Pollutant Concentrations and Emission Rates from Scripted Natural Gas Cooking Burner Use in Nine Northern California Homes

Brett C. Singer, William W. Delp, David M. Lorenzetti, Randy L. Maddalena

Energy Technologies Area

October 2016

DISCLAIMER

Abstract

METHODS: Combustion pollutant concentrations were measured during the scripted operation of natural gas cooking burners in nine homes. In addition to a base condition of closed windows, no forced air unit (FAU) use, and no mechanical exhaust, additional experiments were conducted while operating an FAU and/or vented range hood. Test homes included a $26m^2$ two-room apartment, a $134m^2$ first floor flat, and seven detached homes of $117–226m^2$. There were four single-story, four two-story and one 1.5 story homes. Cooktop use entailed boiling and simmering activities, using water as a heat sink. Oven and broiler use also were simulated. Time-resolved concentrations of carbon dioxide (CO_2), nitric oxide (NO), nitrogen oxides (NO_X), nitrogen dioxide (NO_2), particles with diameters of 6 nm or larger (PN), carbon monoxide (CO), and fine particulate matter ($PM_{2.5}$) were measured in the kitchen (K) and bedroom area (BR) of each home. CO_2, NO, NO_2, and PN data from sequential experiments were analyzed to quantify the contribution of burner use to the highest 1h and 4h time-integrated concentrations in each room.

RESULTS: Four of the nine homes had kitchen 1h NO_2 exceed the national ambient air quality standard (100 ppb). Two other homes had 1h NO_2 exceed 50 ppb in the kitchen, and three had 1h NO_2 above 50 ppb in the bedroom, suggesting substantial exposures to anyone at home when burners are used for a single substantial event. In all homes, the highest 1h kitchen PN exceeded 2×10^5 cm^{-3}-h, and the highest 4h PN exceeded 3×10^5 cm^{-3}-hr in all homes. The lowest 1h kitchen/bedroom ratios were 1.3–2.1 for NO in the apartment and two open floor plan homes. The largest K/BR ratios of 1h NO_2 were in a two-story 1990s home retrofitted for deep energy savings: ratios in this home were 3.3 to 6.6. Kitchen 1h ratios of NO, NO_2 and PN to CO_2 were used to calculate fuel normalized emission factors (ng J^{-1}). Range hood use substantially reduced cooking burner pollutant concentrations both in the kitchen and bedroom of several homes. A hood with large capture volume and a measured flow of 108 L/s reduced concentrations 80-95%.

IMPLICATIONS: These measurements demonstrate that operation of natural gas cooking burners without venting can cause short-term kitchen concentrations of NO_2 to exceed the US outdoor health standard, and can elevate concentrations of NO, NO_2, and ultrafine particles throughout the home. Results are generally consistent with a recent simulation study that estimated widespread 1h NO_2 exposures exceeding 100 ppb in homes that use gas burners without venting. While operating a venting range hood can greatly reduce pollutant levels from burner use (and presumably from cooking as well), performance varies widely across hoods. Increased awareness of the need to ventilate when cooking would substantially reduce in-home exposure to NO_2 and ultrafine particles in California homes. Helping consumers select effective hoods, for example by publishing capture efficiency performance ratings, also would help reduce exposure.

Acknowledgements

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

2

Table of Contents

List of Tables

List of Figures

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

4

1 Introduction

The combustion products of natural gas cooking burners (NGCBs) include pollutants that can impact indoor air quality (IAQ). While complete combustion directly produces water vapor and carbon dioxide (CO_2), the high flame temperatures also produce nitrogen oxides (NO_X), including nitrogen dioxide (NO_2), a respiratory irritant. Incomplete combustion can produce non-negligible emissions of carbon monoxide (CO), formaldehyde (CH_2O), and nanometer-sized particles that form from condensation of partially oxidized organic compounds. These tiny particles grow through coagulation and condensation into particles that are tens of nm in diameter (Rim et al., 2012; Wallace et al., 2008), but remain within the <100 nm diameter threshold that defines ultrafine particles (UFP).

The U.S. EPA sets national ambient air quality standards (NAAQS) for carbon monoxide and NO_2, in order to protect both the general population and sensitive sub-populations (US EPA, 2010; US EPA, 2016). The NAAQS for CO are 35 ppm averaged over 1h, and 9 ppm averaged over 8h. The NAAQS for short-term exposure to NO_2 is 0.1 ppm (100 ppb) over 1h. Formaldehyde is both a mucosal irritant and a human carcinogen (Kaden et al., 2010). Health-based guidelines for short-term formaldehyde exposure span a range of values (Salthammer et al., 2010). An expert elicitation review of the available literature rated the likelihood of increased short-term UFP exposure causing health effects as medium to high (Knol et al., 2009). Another review noted the substantial experimental evidence and plausible mechanisms for respiratory and cardiovascular effects of UFP intake, but deemed the evidence as "not sufficiently strong to conclude that short-term exposures to UFPs have effects that are dramatically different from those of larger particles" (HEI Review Panel on Ultrafine Particles, 2013). The particles emitted from NGCBs typically don't have sufficient mass to be governed by health standards for ambient fine particulate matter ($PM_{2.5}$). There are no standards or guidelines for UFP or fine particle number concentrations.

Emission factors of CO, NO_2, and formaldehyde from NGCBs have been measured in laboratory and field studies (Moschandreas and Relwani, 1989; Singer et al., 2010a; Singer et al., 2010b; Traynor et al., 1996). Several studies have reported emission factors and/or indoor concentrations of ultrafine particles resulting from NGCB use (Bhangar et al., 2011; Rim et al., 2012; Singer et al., 2010a; Wallace et al., 2008).

Many studies have reported elevated concentrations of CO and NO_2 in homes with natural gas cooking burners, compared to homes with electric cooking (Garrett et al., 1999; Ryan et al., 1988; Schwab et al., 1994; Spengler et al., 1994; Spengler et al., 1983; Wilson et al., 1986; Wilson et al., 1993). A recent study of 350 California homes reported that NO_2 and NO concentrations increased with increasing (self-reported) use of NGCBs (Mullen et al., 2016). Several studies have reported substantial ultrafine particle emissions associated with use of NGCBs (Singer et al., 2010a; Wallace et al., 2008).

While several measurement-based studies have reported time-resolved CO, e.g. (Mullen et al., 2016), only a few have reported time-resolved or peak NO_2 concentrations resulting from NGCB use (Fortmann et al., 2001; Franklin et al., 2006; Moschandreas and Zabransky Jr, 1982).

A recent simulation study assessed the impact of NGCB use on concentrations of CO, NO_2, and formaldehyde in a representative sample of Southern California homes (Logue et al., 2014).

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

5

The study used data on home sizes, cooking activities, and home ventilation rates, along with emission factors measured and reported by Singer et al. (2010a). The study concluded that the weekly highest 1h mean NO_2 concentrations exceed 100 ppb in the majority of simulated homes in which NG cooking burners were used without kitchen exhaust ventilation.

The primary strategy for mitigating exposure to pollutants from cooking burners is to use a venting range hood or other kitchen exhaust ventilation (Stratton and Singer, 2014). Recent assessments of range hoods in the U.S. indicate wide performance variations across devices, and across airflow settings and burner configurations for many devices tested (Delp and Singer, 2012; Lunden et al., 2015; Rim et al., 2011; Singer et al., 2012). Several of these studies used capture efficiency, CE, as the performance metric. CE indicates the fraction of pollutants generated at the cooking appliance that are removed or exhausted by the range hood before they can mix into the air of the home. These studies found that for many range hoods, CE is much higher for the back than for the front cooktop burners. The Logue et al. (2014) modeling study of Southern California homes found that routine use of a venting kitchen range hood with a 52% CE (reflecting performance of a common hood for front burner cooking) should dramatically reduce the percentage of homes with 1h mean NO_2 exceeding 100 ppb.

The primary objective of the research reported here was to quantify time-resolved concentrations of NO_2 resulting when NGCBs are used under realistic conditions, and specifically to investigate if the threshold of 100 ppb over 1h is commonly exceeded. We also sought to measure concentrations of NO, NO_X, CO_2, CO, CH_2O, $PM_{2.5}$, and the number of particles with diameters ≥ 6 nm (most of which are UFP) following controlled burner use. Another objective was to conduct a pilot study of the benefits of using venting range hoods to reduce in-home concentrations of pollutants emitted by NGCBs. This report focuses on results for NO, NO_2, CO_2, and particle number concentration. Limited results are presented for CO and $PM_{2.5}$ in the main body of the report, with additional data presented in the Appendix.

2   Methods

2.1   Overview

The study operated NGCBs and measured the resulting pollutant concentrations in nine homes in the San Francisco Bay area. Experiments were conducted, by permission, when residents were away from the home. Researchers controlled the operation of cooking appliances, ventilation, and forced-air heating systems. The NGCB operation sequences were designed to represent common cooking patterns. To avoid generating pollutants from food preparation, pots containing tap water were used as heat sinks. Air pollutants – including NO_X, NO, number concentrations of particles ≥ 6 nm (PN), formaldehyde, CO, CO_2, and estimated $PM_{2.5}$ (using a light-scattering instrument) – were measured in the kitchen and a hallway or bedroom that was far from the kitchen. CO_2 was also measured in a common room between the other two locations but generally closer to the kitchen. NO_2 was inferred as the difference between NO_X and NO, even though that value likely includes non-negligible amounts of nitrous acid (HONO) (Spicer et al., 1994).

The base set of experiments included operation of each available burner set (cooktop, oven bottom burner, and separate broiler burner where available) with windows closed, no mechanical air mixing (i.e., the forced air heating system, if present, was turned off), and no mechanical

exhaust. Additional experiments were conducted with the forced air system operated in fan-only mode when this setting was available, and with a venting range hood when available.

2.2 Study homes

The nine homes varied in size and layout, as described in Table 1. They included seven detached houses, one flat (first floor of two-flat duplex), and a small apartment. There were three homes with open floor plans and no walls enclosing the kitchen. Four of the homes had kitchens that were distinct rooms, connected to other rooms in the home via standard interior doorways. Two homes had semi-open kitchens. One of these (labeled H6) had a small galley kitchen with both a floor-to-ceiling passage and a large pass-through connecting the kitchen to the adjacent dining room. The other (H9) had two wide, open passages between the kitchen and adjacent rooms.

Table 1. Study home descriptions

ID	Floor area (m^2)	Levels	BR/Ba	Year built	Kitchen design	Flooring[1]	Gas burners[2]	Venting range hood?	FAU fan on for mixing?
H1	134	1	2/2	1910	Closed	Hard	CT/O/B	Y	Y
H2	124	1	4/2	1963	Open	Hard	CT/O/B	Y	Y
H3	117	1.5[3]	2/2	1904	Closed	Hard	CT/O	N	N
H4	26	1	1/1	<1990[4]	Closed	Hard	CT/O	N	No FAU
H5	108	1	3/1	1925	Closed	Hard	CT/O/B	Y	No
H6	119	2	2/2.5	1991	Semi-open	Hard L1, carpet on stairs & L2	CT/O/B	Y	Y
H7	226	2	5/3	1990	Open	Hard L1, carpet on stairs & L2	CT	N	Y
H8	219	2	4/3	1990	Open	Hard L1, carpet on stairs & L2	CT	Y	Y
H9	139	2	3/2.5	1986[5]	Semi-open	Hard K, other rooms carpeted	CT/O/B	Y	Y

[1] L1 = level 1 or first story; L2 = level 2 or second story; K = kitchen.
[2] CT = cooktop; O = oven; B = broiler (top of oven compartment)
[3] Small room below kitchen connected via stairwell at back of kitchen (house on hill).
[4] Building was renovated and expanded in 1990.
[5] Home has been retrofitted for energy efficiency including extensive air sealing, insulation and windows; thus has characteristics of new, energy efficient home.

Cooking appliances and ventilation equipment varied across homes. Five homes had a gas range with cooktop, oven bottom burner and waist-high burner; two homes had a gas range with only a cooktop and oven burner; and two homes had a gas countertop cooktop separate from an electric oven. A venting range hood was present in six homes. Six homes had forced air systems that could be operated in fan-only mode.

Study home access was arranged with owners or renters who were paid $200 for each day and $200 for each overnight period that a home was unoccupied and made available for experiments, up to a total allowable payment per home of $600. A single day of experiments required 11h of access to the home without occupants.

2.3 Cooking burners

Table 2 summarizes the natural gas cooking appliances in each study home. The burner firing rates were obtained from the nameplate tag found on the appliance.

Table 2. Natural gas cooking appliances in study homes.

ID	Cooktop type	Cooktop burner type	Left front (LF)	Left rear (LR)	Right rear (RR)	Right front (RF)	Oven	Broiler
			Burner firing rate (kbtu/h)					
H1	Range	Sealed	9.5	16.2	14.2	5	18	15.5
H2	Range	Sealed	9.5	17	14	5	18	15.5
H3	Range	Open	9	9	9	9	18	None
H4	Range	Open	9	9	9	9	18	None
H5	Range	Sealed	12	12	9.2	9.2	18	15
H6	Range	Sealed	9.5	9.5	9.5	9.5	16	13.5
H7	Counter	Sealed	ND	ND	ND	ND	Elec.	Elec.
H8	Counter	Sealed	9.5	14.2	11	5	Elec.	Elec.
H9	Range	Sealed	9.5	12	9.5	5	16	12

ND = not determined.

2.4 Range hoods

Table 3 summarizes the kitchen exhaust fans in the study homes. Six of the homes had exhaust devices above the cooktop. Two of the venting hoods were "microwave over range" (MOR) appliances that combine the functions of a microwave and externally venting exhaust fan. Home H3 and H4 had no range hoods of any kind. H7 had a non-venting (recirculating) range hood that was operated during two experiments.

Table 3. Range hoods in study homes.

ID	Type	Make /model	Airflow from product literature (L/s)			Sound level from product literature (Sones)		
			Low speed	Medium speed	High speed	Low speed	Medium speed	High speed
H1	Vented range hood	Vent-A-Hood B200 MSC	(2)	(2)	531	(2)	(2)	6.5
H2	Micro-wave exhaust	Electrolux FGMV174KFB	85	(2)	142	(2)	(2)	(2)
H5	Vented range hood	Zephyr Cylone AK6500	142	(2)	142	1.5	(2)	5
H6	Micro-wave exhaust	GE Space-maker JVM140	(2)	(2)	230	(2)	(2)	5.5
H7	Non-vented hood	Broan QS3	(2)	(2)	109	0.3–0.5[4]	(2)	4.5–5.5[4]
H8[1]	Vented range hood	Kenmore 233.516891	50	(3)	76	(2)	(3)	6
H9[1]	Vented range hood	Broan 42000E	50	(3)	76	(2)	(3)	6

[1] The hoods in H8 and H9 are the same product, sold under different nameplates.

