” burner; 29 gal	60,000	1352 1348	*1.2* *1.4*	0.9 (ns)	38.1 1.4	0.02 (ns)	0.05 (ns)
AW07	Energy Star, induced draft; “pancake” burner; 40 gal	40,000	1348 1349	1.5 -0.3	4.5 (ns)	36.1 1.7	0.07 (ns)	0.08 (ns)
AW08	Condensing; ultra-low NO_X; “cylinder” burner; 50 gal	100,000	1350 1348	0.6 0.3	1.8 (ns)	*11.6* *5.9*	0.01 (ns)	0.03 (ns)

[1] For CO, NO_2, NO_X, HCHO, and Acetaldehyde, the first value in each cell is the average full burn emission rate for the PG&E line gas tests. The emissions change for a 50 Btu/scf increase in fuel WN, below the average full burn emission rate, is only shown for a p value ≤0.10. Results with p<0.05 are italicized. Low p-values indicate statistically significant results

[2] NO_X = nitrogen oxide, CO = carbon monoxide, NO_2 = nitrogen dioxide, HCHO = formaldehyde, Acetald = acetaldehyde; ns = not significant

[3] PG&E Line Gas Wobbe Number is listed for each experiment

[4] Negative value indicates near zero CO and is within instrument linearity (±2% of Full Scale)

[5] Only one experiment was conducted with PG&E line gas

[3] Only one experiment was conducted with PG&E line gas

Consistent with design intent, the storage water heaters with ultra-low NO_X burner technologies had much lower emissions than those with conventional technology burners. Four of the models had NO_X under 10 ng/J and the fifth had NO_X emissions of 12 ng/J. We note that these results are for the test conditions used in this study and should not be considered as applicable to standards based on regulatory test procedures. Consistent with results obtained by Singer et al. (2010) for the lower-NO_X on-demand water heaters, these ultra-low NO_X water heaters showed substantial and statistically discernible ($p<0.10$) sensitivity to fuel Wobbe number. The storage water heaters with ultra-low NO_X burners had NO_X increases of 15 to 51% with a 50 Wobbe number increase in fuel.

The majority of NO_X was in the form of NO; estimated NO_2 (NO_X-NO) was 2-15% of total NO_X for conventional burners, 12-22% for 4 of 5 ultra-low NO_X devices and 40% for the last device.

The results in Table 109 reveal that, similar to the prior results for conventional technology storage water heaters, advanced technology (ultra-low NO_X, induced draft, and energy efficient condensing) designs have very low emission rates of CO, formaldehyde and acetaldehyde. Only one device – the condensing water heater AW04 – had CO above 10 ng/J. None of the storage water heaters had emissions of either aldehyde exceeding 0.2 ng/J.

Results for the on-demand devices, including the hybrid AT04, are shown in Table 110.

Table 110. Summary of experiments and results for on-demand water heaters, adjusted for effect of water flow rate[1,2]

ID	Description	Rating (Btu/h)	PG&E[3] WN	CO (ng/J)	NO_2 (ng/J)	NO_X (ng/J)	HCHO (ng/J)	Acetald. (ng/J)
AT01	Ultra-low NO_X, non-condensing	11,000-180,000	1348 1349	*36.0* *7.2*	4.7 1.7	*10.6* *4.8*	0.6 (ns)	0.23 (ns)
AT02	Ultra-low NO_X, non-condensing	11,000-150,000	1362 1365	*32.1* *-1.5*	4.9 (ns)	9.5 (ns)	*0.50* *-0.1*	0.14 (ns)
AT03	Ultra-low NO_X, condensing	15,000-150,000	1344 1347	*64.5* *34.5*	6.6 (ns)	19.2 (ns)	0.26 (ns)	0.08 (ns)
AT04	Ultra-low NO_X, hybrid	16,000-100,000	1349 1346	*10.9* *7.1*	*3.1* *0.7*	*8.7* *3.8*	0.05 (ns)	0.11 (ns)

[1] For CO, NO_2, NO_X, HCHO, and Acetaldehyde, the first value in each cell is the average full burn emission rate of the PG&E line gas tests. This value averages emissions from the 1, 2, and 4 gallon per minute flow rate burns. The emissions change for a 50 Btu/scf increase in fuel WN, below the average full burn emission rate, is only shown for a p value ≤0.10. Emission changes in italics indicate p-values ≤ 0.05. Low p-values indicate statistically significant results

[2] NO_X = nitrogen oxide, CO = carbon monoxide, NO_2 = nitrogen dioxide, HCHO = formaldehyde, Acetald = acetaldehyde; ns = not significant

[3] PG&E Line Gas Wobbe Number is listed for each experiment

With PG&E line gas, three of the four had NO_X emissions in range of 8.7 to 10.6 ng/J; AT03 had substantially higher NO_X emissions of 19.2 ng/J with line gas. Only two of the four devices (AT01 and AT04) had NO_X increase with Wobbe number with statistical discernibility; the increase was 44-45% with a 50 Wobbe number fuel change. Estimated NO2 accounted for 34-52% of total NO_X for these devices.

All four of the on-demand water heaters had CO emissions with PG&E line gas exceed 10 ng/J and NO_2 exceed 3 ng/J. Three had formaldehyde exceed 0.2 ng/J. CO emissions for the four on-demand devices operating with PG&E fuel were 11 to 65 ng/J as compared to a range of CO emissions of 19 to 87 ng/J for the tankless water heaters reported by Singer et al. (2010). One interesting difference in the new data is that the device with highest CO – AT03 – also shows the greatest sensitivity to fuel Wobbe number. This result is driven primarily by emissions for the 2 GPM water flow.

Task Conclusions

The controlled experiments conducted in this study indicate that for some advanced technology water heaters, emissions of some pollutants are sensitive to the Wobbe number of the fuel. The most prominent sensitivity was an increase in NO_X emissions with increasing Wobbe number. All five of the ultra low- NO_X storage water heaters and two of the four ultra low- NO_X on-demand water heaters had statistically discernible increases in NO_X with fuel Wobbe number. The largest percentage increases occurred for the ultra low-NO_X water heaters. Another prominent result was a statistically discernible change in CO emissions with Wobbe number for all four of the on-demand devices tested. The device with highest CO emissions with line gas also had the largest CO increase (53%) with increasing fuel Wobbe number.

6.0 References

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7.0 Glossary of Abbreviations

ANSI	American National Standards Institute
APT	Automated Performance Testing System
Btu	British Thermal Unit
CEC	California Energy Commission
CO	Carbon monoxide
DR	Dilution ratio
HCHO	Formaldehyde
J	Joule
LBNL	Lawrence Berkley National Laboratory
LNG	Liquefied natural gas
MJ	Megajoules
NDIR	Non-dispersive infrared
ng	nanograms
NO_2	Nitrogen dioxide
NO_X	Nitrogen oxide
PG&E	Pacific Gas and Electric Company
PN	Particle number
ppm	Parts per million
RH	Relative humidity
T	Air temperature
TW	Tankless water heaters
UHP	Ultra high purity
UV	Ultraviolet
WH	Storage water heaters
WN	Wobbe number