[2] Not provided with product literature

[3] Setting not available; only 2 settings on this model.

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

8

2.5 Burner operation and simulated cooking

A procedure was developed to simulate common usage scenarios for the cooktop, oven, and broiler burners. The procedures, used in homes H2 to H9, are described in Table 4. The "Boil/Simmer" and "Sautee/Simmer" activities were combined into a single "Cooktop" procedure.

The procedures in Table 4 were not finalized until after experiments were completed in H1; experiments conducted in H1 thus included variations and combinations of the procedures. In H1, the simulated Roast activity involved 60 min total of appliance operation, corresponding to roughly 40 min of operation after the pot was added. The simulated Broil activity lasted for 40 min total, including 20 min of preheat and 20 min after the pot with water was added (compared to 15 min of simulated broil in H2–H9). Cooktop experiments were conducted either with two fry pans or with two boil/simmer pots. An experiment that was done only in H1 combined a slight variation of the Roast (oven set to 450 °F instead of 425 °F) and the standard Cooktop (Boil + Sautee) activities.

In H1, H3, and H4, an additional cooktop experiment was conducted in which two or more cooktop burners were operated at high setting without pots.

Table 4. Burner operating procedures used for most experiments in homes H2 to H9.

Simulated Activity	Description
Boil/Simmer on Cooktop	Add 4L cold tap water to 5L stainless steel pot with 23 cm diameter base. Place uncovered on largest cooktop burner At start, set burner to high. When water reaches rolling boil, cover and turn down burner to just below boiling. Maintain this condition to complete 30 min total burn.
Sautee/Simmer on Cooktop	Place stainless steel fry pan with 30.5 cm diameter base on second largest burner. At start, set burner to high. At 2 min from start, slowly add 1L cold tap water. At 6 min from start, turn burner to medium setting. Adjust burner down as needed to avoid boiling. Stop burner at 30 min total burn.
Roast with Oven Burner	Remove top oven rack and place bottom rack to allow 5L stainless steel pot to fit into oven. At start, set oven temperature to 218 ℃ (425 °F). When oven reaches setpoint (or after 20 min if setpoint not yet reached), place uncovered pot containing 1L water on bottom oven rack. Maintain this condition for 30 min; then oven off and remove pot. (Note: total burn time varies with time to reach setpoint temperature.)
Broil with Broiler Burner	Remove top oven rack and place bottom rack such that top of 5L stainless steel pot on rack is approximately 13 cm below broiler burner at top of oven. At start, set oven to "broil" with oven door ajar. After 20 min, place 5L stainless steel pot containing 1L water into oven. With door ajar, maintain this condition for 15 min. Turn burner off, remove pot, and close door.

Cooking appliances generally were operated as found. In a couple of cases the appliances were wiped with wet paper towels to remove large debris.

2.6 Execution of experiments

Upon arriving to each home, we reviewed the planned experimental procedures with the host (homeowner or renter) and obtained her/his signature for the agreed usage periods. Together with the host, we conducted a walk-through to identify potential hazards, locate controls for the forced air unit (if relevant), and confirm acceptability of the planned placement of monitoring equipment (for electrical capacity). The host then left the home to return at the agreed time.

Study homes were used for varying duration as summarized in Table 5. In the homes where we had access during consecutive days but not the intervening night, all instruments were shut down when the host returned at the end of the first day, and restarted when the host left the home the following morning. When the home was accessible for a night-day sequence, monitoring instruments operated continuously overnight.

Table 5. Dates and periods that homes were used for this study.

Home ID	Dates	Sequence[1]
H1	Feb 2-4	N-D-N-D
H2	Feb 17-18	D-D
H3	Feb 19-20	N-D
H4	Feb 21-22	N-D
H5	Feb 25-26	D-N-D
H6	Feb 27-28	D-N-D
H7	Feb 29	D
H8	Mar 1	D-D
H9	Mar 4-6	D-N-D

[1] D=Day; N=Night

The protocol prior to starting cooking experiments included set-up and airflow checks of air quality instrumentation, recording information about the home and appliances, measurements to characterize performance of the range hood (if it vented to outdoors), and a check that all windows were closed and interior doors open. There were two exceptions to the general approach of operating homes with all windows closed and interior doors open. It was discovered mid-way through experiments at H4 that there was a bathroom window open about 15 cm; the window was left in this position for all experiments in H4. And in H8 there was a large opening in the master bathroom ceiling, related to a home construction project; this was addressed by keeping the door to the master bath closed throughout experiments in H8.

Each experiment included the following elements. (1) Air mixing in the home was either driven by the ambient temperature and pressure drivers, or by operation of the forced air unit (FAU) mixing fan. (2) If present, the venting range hood was either operated or not. (3) The simulated cooking procedure was followed. (4) Following the end of the cooking procedure, and range hood use if it was part of the experiment, ventilation and mixing in the home were held in the same condition for 60-90 minutes or more, to enable analysis of mixing and decay. When the FAU mixing fan was used, in most cases it was started approximately 10 min prior to the start of the cooking activity, and operated until the mixing condition was established for the next

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

10

experiment. For experiments involving range hood use, the hood was started approximately 1 min prior to the start of cooking, and remained in operation until 5 min after the cooking procedure ended. Range hoods were most commonly operated on the highest setting, though lower settings were used in several experiments. Excluding one experiment in H1 in which the range hood was started 15 min after the end of a cooking procedure, mixing and decay periods varied from a minimum of 54 minutes to a maximum of overnight.

Summary descriptions of conditions for all experiments conducted in each home are provided in a series of tables in the Results section. The sequence of experiments varied across homes.

2.7   Air quality measurements

We continuously monitored the concentrations of carbon dioxide (CO_2), carbon monoxide (CO), nitric oxide (NO), nitrogen oxides (NO_X), formaldehyde (CH_2O), total number concentration of particles greater than 6 nm (PN), number concentrations of particles in 6 size bins from 0.3 μm to 10 μm, and the estimated mass of $PM_{2.5}$ via forward light scattering. Temperature and relative humidity were also monitored. The instruments used to measure each of these parameters are noted in Table 6. The values reported for NO_2 are based on the difference between measured NO_X and NO, and likely include HONO (Spicer et al., 1994); for simplicity, we refer to the NO_2 value reported by the instrument as NO_2 throughout the remainder of this report.

Table 6. Description of IAQ devices and location specific packages

Target Metric	Symbol	Units	Instrument or device (Measurement principle)	Locations [1]
Nitric oxide	NO	ppbv	Thermo Scientific Analyzer Model 42	L1
Nitrogen dioxide	NO_2		TSI-API Analyzer Model 200E	L3
Nitrogen oxides	NO_X		(Chemiluminescence; catalytic NO_2 reduction)	
Nitrogen dioxide[2]	NO_2	ppbv	Aeroqual Series 500 with NO_2 sensor[2] (Electrochemical sensor)	Varied
Carbon Monoxide	CO	ppmv	Lascar EL-USB-CO data logger (Electrochemical)	L1, L2, L3
Carbon Dioxide	CO_2	ppmv	ExTech SD800 (Infrared absorption)	L1, L2, L3
Temperature	T	°C	HOBO UX100-003 and Extech SD800	L1, L2, L3
Relative humidity	RH	%		
Formaldehyde	CH_2O	ppbv	Shinyei FMM-MD (Colorimetric) [2]	L1, L2, L3
Estimated $PM_{2.5}$ (mass)	PM	$\Box g/m^3$	TSI DustTrak II Model 8530 (Forward light scattering)	L1, L3
Number conc. of particles >6 nm	PN	#/cm^3	TSI 3781 Condensation Particle Counter (Growth by H_2O condensation; laser counting)	L1, L3
Number conc. of particles 0.3–2.5 um	$P(2)_{ange}$	#/cm^3	MetOne BT-637S [2] (Laser particle counter)	L1, L3

[1] L1=kitchen, L2=central; L3=distant.
2Data collected with these instruments has not been analyzed and is not presented or discussed in this report.

Air quality monitoring occurred in two primary locations and one secondary location in each home. The primary locations were the kitchen and a room or hallway far from the kitchen. The distant location was used to determine an approximate lower bound of combustion pollutant

concentrations and potential exposures. The kitchen and distant location had nearly identical collections of instruments, mounted on mobile carts. The kitchen cart was placed no closer than two meters from the cooktop in all homes other than the small apartment H4, in which the cart was as far from the stove as possible (see photo in Appendix). The devices on the cart sampled air at heights of roughly 1.4-1.65 m. The third monitoring package was installed on a table in a common room (living room, dining room, great room) closer to the kitchen, or connected to the kitchen in an open floor plan (L2 or "central" location is defined in Table 6). Figure 1 shows the kitchen cart in H1, and Figure 2 shows the bedroom cart in H9. Figure 3 shows the table for the central monitoring location, along with the kitchen cart in the background, in H9. Images of monitoring configurations in some of the other homes are provided in the Appendix.

Figure 1. Air quality measurement instrumentation in kitchen of H1 (researcher behind cart).

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

12
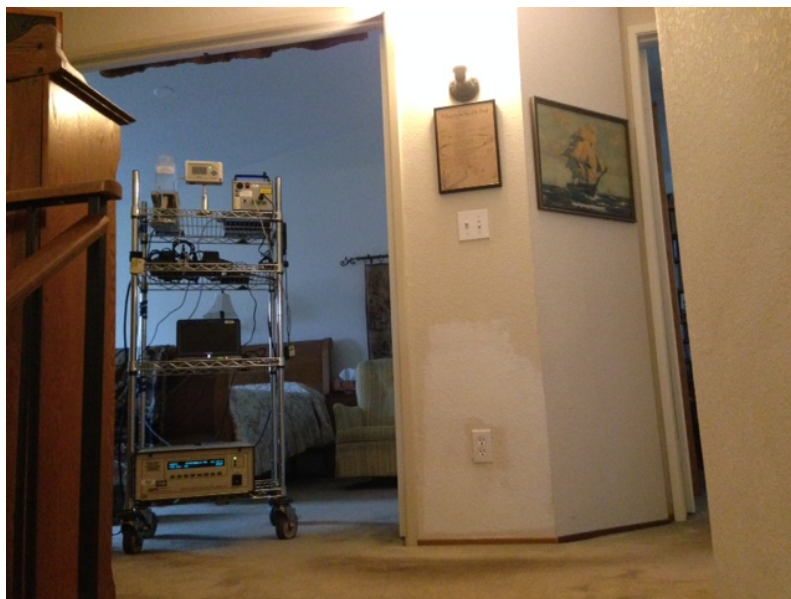
Figure 2. Air quality measurement instrumentation in distant location (upstairs) of H9.

Figure 3. Air quality measurement instrumentation at central location (table) and kitchen of H9.
Passage between kitchen and dining room (left, background) is of similar size to kitchen entry shown.

Air quality data were recorded at 1 min or more frequent intervals for the majority of analytes. The formaldehyde sensor recorded a reading every 30 minutes.

Particle instruments were operated side-by-side in a Lab test chamber to confirm consistency prior to deployment. CO_2 instruments were calibrated after the field study and calibration factors were applied to the raw data. CO instruments were used as received new from the manufacturer, without an independent calibration. The NO_X and NO_2 analyzers were single-point calibrated at

the start of the field study, then checked for zero and span calibration in the laboratory prior to most home deployments. Despite this, it was observed that in most homes, the NO and NO_2 (NO_X–NO) concentrations were offset between instruments, at times when the home was thought to be well mixed. The observed differences between the two NO_X analyzers were used to determine an offset adjustment. Because the NO concentrations reported by the bedroom instrument were consistently in line with data obtained from nearby regulatory monitoring sites, at times when the homes were not impacted by indoor NO_X emissions, the offset was typically applied to the NO_X analyzer on the kitchen cart.

2.8   Range hood performance characterization

Measurements were made to quantify airflow and sound characteristics of all the venting range hoods in the study. The capture efficiency (CE) of cooking burner combustion products was measured for five of the six venting hoods. CE could not be determined for the hood in H1 because the range hood vent was inaccessible.

Exhaust air flow from the hoods was measured using a balanced-pressure flow hood method described by Walker et al. (2001). The method uses a calibrated and pressure-controlled variable-speed fan (Minneapolis Duct Blaster, Energy Conservatory[1]) connected to either the exhaust inlet (preferred approach) or outlet. The Duct Blaster is connected using a customized transition that was fabricated / adapted at each site using cardboard and tape. An example, in H8, is shown in Figure 4. Using a pressure sensor, the Duct Blaster fan is controlled to match the flow of the exhaust fan while maintaining the pressure at the exhaust inlet at its normal value when the Duct Blaster is not installed. The pre-calibrated speed versus flow relationship of the Duct Blaster provides the flow through the exhaust fan.
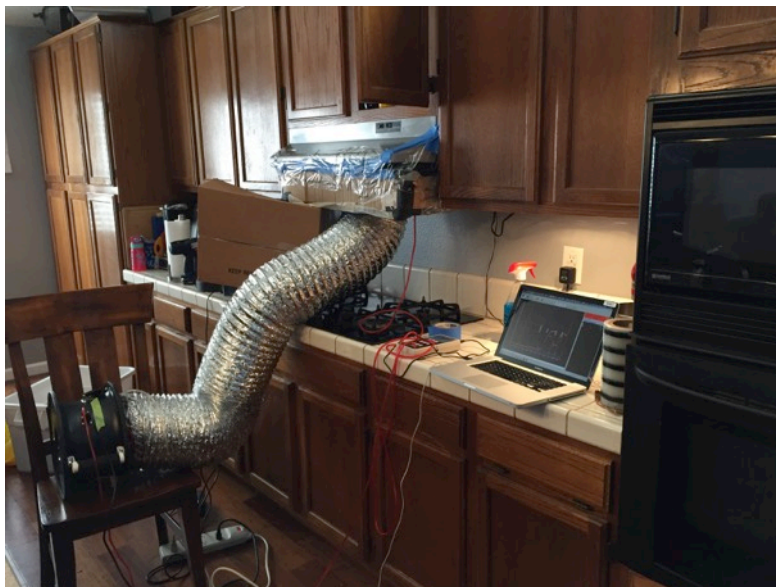
Figure 4. Example of pressure-balanced flow-hood airflow measurement (H8). Note the blower resting on the chair.

---

[1] www.energyconservatory.com

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

14

Sound levels were measured using the AudioTools app (version 8.9.X) from Studio Six Digital[2] on an iPhone6. We used the "Real Time Analyzer" tool, a 1/3-octave band analyzer, which provides sound pressure (in decibels, dB) as a function of frequency. The sound pressure distribution was measured for background conditions (hood off) and for each available fan speed when the house was in quiescent condition, i.e. with no air quality monitoring devices operating. We report the A-weighted total sound pressure (dBA) reported by the app as a summary statistic. Additionally, we applied the procedure that is used to determine the sound level reported by the Home Ventilation Institute (HVI) in their Certified Home Ventilating Products Directory; the calculation procedure is described in HVI Publication 915, available on the HVI web site.[3]

Capture efficiency (CE) refers to the fraction of pollutants emitted from the cooking burner (and cooking, when applicable) that are removed by the venting range hood before mixing into the air of the kitchen. CE can be estimated by calculating both the mass flow of CO_2 exiting through the range hood, and the mass generation rate based on fuel composition and the assumption of complete combustion (Singer et al., 2012). In this study, we used a simpler approach that compares the flow of CO_2 through the hood under the normal operating condition to the flow of CO_2 when a foil curtain is used to extend the hood over the cooktop to ensure perfect or nearly perfect capture. This approach assumes no change in airflow between the conditions, meaning the CO_2 mass flow changes proportionally with the CO_2 concentration. CE is calculated using CO_2 concentrations measured under the normal operating condition (C_N) and with the hood extended to create nearly perfect capture conditions (C_{100}), and background concentrations with the cooking burners off (C_0), as shown in Equation 1.

$$CE = (C_N - C_0) / (C_{100} - C_0) \qquad (1)$$

CO_2 concentrations in the exhaust from the range hood were measured using a PPSystems EGM-4 analyzer drawing from the ducting above the range hood. An example of the setup for this procedure, from H8, is shown in Figure 5.
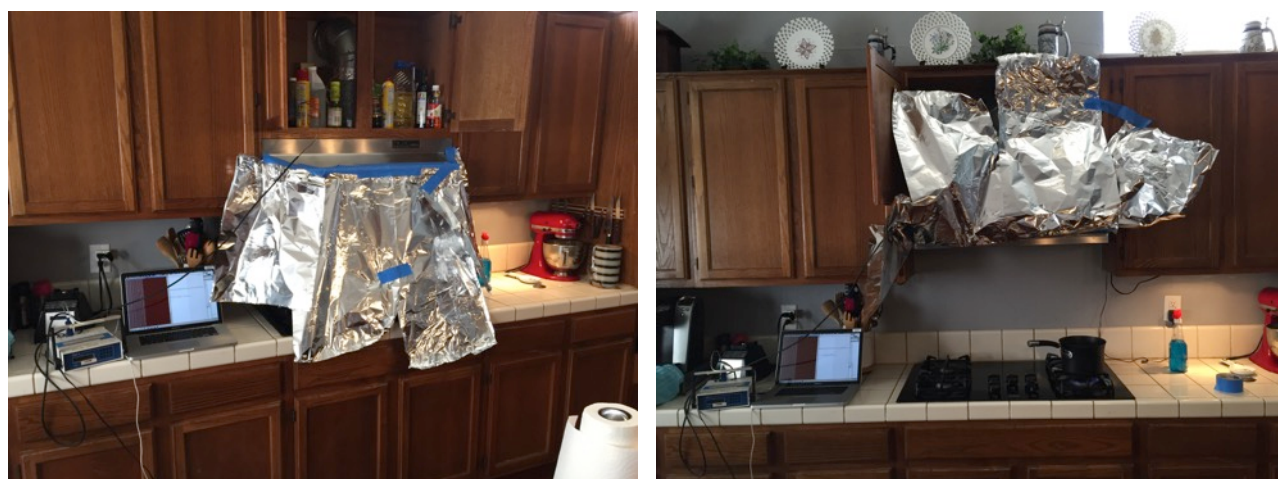
Figure 5. Measurement of range hood capture efficiency in H8.

Left panel shows hood with foil curtain to achieve 100% capture. Right panel shows foil curtain lifted and taped to cabinetry above to measure CE without curtain.

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

15

2.9   Attributing concentration profiles to individual cooking events

The primary objective of this study was to quantify the impact of using NGCBs on pollutant concentrations. However, in order to complete as many experiments as possible in the limited time available in each house, the interval between experiments was not long enough to allow concentrations to return to background levels before the next experiment. Therefore the analysis included a *disentanglement* procedure, in which the data for each analyte were decomposed into estimated concentration profiles for each cooking event.

Disentangling the data for a particular cooking event involved four steps: (1) fitting a first-order decay model to the experimental data; (2) using this model to predict how the previous cooking event would have evolved, had the current event not taken place; (3) using the same model to predict how the current cooking event would have evolved, had the next event not taken place; and (4) finding the difference between the two, in order to estimate what the current event would have looked like in the absence of other events.
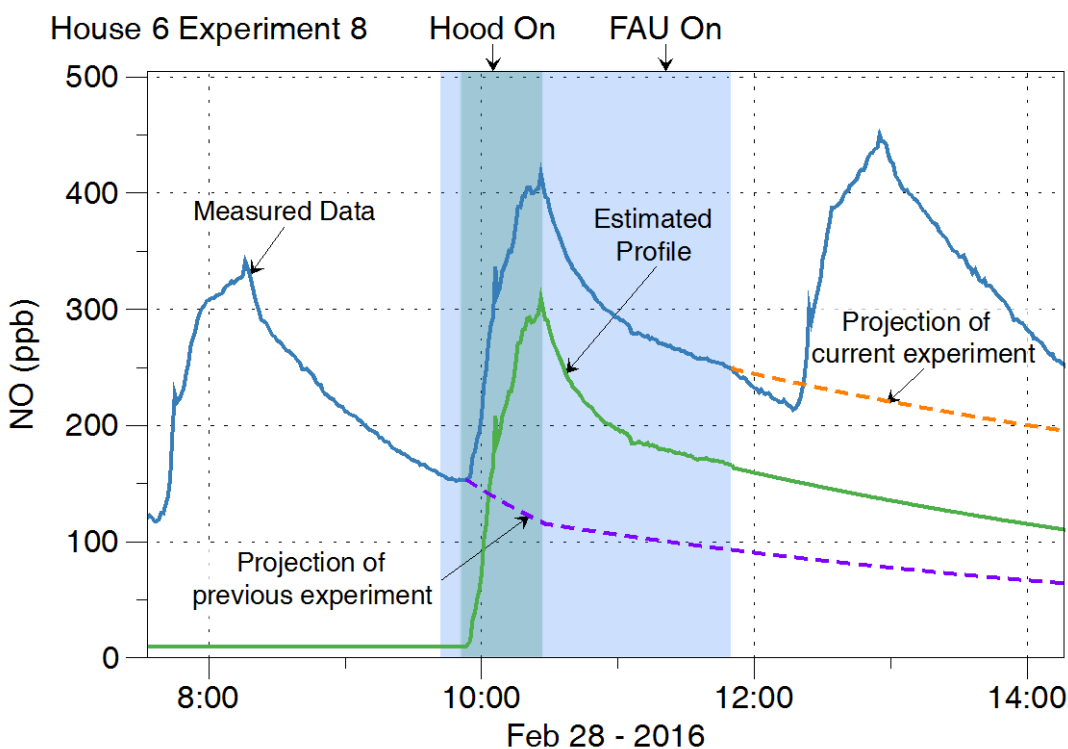
Figure 6. Disentangling NO data for Experiment H608 (middle peak) in the kitchen of H6.
The experiments occur too closely in time to distinguish individual concentration profiles in the measured data (solid blue line). Therefore we projected (dashed purple line) the profile from the preceding cooking event, past the start of the event being analyzed (here, Experiment H608). This projection accounts for the higher removal rate that occurred from range hood use during the first part of H608. Similarly, we projected the profile for H608 (dashed orange line), to remove the effects of the following experiment. The difference between the projections gives the estimated profile for H608 (solid green line), disentangled from the preceding and following experiments. We use this profile to estimate the integrated

concentrations that would have occurred had H608 taken place without confounding experiments before and after.

Figure 6 shows an example. Here we wished to find the concentration profile for the second of the three cooking events shown (the 8th experiment in H6, identified as H608). First, we estimated the first-order decay rate for the current event, using the data recorded after the cooking itself ended. This involved fitting a decaying exponential model to a span of data starting after the range hood turned off, and ending before the FAU turned off. In selecting intervals for fitting data, we considered the movement of pollutants across zones of the house, as indicated by the dynamics of the two measured locations. In general, we waited until the two series "came together" – ideally by reaching or approaching the same concentration, and alternately by starting to follow the same downward trend. For the distant location, the decay interval often extended past the start of the simulated cooking event.

The decay rate was estimated using a least-squares fit to the measured data, with an assumed background concentration. The background represents the indoor concentration that would result from outdoor pollutant entry and indoor losses (including air exchange for all pollutants, and deposition for NO_2 and PN). When choosing the background concentration, we performed least-squares fits to find both decay rates and backgrounds and considered all experiments that had the same airflow conditions (e.g. central mixing fan on or off) during the same day, in addition to considering measurements at the start and end of the day or at any other time that informed the background estimate. For Experiment H608, the background was set at 10 ppb and the resulting fit gave a decay rate of 0.17 h^{-1}.

After fitting a decay model to the data following a generation event, we used it to project the profile from the prior cooking event. In Figure 6, this projection has two stages: a short period, from the start of the current cooking event, up to the time the range hood turns off; and a longer period, during which only the FAU is on (dashed purple line). The decay rate for the first stage, during which both the hood and the FAU operate, was estimated by adding the decay rates for the FAU and the hood in quadrature, i.e., as the square root of the sum of the squares of the individual rates (the decay rate for the hood was estimated as the hood flow rate divided by the house volume). Note that it was not possible to estimate the decay rate for this first stage directly from the data, because there is simultaneous generation with a source of unknown strength.

The projection of the prior cooking event represents a prediction of how the prior experiment would have evolved, had the current event not taken place. Similarly, we used the same decay model to project the current event, past the first change related to the following experiment (dashed orange line). In this experiment, that first change was turning off the FAU; in other experiments, it was the beginning of the cooking itself. Extending the current experiment was necessary to estimate the four-hour time-integrated concentration due to the event.

Note that both the projection of the prior experiment, and the projection of the current experiment, used the same decay rate and background, as estimated from the data collected immediately after cooking ended for the current experiment. This ensured the disentanglement for a given experiment most closely reflected the measurements made during that experiment. It also means that a single span of data could be processed using two different decay rates. Consider, for example, projecting the results of H608 past the beginning of the next event, H609. When predicting exposures due to H608, we used the decay rate observed for this event.

However, when predicting exposures due to H609, we use the decay rate observed for that experiment.

Subtracting the projection of the previous experiment from the measured and projected data for the current experiment yielded the estimated profile for the current experiment, i.e., a prediction of what the current experiment would have yielded, had there been no cooking events immediately before or after it (solid green line). These adjusted data also have the assumed background concentration added in, since otherwise the current event would start with zero concentration.

This extrapolation and subtraction procedure was applied separately for CO_2, NO, NO_2, and PN, in the kitchen and bedroom, as data were available. The time intervals used for decay fits are shown as shaded areas in data plots provided for each home in the Appendix. Inferred baselines and decay rates are provided for the four analytes in the Appendix.

The measurements and extended concentration profiles were analyzed to determine the highest 1h average concentration of each pollutant at each location, and also to find the integrated concentration over 4 h.

2.10 Estimating emission factors from ambient concentrations

We used the highest 1h concentrations to estimate fuel-normalized emission factors for NO_2, NO_X, and PN, using the method described in (Singer et al., 2010a). Briefly, this approach calculates the emission rate of CO_2 from natural gas combustion, and uses the measured concentration ratios for each pollutant to CO_2 to calculate an emission factor. For NO_X and NO_2, the calculation proceeds according to Equation 1, where the first term on the right side is the ratio of NO or NO_X to CO_2, and the second term is a property of the fuel; we used 1.1 mol CO_2 / MJ fuel based on Singer et al. (2010a).

$$E_i \left[\frac{ng}{J} \right] = \frac{\left(\frac{mol\ i}{mol\ air} \right)}{\left(\frac{mol\ CO_2}{mol\ air} \right)} \left(\frac{mol\ CO_2}{MJ\ fuel} \right) \left(\frac{g\ i}{mol\ i} \right) \left(\frac{MJ}{10^6 J} \right) \left(\frac{10^9 ng}{g} \right)$$

(1)

Equation 2 was used to calculate PN emission factors.

$$E_i \left[\frac{\#}{J} \right] = \frac{\left(\frac{\#}{cm^{-3}\ air} \right)}{\left(\frac{mol\ CO_2}{mol\ air} \right)} \left(\frac{23000\ cm^{-3}\ air}{mol\ air} \right) \left(\frac{mol\ CO_2}{MJ\ fuel} \right) \left(\frac{MJ}{10^9 J} \right)$$

(2)

3 Results

3.1 Measured range hood performance

Measurements of range hood performance parameters are presented in Table 7. Consistent with a prior study by our research group (Singer et al., 2012), the measured airflows were substantially below rated values for five of the six installed hoods. Interestingly, the estimated sound ratings (in sones) were lower than the rated values for many of the hood settings.

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

18

Table 7. Measured performance parameters of range hoods in study homes.

Home ID	Type	Measured flows [L/s] (% of rated flow)			Bkg [dBA]	Measured sound [dBA] (Calculated Sones)		
		Low speed	Medium speed	High speed		Low speed	Medium speed	High speed
H1	Hood	66 (2)	108 (2)	148 (59%)	30.1	57.3 (3.0)	(2)	59.2 (3.7)
H2	Microwave oven/ exhaust	66 (78%)	(2)	76 (54%)	36.8	63.9 (4.6)	(2)	72.1 (6.2)
H5	Hood	135 (98%)	(2)	153 (2)	28.9	58.9 (4.0)	62.0 (4.1)	66.7 (4.8)
H6	Microwave oven/ exhaust	43 (2)	(2)	49 (45%)	30.7	59.2 (3.6)	(2)	62.5 (4.6)
H8[1]	Hood	20 (40%)	(3)	30 (40%)	32.9	54.0 (2.2)	(3)	58.2 (3.7)
H9[1]	Hood	39 (79%)	(3)	19 (64%)	39.8	54.1 (2.0)	(3)	61.4 (3.7)

[1] The hoods in H8 and H9 are the same product, sold under different nameplates.
[2] Setting available but performance information not provided with product literature
[3] Setting not available; only 2 settings on this model.
[4] Varies with vent geometry.

Table 8 presents the estimated capture efficiencies measured with the new field test method described in Section 2.8. Consistent with a prior field study (ibid), the performance of several of the hoods was dramatically different for the front and back cooktop burners. For most ranges, the performance of the back cooktop burners is a good indicator of capture for oven emissions.

Table 8. Measured capture efficiency of range hoods in study homes.

Home ID	Hood type	Low speed		High speed	
		Front burners	Back burners	Front burners	Back burners
H1	Hood	NM[1]	NM[1]	NM[1]	NM[1]
H2	Microwave	25%	>95%	35%	>95%
H5	Hood	61%	68%	72%	84%
H6	Microwave	31%	88%	31%	93%
H8[1]	Hood	59%	68%	65%	80%
H9[1]	Hood	25%	74%	36%	75%

[1] Not measured; there was no way to access the range hood exhaust duct without aesthetic damage.

3.2 Experiments conducted

All experiments conducted in the nine study homes are listed in **Table 9**,
Table 10, and **Table 11**.

Table 9. Experiments conducted in study homes H1-H3.

Expt ID	Date	Burners & use	Burn start time	Burn end time	Decay - conditions unchanged (min)	Range hood setting	Mixing fan
H101	2-Feb	CT: 3 burners, no pots	20:10	20:30	Overnight		
H102	3-Feb	BR: Broil	10:09	10:49	60 min		
H103	3-Feb	CT: Fry 2 pans	11:50	12:20	97 min		
H104	3-Feb	OV: Roast	13:57	14:57	68 min		
H105	3-Feb	CT: Boil 2 pots	16:05	16:35	62 min		
H106	3-Feb	OV+CT	17:37	18:37	Overnight		
H107	4-Feb	BR: Broil	7:01	7:41	54 min	High	
H108	4-Feb	CT: Fry 2 pans	8:40	9:11	54 min	High	
H109	4-Feb	OV: Roast	10:11	11:11	54 min	High	
H110	4-Feb	CT: Boil + fry	12:11	12:41	54 min	High	
H111	4-Feb	OV+CT	13:41	14:41	60 min	High	
H112	4-Feb	BR: Broil	15:41	16:21	15 min	Off / High	
H113	4-Feb	BR: Broil	18:15	18:55	60 min		On
H114	4-Feb	OV+CT	19:55	20:55	Overnight		On
H201	17-Feb	OV: Roast	10:15	10:56	90 min		
H202	17-Feb	CT: Boil + fry	12:26	12:52	90 min		
H203	17-Feb	BR: Broil	14:22	14:57	90 min		
H204	17-Feb	CT: Boil + fry	16:27	16:52	90 min		
H205	18-Feb	CT: Boil + fry	8:46	9:11	85 min	High	
H206	18-Feb	OV: Roast	10:41	11:22	80 min	Medium	
H207	18-Feb	CT: Boil + fry	12:57	13:24	76 min		On
H208	18-Feb	BR: Broil	14:45	15:20	100 min	High	
H301	19-Feb	CT: 4 burners, no pots	22:15	22:20	Overnight		
H302	20-Feb	OV: Roast	8:10	9:00	90 min		
H303	20-Feb	CT: Boil + fry	10:30	11:05	90 min		
H304	20-Feb	OV: Roast	12:35	13:25	90 min		
H305	20-Feb	CT: Boil + fry	14:55	15:30	100 min		

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

20

Table 10. Experiments conducted in study homes H4-H6.

Expt ID	Date	Burners & use	Burn start time	Burn end time	Decay - conditions unchanged (min)	Range hood setting	Mixing fan
H401	21-Feb	CT: 2 burners, no pots	20:45	21:10	Overnight		
H402	22-Feb	OV: Roast	5:30	6:20	90 min		
H403	22-Feb	CT: Boil + fry	8:15	8:45	92 min		
H404	22-Feb	OV: Roast	10:40	11:32	88 min		
H405	22-Feb	CT: Boil + fry	13:25	13:55	125 min	Bath fan	
H501	25-Feb	OV: Roast	15:30	16:10	90 min		
H502	25-Feb	CT: Boil + fry	17:40	18:12	90 min		
H503	25-Feb	BR: Broil	19:43	20:18	87 min		
H504	25-Feb	CT: Boil + fry	21:45	22:15	Overnight		
H505	26-Feb	CT: Boil + fry	5:30	6:02	88 min	High	
H506	26-Feb	OV: Roast	7:30	8:13	100 min	Medium	
H507	26-Feb	CT: Boil + fry	9:53	10:29	95 min	Medium	
H508	26-Feb	OV: Roast	12:05	12:47	92 min		
H601	27-Feb	OV: Roast	11:30	12:10	90 min		
H602	27-Feb	CT: Boil + fry	13:40	14:10	90 min		
H603	27-Feb	BR: Broil	15:40	16:15	105 min		
H604	27-Feb	CT: Boil + fry	18:00	18:30	125 min		On
H605	27-Feb	OV: Roast	20:45	21:25	Overnight		
H606	28-Feb	CT: Boil + fry	5:25	5:55	89 min	High	
H607	28-Feb	OV: Roast	7:30	8:12	85 min	High	
H608	28-Feb	CT: Boil + fry	9:52	10:22	83 min	Med	On
H609	28-Feb	OV: Roast	12:10	12:51	119 min		

Table 11. Experiments conducted in study homes H7-H9.

Expt ID	Date	Burners & use	Burn start time	Burn end time	Decay - conditions unchanged (min)	Range hood setting	Mixing fan
H701	29-Feb	CT: Boil + fry	9:13	9:40	89 min		
H702	29-Feb	CT: Boil + fry	11:10	11:38	87 min	High*	
H703	29-Feb	CT: Boil + fry	13:20	13:47	92 min		On
H704	29-Feb	CT: Boil + fry	15:20	15:47	88 min	High*	On
H801	1-Mar	CT: Boil + fry	9:00	9:30	90 min		
H802	1-Mar	CT: Boil + fry	11:30	12:00	75 min	High	On
H803	1-Mar	CT: Boil + fry	13:40	14:10	84 min	High	
H804	1-Mar	CT: Boil + fry	15:50	16:20	70 min		On
H901	5-Mar	OV: Roast	10:10	11:00	90 min		
H902	5-Mar	CT: Boil + fry	12:30	12:58	93 min		
H903	5-Mar	CT: Boil + fry	14:41	15:11	83 min		On
H904	5-Mar	BR: Broil	16:34	17:09	Overnight		
H905	6-Mar	CT: Boil + fry	8:04	8:34	65 min	High	On
H906	6-Mar	OV: Roast	9:46	10:36	78 min	High	
H907	6-Mar	CT: Boil + fry	12:06	12:36	84 min	Low	On
H908	6-Mar	OV: Roast	14:00	14:48	82 min		On

*Recirculating (non-venting) range hood.

3.3 Measured pollutant concentrations

To elucidate some of the major themes seen in the data, sample results for base conditions are presented in Figure 7 and Figure 8. These plots present data for NO_2, NO, PN, and CO_2, in both the kitchen and the distant bedroom monitoring locations. The same parameters are presented for each full day of experiments in a series of plots in the Appendix.

Figure 7 presents data from Day 1 in H3. As expected, kitchen CO_2, NO, NO_2 and PN increased quickly as burners fired at the maximum settings: cooktop burners set to the highest flame, or oven or broiler burner firing continuously. Concentrations remained elevated throughout the simulated cooking events as the cooktop burners were set to medium-low, oven burners cycled to maintain temperature, and broiler burners continued to fire continuously. The kitchen traces show more short-term variability owing to their proximity to the source. After the burners were switched off at the end of a simulated cooking event, concentrations in the kitchen started to decay as pollutants mixed throughout the house and were removed by ventilation and infiltration. NO_2 and PN also were removed by deposition. With each burner use, concentrations in the bedroom started to rise after a short delay, representing the transport / mixing time from the kitchen to the distant location.

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

22

Figure 7. Air pollutant concentrations measured on first day of testing at House H3 under base conditions (no range hood or FAU operation).

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

23

Bedroom concentrations increased over a time interval that was similar in duration to burner use, but shifted later in time. For NO and CO_2, concentrations decayed slower in the bedroom than in the kitchen, presumably due to lower rates of outdoor air directly entering the bedroom, compared to the kitchen. For PN and NO_2, each of which deposit indoors at rates that are fast enough to compete with air exchange as a removal process, the kitchen and bedroom concentrations decayed at the same rate in the two rooms.

Day 1 in H5 shows a somewhat different pattern (Figure 8). In this house, the distant bedroom had less indoor air exchange with the kitchen. Following the start of an emission event without the FAU operating, the bedroom concentrations increased more slowly, and reached peak levels that were much lower than in the kitchen. Concentrations in the kitchen and bedroom converged for NO and almost converged for CO_2 only in the first and fourth experiments. Decay rates in the kitchen and bedroom were similar.

The absolute concentrations, relative dynamics and peak concentrations, and the effect of FAU operation on the relative dynamics of pollutants in the kitchen and bedroom varied widely across homes. In general, as the delay increased, so did the difference between the kitchen and distant room peak concentrations. The closest coupling without FAU use occurred in H4, H7, and H8. The coupling in H4 is explained by it being a small, 2-room apartment. H7 and H8 are newer homes with open floor plans that resulted in closer connections between spaces. FAU operation substantially increased PN decays in H9, which had a high-performance (MERV13) filter installed in the FAU. In the single FAU experiment in H6 (on Day 2), NO_2 decays were much faster than they were in the experiments without the FAU operating; this suggests removal of NO_2 in the air handler.
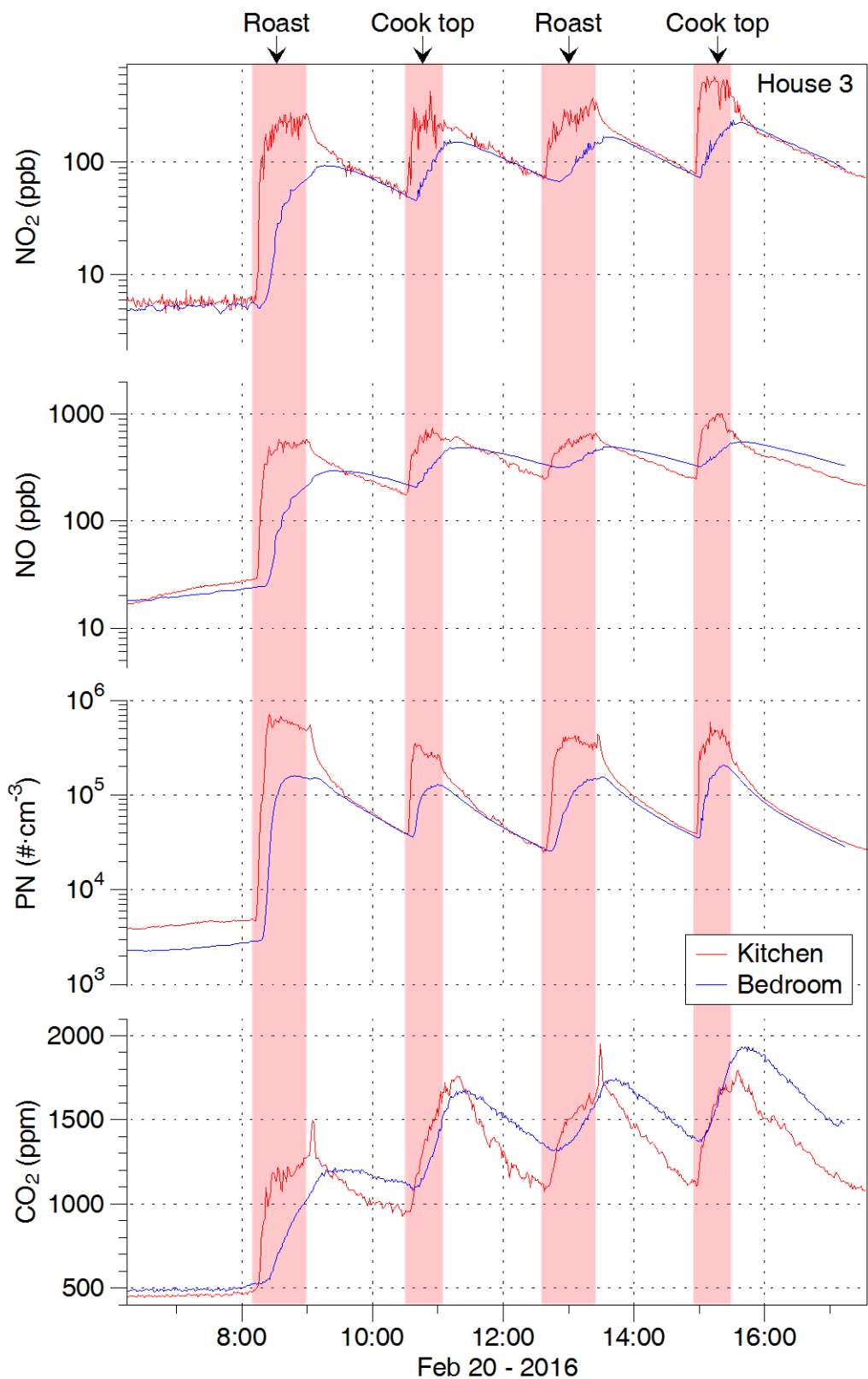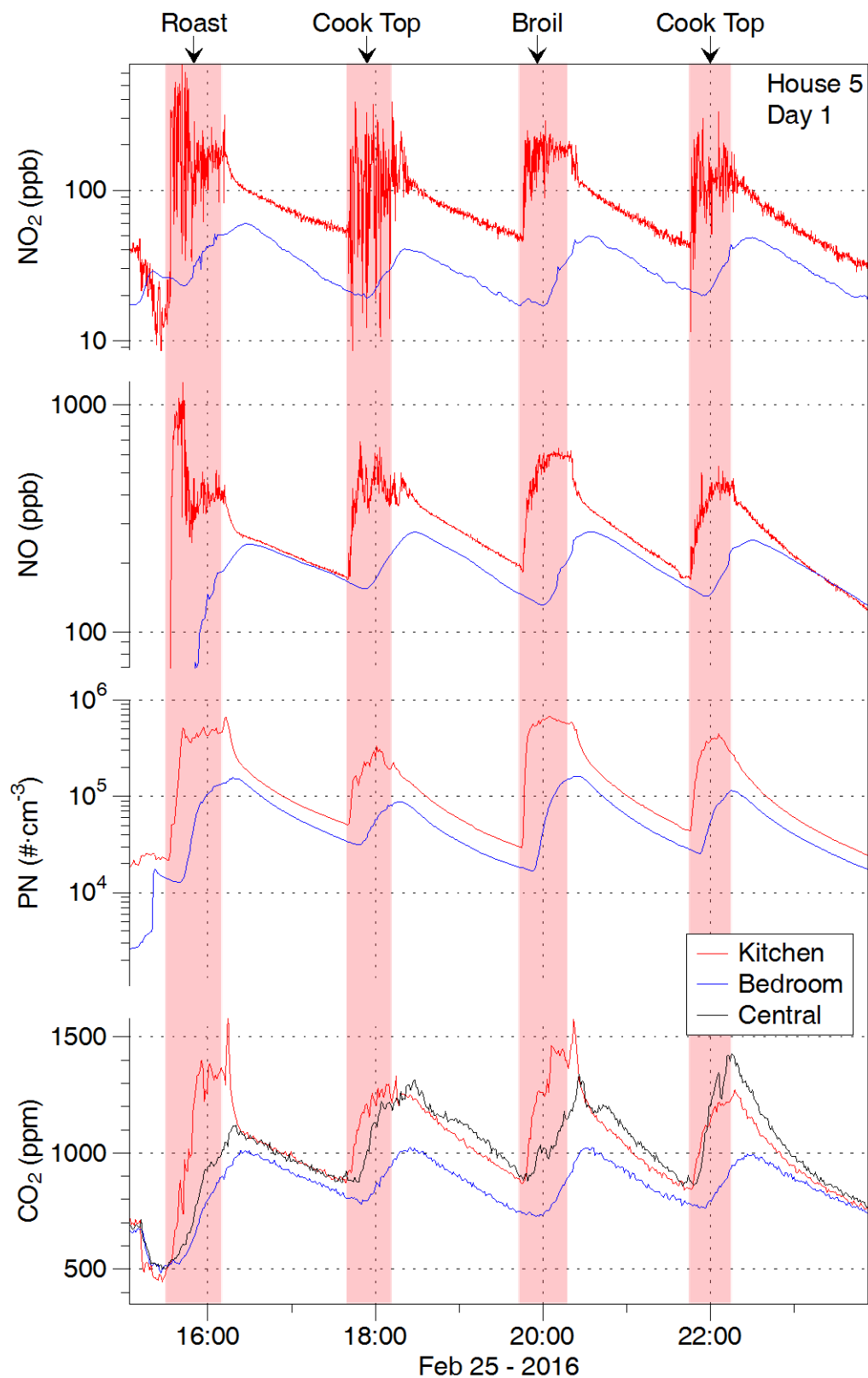
Singer et al. (LBNL) Pollutants from Gas Cooking Burners

24

Figure 8. Air pollutant concentrations measured on first day of testing at House H5 under base conditions (no range hood or FAU operation).

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

25

3.4 Time-integrated pollutant concentrations under base conditions

Summary results for all experiments with base conditions of no mechanical mixing (no FAU operation) and no use of range hood or other exhaust fan are provided in Figure 9 and Figure 10. These figures show the highest 1h and 4h time-integrated concentrations in the kitchen and bedroom locations following each simulated cooking event. For this presentation, the homes are grouped according to the opening between the kitchen and the rest of the home, and ordered by home size. Data are presented for NO, NO_2, and PN.

Overall, concentrations of each pollutant varied widely both across and within homes. As expected, bedrooms had substantially lower pollutant concentrations than kitchens, across all homes except for the two-room apartment, H4, and the open floor plan house, H8. For NO and NO_2, there was no trend across homes associated with the burner used in the simulated cooking event (cooktop, oven or broiler). For PN, there were several homes that had much higher concentrations when using the oven or broiler burner compared to the cooktop, but no homes in which the cooktop produced substantially higher PN. Unsurprisingly given its very small size, H4 had the highest concentrations of NO and NO_2. That H4 did not have higher PN concentrations than other homes suggests that the variance in PN emission rates had a larger impact than variations in home size. The data also indicate a trend of higher kitchen concentrations in homes with enclosed kitchens (H1, H3, H4, and H5) relative to homes with semi-open kitchens (H6 and H9) or open floor plans (H2, H8, H9). The trio with open floor plans included the two largest homes, which contributed to the generally lower concentrations observed in those homes.

The plot of highest 1h concentrations shows the NAAQS benchmark of 100 ppb NO_2 over 1h. Four of the nine homes had kitchen levels exceed this value, and two other kitchens had 1h NO_2 concentrations of at least half this value. Three of the nine homes had bedroom NO_2 levels exceed 50 ppb. This suggests significant exposures may occur for anyone at home when natural gas burners are used for even a single, substantial cooking event.

For the vast majority of experiments, there were negligible increases in CO and $PM_{2.5}$. We thus limited quantitative analysis for these pollutants only to those cases in which concentrations were observed to increase by approximately 9 ppm for CO and 20 $\mu g\ m^{-3}$ for $PM_{2.5}$. These criteria were satisfied by 3 experiments for CO, and three for $PM_{2.5}$, and those only in the kitchen. Results for these experiments are provided in Table 12.

Table 12. Result for CO and PM2.5 in experiments meeting criteria of CO rising at least 9 ppm and $PM_{2.5}$ rising at least 20 $\mu g\ m^{-3}$.

Expt	Cooking	FAU	Parameter [units]	Highest 1h	Highest 4h
H402	OV	No	$PM_{2.5}$ [$\mu g\ m^{-3}$ h]	238	378
H404	OV	No	$PM_{2.5}$ [$\mu g\ m^{-3}$ h]	86	131
H603	BR	No	$PM_{2.5}$ [$\mu g\ m^{-3}$ h]	24	53
H402	OV	No	CO [ppm h]	9.5	21.7
H403	CT	No	CO [ppm h]	8.6	17.7
H405	OV	No	CO [ppm h]	7.4	11.5

Figure 9. Highest 1h time-integrated concentrations in kitchen and bedroom resulting from use of natural gas burners in simulated cooking activities.

Singer et al. (LBNL) Pollutants from Gas Cooking Burners
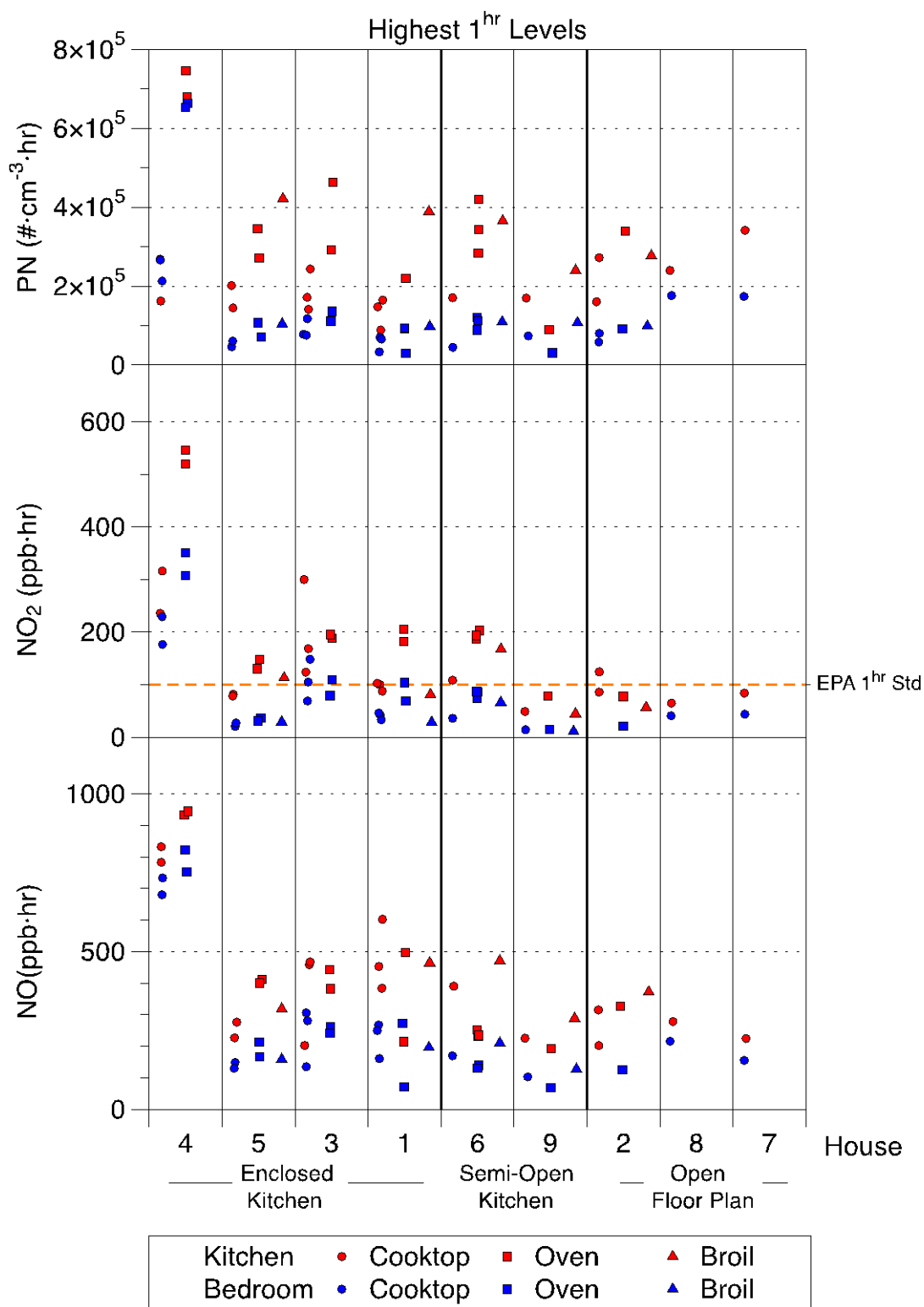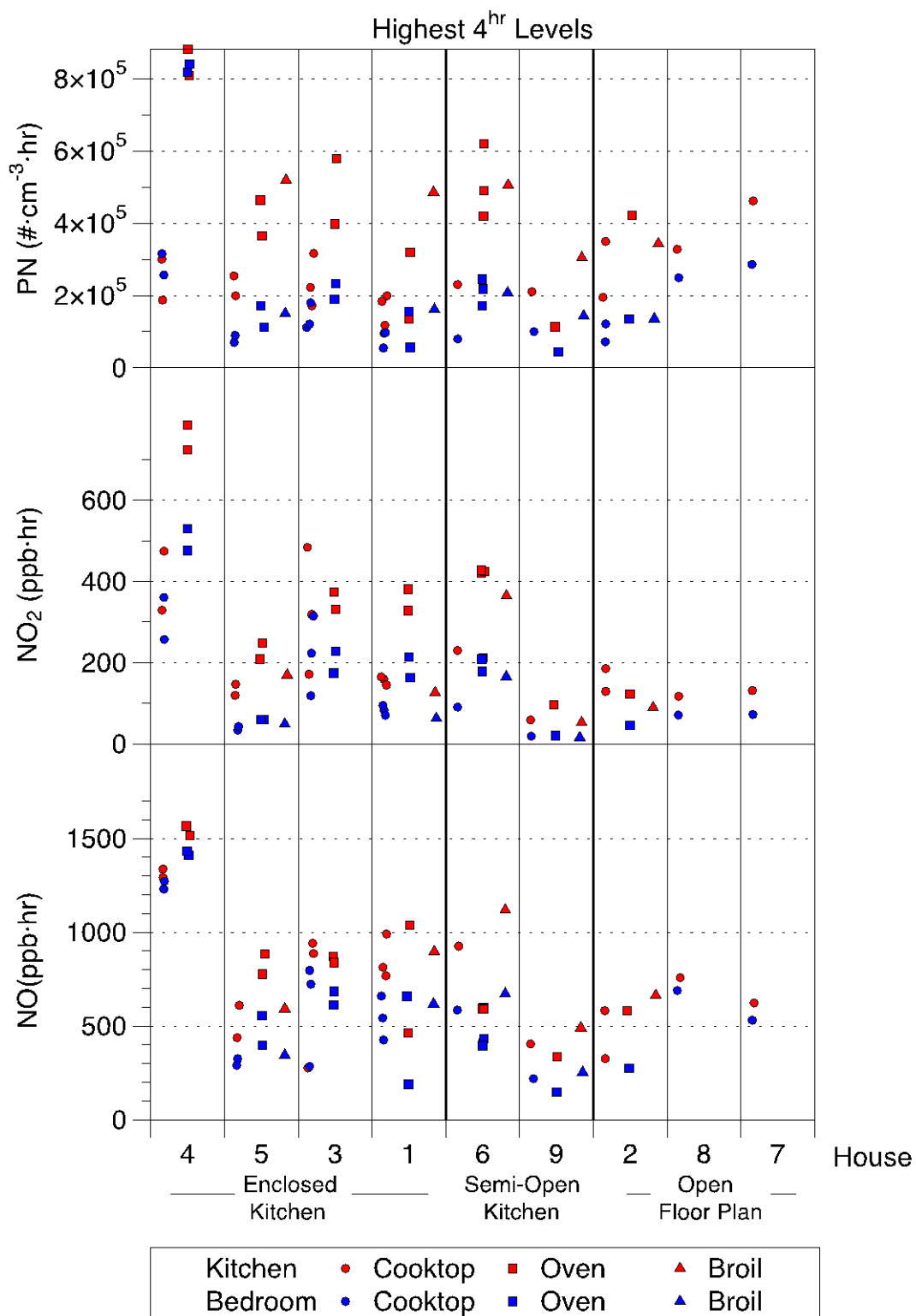
27

Figure 10. Highest 4h time-integrated concentrations in kitchen and bedroom resulting from use of natural gas burners in simulated cooking activities.

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

28

Whereas short-term CO concentrations in homes using gas and electric cooking burners have been reported in several studies, including the recent work of (Mullen et al., 2016), we are aware of few published reports of short-term NO_2 or NO measurements associated with cooking burner use in homes. In a UK-based study with limited relevance to the US owing to differences in cooking equipment, (Franklin et al., 2006) used an innovative approach in asking participants to open a passive sampler whenever the oven or hot plate was used at least 15 min. A companion passive sampler was open continuously through the study period. Data were collected in 24 homes with flued gas cookers, 8 homes with unflued gas cookers, and 21 homes with non-gas cookers. Peak samplers were open an average (SD) of 3.7 (2.6) h and long-term samplers were open for 74.1 (5.8) h. Peak NO_2 concentrations were significantly higher in homes with flued and unflued gas cooker compared to homes with non-gas cookers. In the homes with unflued gas cookers, the geometric mean (95% confidence interval) peak concentrations were 44 (26–75) ppb. In the homes with non-gas cookers the peak concentrations were 13 (10–19) ppb. (Note that results have been converted from the published units of $\mu g\ m^{-3}$ to ppb).

In an extensive study of air pollutant emissions associated with cooking, (Fortmann et al., 2001) measured time-resolved concentrations of CO, NO, and NO_2 outdoors and in the kitchen, living room, and master bedroom of a 76.6 m^2 (824 ft^2) single story house, which appears from the floor plan to have had an enclosed kitchen. Boiling water on the natural gas cooktop burner over 1h produced concentrations (across the three rooms) of 2.8–3.5 ppm CO, 219–293 ppb NO, and 53–74 ppb NO_2. Operation of the oven for 2h without food produced concentrations of 2.0–2.1 ppm CO, 272-280 ppb NO, and 79–94 ppb NO_2 across the rooms. Outdoor concentrations during the cooktop and oven experiments were 1.2 and 0.5 ppm CO, 56 and 24 ppb NO, and 19 and 17 ppb NO_2. Concentrations over the cooking events exceeded 9 ppm CO during a fish broil (8.6–10.1 ppm) and oven cleaning (14.8–19.9 ppm) with gas burners and were also elevated (7.5–7.9 ppm) during electric oven cleaning. Average NO_2 concentrations during the cooking period exceeded 90 ppb in at least one room during fish broiling, making French fries, baking lasagna, preparing a full meal, and oven cleaning with gas burners. The highest NO_2 with an electric burner was during oven cleaning: LR concentrations of NO_2 reached 42 ppb with outdoor concentrations at 22 ppb.

We identified only a few studies that reported the impact of gas cooking burners, distinct from food preparation, on particle number concentrations in homes (Fortmann et al., 2001; Wallace, 2006; Wallace et al., 2008). In a 76.6 m^2 (824 ft^2) single story house, which appears from the floor plan to have had a closed kitchen, (Fortmann et al., 2001) reported PN (>30 nm) of 44 x10^3 cm^{-3} when operating the gas cooktop with a pot of water over 1h and 88.5 x10^3 cm^{-3} when the gas oven was operated for 2h without food. Concentrations in the kitchen were 5.5 x10^3 cm^{-3} and 3.9 x10^3 cm^{-3} before cooktop and oven use, respectively. In a 400 m^3, 3-story townhouse, (Wallace, 2006) reported concentrations of PN (>10 nm) of 5.8 x10^3 cm^{-3} during 36 events of tea preparation using the gas stove, compared to PN of 3.4 x10^3 cm^{-3} during 888 periods when no indoor sources were present. Results from (Wallace et al., 2008) indicate that the PN levels reported in these two prior studies, and even in the current study, are likely under-reported: the median diameter of PN emitted from their gas stove was is in the range of 4-7 nm for a naked cooktop burner (no pots, and grate removed), 5.5–20 nm when a pot or pan was used to boil water or cook, and 4–24 nm when the over or broiler burner was used. For the stovetop without the grate, peak concentrations of 2-64 nm particles were 290–2200 x10^3 cm^{-3} in the kitchen and 90–740 x10^3 cm^{-3} in the master bedroom. Peak concentrations of 2-64 nm particles were 48–450 x10^3 cm^{-3} in the master bedroom.

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

29

3.5 Repeatability

Results for replicate experiments are provided in the following two tables. Table 13 presents the highest 1h time-integrated concentrations, and Table 14 presents the highest 4h results. Replicates were most consistent for NO and least consistent for PN. For NO, NO_2, and PN, replicates showed similar consistency for 1h and 4h results. By contrast, CO_2 had much more variability in 4h vs. 1h results.

Table 13. Relative deviations (RD) and relative standard deviations (RSD) of highest 1h time-integrated concentrations for replicated conditions.

Replicates		CO$_2$		NO		NO$_2$		PN	
		B	K	B	K	B	K	B	K
H202	CT	385	653		315		124	80241	272426
H204	CT	222	428	No data	202	No data	86	58288	160641
RD		54%	42%		44%		37%	32%	52%
H302	OV	676	769	260	443	79	188	136108	462680
H304	OV	607	774	241	382	109	195	111229	292114
RD		11%	1%	8%	15%	32%	3%	20%	45%
H303	CT	656	815	306	458	105	168	75519	171467
H305	CT	723	707	281	467	148	300	117536	243596
RD		14%	9%	2%	34%	56%	44%	35%	35%
H402	OV		2105		933		519		745969
H404	OV	No data	1836	No data	944	No data	546	No data	678747
RD			14%		1%		5%		9%
H501	OV	439	692	213	411	36	148	107478	345440
H508	OV	339	607	166	400	31	130	71321	271881
RD		26%	13%	25%	3%	15%	13%	40%	24%
H502	CT	291	408	149	276	20	82	46321	144795
H504	CT	264	392	130	227	27	78	60987	201738
RD		10%	4%	13%	20%	26%	4%	27%	33%
H601	OV	474	756	130	231	73	187	120050	419191
H605	OV	460	795	139	251	85	203	112871	342922
H609	OV	432	747	130	234	86	193	88439	284396
RSD		5%	3%	4%	2%	9%	4%	15%	5%
Mean		**19%**	**13%**	**12%**	**12%**	**23%**	**17%**	**30%**	**29%**
SD		18%	14%	8%	15%	11%	20%	11%	19%
N		6	7	5	7	5	7	6	7

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

30

Table 14. Relative deviations (RD) and relative standard deviations (RSD) of highest 4h time-integrated concentrations for replicated conditions.

Replicates		CO$_2$		NO		NO$_2$		PN	
		B	K	B	K	B	K	B	K
H202	CT	816	1335		582		185	121702	350038
H204	CT	321	690	No data	326	No data	129	72353	195312
RD		87%	64%		57%		36%	51%	57%
H302	OV	2089	2178	685	871	174	331	233139	578513
H304	OV	1634	1974	610	838	228	373	189379	398404
RD		24%	10%	12%	4%	27%	12%	21%	37%
H303	CT	1828	1958	797	942	223	319	121421	222836
H305	CT	2047	1918	724	887	315	484	180079	316888
RD		11%	2%	10%	6%	34%	41%	39%	35%
H402	OV		3789		1565		724		881460
H404	OV	No data	3293	No data	1516	No data	784	No data	808337
RD			14%		3%		8%		9%
H501	OV	1112	1711	556	885	59	248	171779	464093
H508	OV	835	1426	398	777	60	208	111801	364780
RD		28%	18%	33%	13%	1%	18%	42%	24%
H502	CT	630	989	325	610	33	147	70646	199512
H504	CT	605	819	290	437	43	119	90334	254752
RD		4%	19%	11%	33%	25%	21%	24%	24%
H601	OV	1543	2089	410	598	178	420	245526	620264
H605	OV	1437	1898	431	592	211	425	218415	490175
H609	OV	1353	2057	394	588	208	428	172328	419537
RSD		2%	1%	1%	1%	4%	2%	8%	3%
Mean		**26%**	**18%**	**13%**	**17%**	**18%**	**20%**	**31%**	**27%**
SD		32%	21%	12%	20%	15%	15%	16%	19%
N		6	7	5	7	5	7	6	7

3.6 Effect of range hood use

The effects of operating a venting range hood during cooking are presented in Figure 11. This figure presents the percentage reduction in the highest 1h concentration, calculated as the difference between experiments with range hood use and analogs without range hood use. Included in this figure are the calculated reductions from using the bath fan as the only available exhaust device in H4, and the recirculating range hood in H7.

Broadly, these results indicate that use of range hoods can yield substantial reductions in cooking burner pollutant concentrations both in the kitchen and throughout the house. The positive impact of the range hood was larger than the variability of the experimental method, producing net reductions in all cases. The most benefit was seen in H1, which had a range hood

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

31

with large capture volume and a measured airflow of 108 L/s. This hood, which produced reductions mostly in the range of 80–95%, was of similar design to hoods that showed very high capture efficiency in prior studies: hood B5 in the field study by (Singer et al., 2012), and hood P1 in the lab study by (Delp and Singer, 2012). The next most effective hood, in house H5, also had characteristics reported by (Singer et al., 2012) to be important to performance: it extended to fully cover the front burners and it had airflow substantially above the benchmark of 95 L/s.

The only other hood with reductions mostly exceeding 50% was the over-the-range microwave with exhaust fan in H2, with an exhaust fan that moved 76 L/s at high speed. Prior studies (Delp and Singer, 2012; Lunden et al., 2015; Singer et al., 2012) have found over the range microwave exhaust fans to vary widely in their capture efficiency, in large part explained by variations in airflow but likely also relating to disadvantageous geometry. The reductions observed for H5 were consistent with those measured for hood H2 operating at similar airflow in (Singer et al., 2012). The range hoods in H6, H8 and H9 had calculated reductions of 0–50% with more than half of the results falling in the top half of that range. These hoods had substantially lower airflows and did not extend to cover front burners fully. The bath fan in H4 reduced concentrations by 15–40% across the measured species, suggesting a modest benefit that could have been caused by method variability. The recirculating range hood in H7 showed small net reductions ($\leq$10%) for NO_2, NO, and CO_2 (which had the same reduction as NO), and a larger reduction for PN (~30%). All were within the variability of replicate experiments.

The relationships of range hood effectiveness for PN, airflow, and burner position have been discussed by (Rim et al., 2012) and (Lunden et al., 2015). In measuring particles down to 2 nm, Rim et al. found that removal effectiveness was lower for 2–6 nm particles than for particles >6 nm. Since a large number of particles are in the lower size range, that effect is expected to reduce the overall effectiveness reported by Rim et al. relative to what would be reported for 6 nm and larger particles, as measured in this study. The "A" hood in the Rim et al. study was similar in design and airflow to the hood in H8 and H9 in this study. The roughly 40% reductions in cooktop-emitted PN calculated with range hood operation in those homes is roughly midway between the 31(6)% for front burners and 54(9)% for back burners reported by Rim for Hood A. The "B" hood tested by Rim et al. was similar in design to the hood in H5 in this study and the measured airflows of the hood in H5 were between the medium and high flows measured for Hood B in Rim et al. Yet the effectiveness for PN was substantially lower in H5 than reported for by Rim et al. for their Hood B. The apparent difference may simply result from the greater variations in PN associated with our experimental approach of this study.

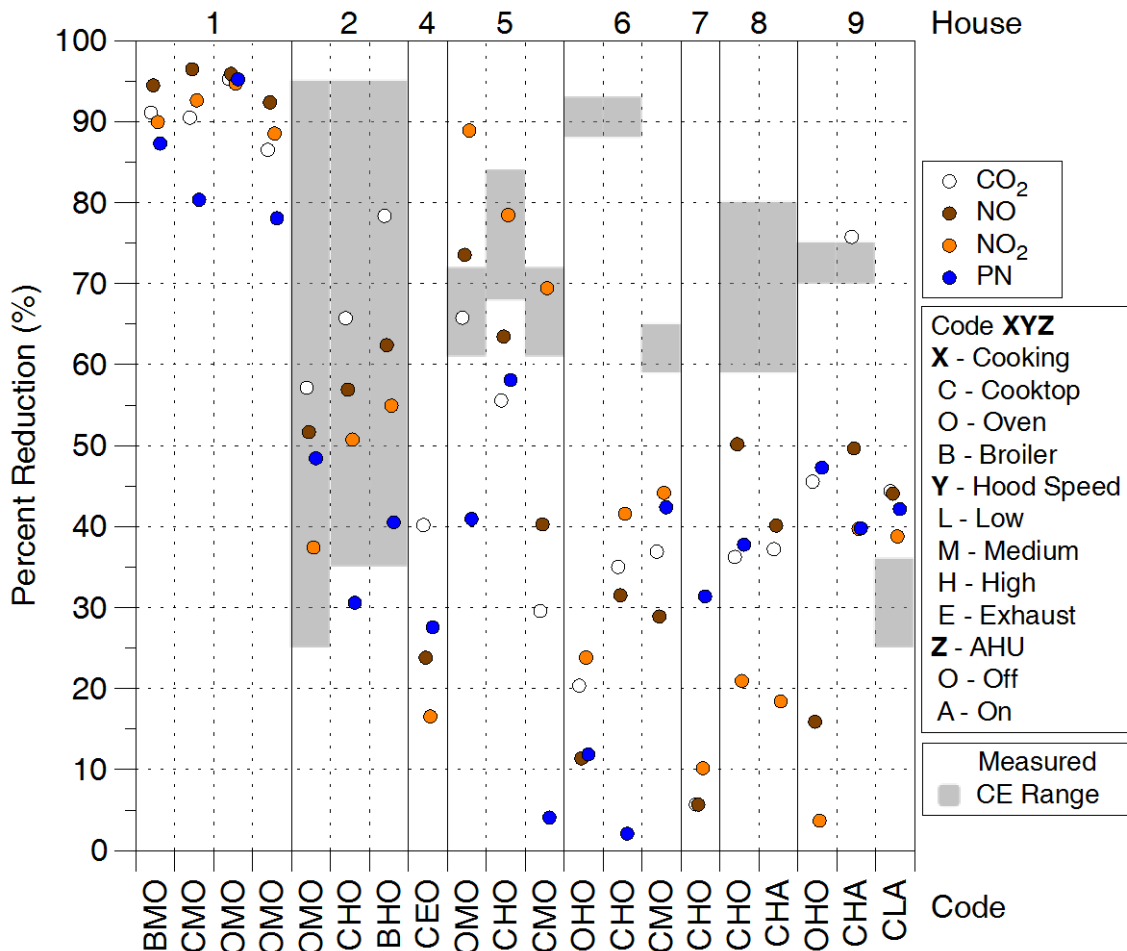Singer et al. (LBNL) Pollutants from Gas Cooking Burners

32

Figure 11. Percent reductions in highest 1h kitchen concentrations calculated by comparing experiments with range hood use to analogous experiments without range hood use.

Shaded grey areas show the range – back burner to front burner – of capture efficiency measured for the hood at the flow rate used in the experiment which is overlaid.

3.7   Effect of FAU Use

Table 15 presents results for the experiments in which the air handler of the forced air heating system (FAU) was operated starting approximately 10 min before cooking and through the decay period. The experiments with FAU use are compared to experiments with the same cooking activities with no FAU use. From the basic physical consideration that it increases mixing, we expected the FAU to reduce kitchen concentrations and increase bedroom concentrations relative to the same cooking activity with no mixing – unless there are losses in the forced air system (e.g. removal by a furnace filter). The trend of a more positive increase in the bedroom relative to the kitchen is evident in the highest 1h CO_2, NO, and NO_2 in two H1 experiments, the experiment in H6, and the CO_2 and NO_2 data in H8. Concentrations in the kitchen either decreased or increased very slightly (which is expected from variability in emissions), whereas concentrations in the bedroom were dramatically higher with FAU operation. The PN results for FAU use in H1 don't follow this trend, but in H6 there was still a much larger increase in bedroom PN vs. kitchen PN when the FAU operated. The trend was not apparent in the FAU

experiments in H7 and H9. The experiment in H2 had only CO_2 and PN data to compare. Overall, there was not a consistent trend of FAU impacts in this study.

Table 15. Highest 1h concentrations in paired experiments to investigate the impact of operating the forced air unit (FAU) mixing fan compared to base conditions.

Cooking Expts FAU	CO_2		NO		NO_2		PN	
	B	K	B	K	B	K	B	K
BR								
H102 Off	352	673	196	464	28	81	97905	389076
H113 On	452	573	222	337	46	87	67338	215539
FAU effect	28%	-15%	13%	-27%	63%	8%	-31%	-45%
OV+CT								
H106 Off	622	838	272	496	104	205	93620	218952
H114 On	741	851	315	426	128	211	56138	148643
FAU effect	19%	1%	16%	-14%	24%	3%	-40%	-32%
CT								
H202 Off	385	653	-	315	-	124	80241	272426
H204 Off	222	428	-	202	-	86	58288	160641
H207 On	377	576	165	303	47	114	78438	270065
FAU effect	24%	6%	-	17%	-	9%	13%	25%
CT								
H602 Off	313	779	170	390	36	108	45193	170603
H604 On	568	627	283	320	59	85	107997	238636
FAU effect	81%	-20%	67%	-18%	64%	-22%	139%	40%
CT								
H701 Off	362	468	155	225	44	84	173800	341730
H703 On	286	447	132	230	46	91	133297	242676
FAU effect	-21%	-5%	-15%	2%	5%	9%	-23%	-29%
CT								
H801 Off	381	431	215	278	41	65	176137	239857
H804 On	292	403	164	217	28	60	124629	-
FAU effect	-23%	-6%	-24%	-22%	-31%	-7%	-29%	
OV								
H901 Off	209	346	68	192	15	78	30641	89573
H908 On	190	305	72	162	21	75	5105	29406
FAU effect	-9%	-12%	6%	-16%	37%	-4%	-83%	-67%
CT								
H902 Off	196	331	103	225	14	49	73952	169964
H903 On	262	393	137	274	18	69	40350	175894
FAU effect	34%	19%	33%	22%	29%	42%	-45%	3%

The lack of a clear trend across all the data collected for this study does not mean that FAU use does not impact pollutant spatial distributions in homes. Rather, the results suggest that the mixing effect was of the same order of magnitude or less than variations caused by other factors, including emission rate and variability of non-mechanical mixing, for the homes studied.

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

34

3.8 Spatial variations

The calculated time-integrated concentrations in the kitchen and bedroom were compared for each experiment to quantify the potential spatial variations in cooking pollutant exposures in homes; results are shown in Figure 12 and Figure 13. Across the sample, the least pronounced spatial variations occurred in the small two-room apartment (H4) and two of the homes with open floor plans (H8 and H7). Spatial variations of highest 1h NO in these three homes were almost all in the range of 1.3 to 2.1 (there was one outlier in H8). The greatest spatial variations of 1h NO_2 were in H9, the two-story 1990s home retrofitted for deep energy savings: K/BR ratios in this home were 3.3 to 6.6. For many of the homes, the kitchen to bedroom ratios were somewhat higher for the highest 1h compared to the 4h time-integrated concentrations. This is consistent with the difference between the two locations being largest during the period during and just after cooking. Within each home, spatial variations for NO (and CO_2, not shown in the Figures) were smaller than for NO_2 and PN. This results because deposition loss rates for NO_2 and PN were competitive with mixing times in all of the homes.
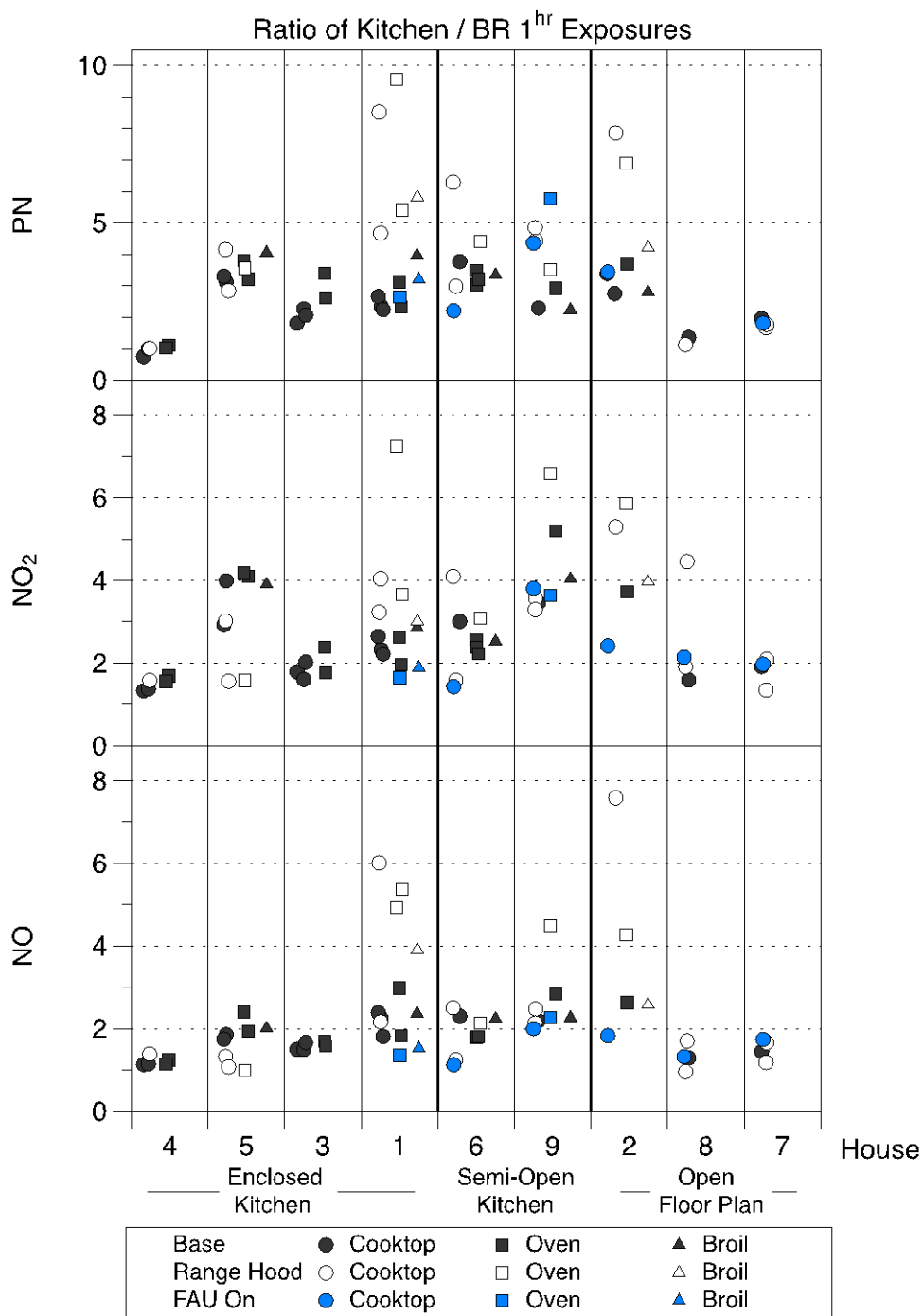
Singer et al. (LBNL) Pollutants from Gas Cooking Burners

35

Figure 12. Ratios of highest 1h time-integrated concentrations in kitchen and bedroom.

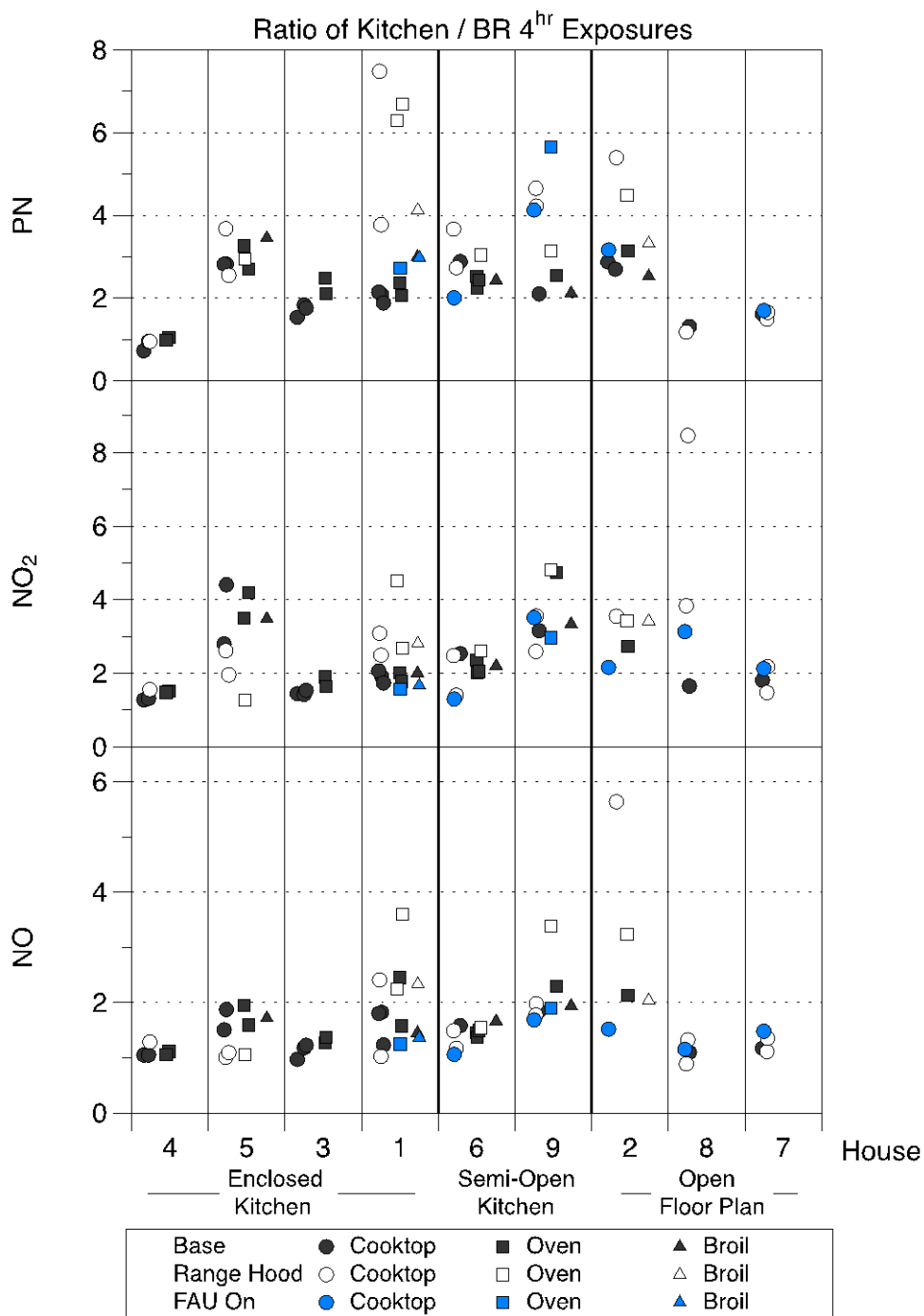Singer et al. (LBNL) Pollutants from Gas Cooking Burners

36

Figure 13. Ratios of time-integrated concentrations in kitchen and bedroom over 4h after cooking burner use commenced.

3.9 Emission factors

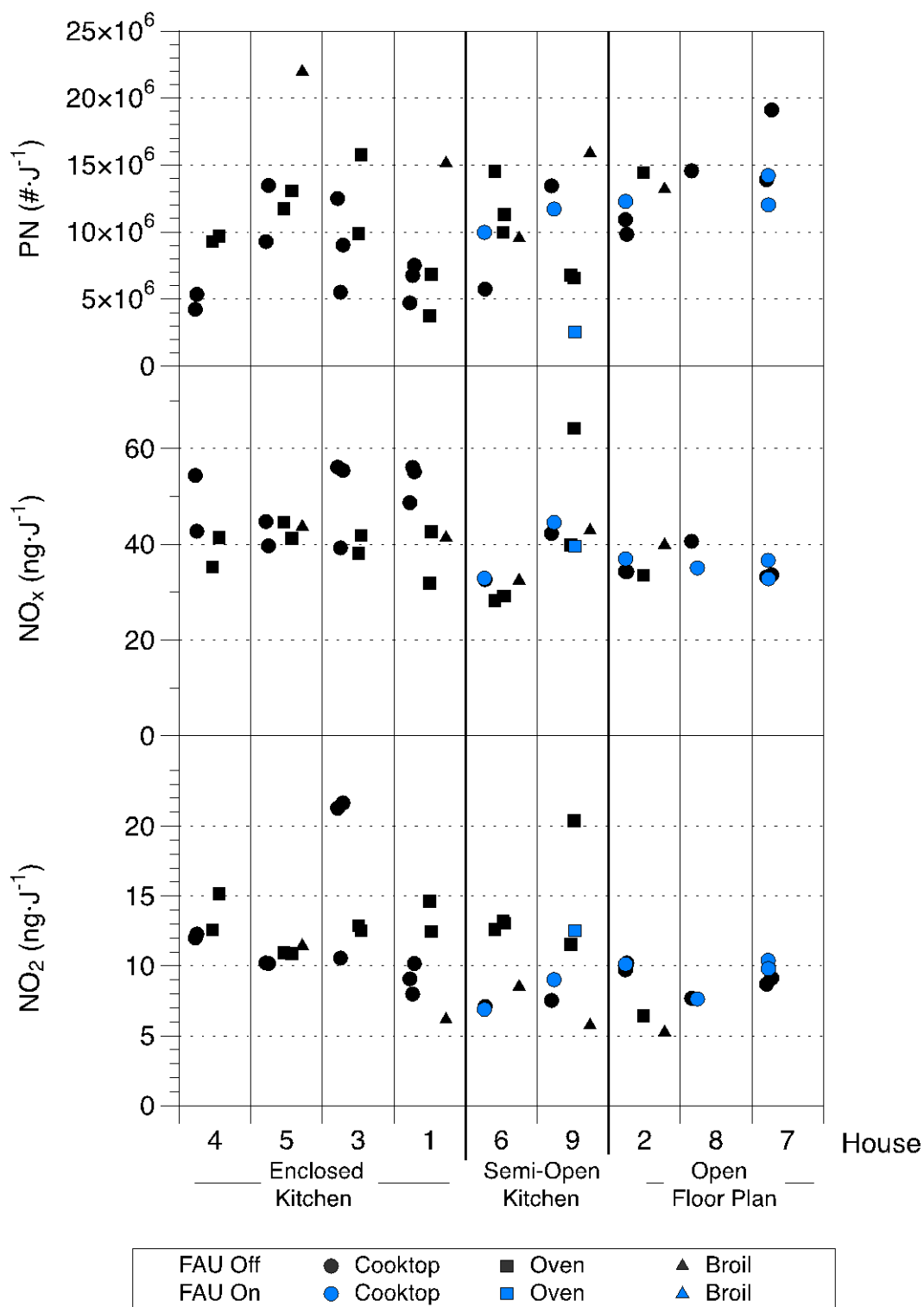Calculated emission factors for NO_2, NO_X, and PN are shown in Figure 14.

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

37

Figure 14. Emission factors calculated from ratios of highest 1h NO_2, NO_X, and PN to highest 1h CO_2. Mass emission rates for NO_X calculated using a molecular mass of 46 g/mol by convention.

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

38

The emission factors derived from the simulated cooking experiments can be compared with those presented for samples of burners in two earlier reports: (1) a compilation of data from studies completed prior to 1990, mostly from the 1970s and early 1980s (Traynor et al., 1996); and (2) a study that reported emission factors for previously used appliances including 13 cooktops, 12 oven burners and 6 broiler burners that were first sold in 1992 to 2007 and tested at ages 2 to 17 years (Singer et al., 2010a). Note that NO_2 emission factors from the 25 gas ranges reported by (Moschandreas and Relwani, 1989) are included in the Traynor review. (Traynor et al., 1996) presented results for NO_X and (Singer et al., 2010a) presented results for NO_X, NO_2, and PN.

NO_X emission factors from the current study ranged from 28 to 64 n⬚ with most of the data between 30 and 45 n⬚ and a geometric mean of 40. These are a bit higher than the emission factors reported by (Singer et al., 2010a), which ranged from 17 to 47 n⬚ with most of the data between 30 and 36 n⬚ and the results reported by (Traynor et al., 1996), which had a geometric mean of 32 n⬚⬚⬚.

Most of the NO_2 emission factors calculated in the current study were between 5 and 15 n⬚ with geometric mean 10.3 n⬚ The prior study by (Singer et al., 2010a) reported similar results with 28 of the 31 burner sets having NO_2 emissions within the range of 5-15 n⬚⬚⬚.

The biggest difference between the current results and previously reported emission factors is for PN. In this study, the calculated PN emission rates ranged from 2.5×10^9 J^{-1} to 2.2×10^{10} J^{-1} with a geometric mean of 1.0×10^{10} J^{-1}. In the results reported by (Singer et al., 2010a), PN emissions were much more variable. The highest emission factors for each burner type were in the same range as those determined in the current study: 1.4, 0.5, and 2.6 $\times 10^{10}$ J^{-1} for CT, OV and BR burners respectively. But for each burner type reported in the earlier study, there were many more burners with PN emission factors below the lowest values reported for the current study. This difference may result from the cleaning, pre-conditioning, and more repeat experiments in the earlier study. This observation derives from the hypothesis that the particles were formed by volatilization of organics compounds that were deposited on cooktop, oven or broiler burner surfaces, as reported by (Wallace et al., 2015) for electric burners and other hot surfaces.

4   Summary and Conclusions

The short-term indoor air quality impacts of using natural gas cooking burners were investigated through controlled experiments in nine residences in Northern California. Cooktop, oven, and broiler burners were operated in a prescribed manner intended to simulate use during typical cooking activities, while avoiding emissions associated with food preparation. Homes were set to defined ventilation and mixing conditions with a baseline configuration of windows closed and no operation of the air distribution system of the forced air heating unit (FAU). The impact of FAU operation was investigated in a limited way through experiments conducted in six of the homes. Air pollutants were monitored continuously in the kitchen and the bedroom area to quantify concentrations of NO, NO_X, CO_2, CO, and the number of particles with diameters ≥ 6 nm as an indication of ultrafine particles (UFP). The difference between NO_X and NO was calculated and reported as NO_2 even though that value likely includes non-negligible amounts of nitrous acid (HONO). Estimated $PM_{2.5}$ was measured by light scattering. A pilot investigation of the benefits of range hoods and kitchen exhaust ventilation was conducted with experiments in

eight homes, including six with venting range hoods, one with an exhaust fan in a room adjacent to the kitchen, and one with a recirculating range hood. A total of 65 experiments were conducted during 15 days and 7 overnight periods.

The data were analyzed to disentangle the time-concentration profile for each experiment from the effects of prior and subsequent experiments. This enabled estimation of the highest 1h and 4h time-integrated concentrations for CO_2, NO, NO_2, and PN in each experiment. The results were used to quantify the pollutant concentrations in each room and relative levels of pollutants in the two locations over time. The highest 1h concentrations of NO_X, NO_2, PN, and CO_2 were used to estimate fuel-normalized emission factors (ng J^{-1} and particles J^{-1}). Differences between experiments with range hood use and analogous experiments – defined by cooking burner and home mixing condition – without range hood use were used to calculate pollutant reductions from using the range hoods.

Pollutant concentrations varied widely across and within homes. Concentrations were much lower in bedrooms versus kitchens, except for a small two-room apartment, H4, and an open floor plan house, H8. In several homes PN concentrations were much higher when using the oven or broiler burner compared to the cooktop. No clear trends by burner were observed for NO or NO_2 across apartments. The data show larger deviations between kitchen and bedroom concentrations in homes with enclosed kitchens (H1, H3, H4, and H5) relative to homes with semi-open kitchens (H6 and H9) or open floor plans (H2, H8, H9). The trio with open floor plans included the two largest homes, which contributed to the generally lower concentrations observed in those homes. Four of the nine homes had kitchen levels exceed the national ambient air quality standard threshold of 100 ppb NO_2 over 1h, and two others had 1h NO_2 concentrations of at least half this value. Three of the nine homes had bedroom NO_2 levels exceed 50 ppb. This suggests significant exposures may occur for anyone at home when natural gas burners are used for even a single, substantial cooking event.

Results from the pilot of study of kitchen ventilation indicate that range hoods can substantially reduce cooking burner pollutant concentrations, both in the kitchen and throughout the house. The positive impact of the range hood was larger than the variability of the experimental method, producing net reductions in all cases. An 80-95% reduction was observed in H1, which featured a range hood with large capture volume and a measured airflow of 108 L/s. The hood in H5 also had characteristics important to performance: it extended to fully cover the front burners, and it had airflow substantially above the benchmark of 95 L/s. When operated on high speed, it reduced 1h concentrations by 56–78%. The only other hood with reductions mostly exceeding 50% was the over-the-range microwave with exhaust fan in H2. The range hoods in H6, H8 and H9 had reductions of 0–50% with more than half of the results falling in the top half of that range. These hoods had substantially lower airflows and did not extend to cover front burners fully. The bath fan in H4 reduced concentrations by 15–40% across the measured species, indicating a modest benefit. The recirculating range hood in H7 showed small net reductions (≤10%) for NO_2, NO, and CO_2, and a larger reduction for PN (~30%) that were all within the variability of replicate experiments.

The results of this limited field study generally confirm the finding of a recent simulation study (Logue et al., 2014) that using natural gas cooking burners without venting commonly produces short-term NO_2 concentrations in homes that approach or exceed the federal ambient air quality standard of 100 ppb.

The results also show that operation of a venting range hood with airflow and geometry described by Singer et al. (2012) substantially reduces concentrations of cooking related pollutants throughout the home.

5   Recommendations

Based on the findings of this field study and the related, prior work referenced herein, the authors offer the following policy recommendations.

Efforts should be made to increase awareness (a) that natural gas cooking burners are a source of air pollutant emissions into homes, and (b) that these pollutants can be controlled with an appropriately-sized venting range hood or other kitchen exhaust ventilation. Since cooking with electric burners also produces pollutants, kitchen exhaust ventilation should be available in all homes, and operated as a precaution whenever cooking occurs. Since the performance of most hoods is much better when cooking is done on the back cooktop burners, this practice should be encouraged to improve safety. Gas utilities could play a valuable role in publicizing these messages.

Building standards should require that range hoods have airflows of at least 95 L/s and cover front burners or preferably demonstrate performance through a standard test. Such a test is currently under development by ASTM.

6   References

Bhangar, S., Mullen, N.A., Hering, S.V., Kreisberg, N.M. and Nazaroff, W.W. (2011) Ultrafine particle concentrations and exposures in seven residences in northern California, *Indoor Air*, **21**, 132-144.

Delp, W.W. and Singer, B.C. (2012) Performance Assessment of U.S. Residential Cooking Exhaust Hoods, *Environ. Sci. Technol.*, **46**, 6167-6173.

Fortmann, R., Kariher, P. and Clayton, R. (2001) Indoor air quality: Residential cooking exposures, Sacramento, CA, Prepared for California Air Resources Board, ARB Contract Number 97-330.

Franklin, P., Runnion, T., Farrar, D. and Dingle, P. (2006) Comparison of peak and average nitrogen dioxide concentrations inside homes, *Atmos. Environ.*, **40**, 7449-7454.

Garrett, M.H., Hooper, M.A. and Hooper, B.M. (1999) Nitrogen dioxide in Australian homes: Levels and sources, *Journal of the Air & Waste Management Association*, **49**, 76-81.

Hei Review Panel on Ultrafine Particles (2013) Understanding the Health Effects of Ambient Ultrafine Particles. HEI Perspectives 3. , Boston, MA., Health Effects Institute.

Kaden, D.A., Mandin, C., Nielsen, G.D. and Wolkoff, P. (2010) 3. Formaldehyde, *WHO Guidelines for Indoor Air Quality: Selected Pollutants.*, Geneva, World Health Organization.

Knol, A.B., De Hartog, J.J., Boogaard, H., Slottje, P., Van Der Sluijs, J.P., Lebret, E., Cassee, F.R., Wardekker, A., Ayres, J.G., Borm, P.J., Brunekreef, B., Donaldson, K., Forastiere, F., Holgate, S.T., Kreyling, W.G., Nemery, B., Pekkanen, J., Stone, V., Wichmann, H.E. and Hoek, G. (2009) Expert elicitation on ultrafine particles: likelihood of health effects and causal pathways, *Particle and Fibre Toxicology*, **6**.

Logue, J.M., Klepeis, N.E., Lobscheid, A.B. and Singer, B.C. (2014) Pollutant Exposures from Natural Gas Cooking Burners: A Simulation-Based Assessment for Southern California, *Environ. Health Perspect.*, **122**, 43-50.

Lunden, M.M., Delp, W.W. and Singer, B.C. (2015) Capture efficiency of cooking-related fine and ultrafine particles by residential exhaust hoods, *Indoor Air*, **25**, 45-58.

Moschandreas, D.J. and Relwani, S.M. (1989) Field-measurements of NO2 gas range-top burner emission rates, *Environ. Int.*, **15**, 489-492.

Moschandreas, D.J. and Zabransky Jr, J. (1982) Spatial variation of carbon monoxide and oxides of nitrogen concentrations inside residences, *Environ. Int.*, **8**, 177-183.

Mullen, N.A., Li, J., Russell, M.L., Spears, M., Less, B.D. and Singer, B.C. (2016) Results of the California Healthy Homes Indoor Air Quality Study of 2011-2013: impact of natural gas appliances on air pollutant concentrations, *Indoor Air*, **26**, 231-245.

Rim, D., Wallace, L., Nabinger, S. and Persily, A. (2012) Reduction of exposure to ultrafine particles by kitchen exhaust hoods: The effects of exhaust flow rates, particle size, and burner position, *Sci. Total Environ.*, **432**, 350-356.

Rim, D., Wallace, L. and Persily, A. (2011) Reduction of exposure to ultrafine particles by kitchen exhaust fans of varying flow rates. In: Proceedings of Indoor Air 2011, Vol. Paper 806, pp. Pape 806.

Ryan, P.B., Soczek, M.L., Treitman, R.D. and Spengler, J.D. (1988) The Boston Residential NO2 Characterization Study: 2. Survey methodology and population concentration estimates, *Atmos. Environ.*, **22**, 2115-2125.

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

42

Salthammer, T., Mentese, S. and Marutzky, R. (2010) Formaldehyde in the Indoor Environment, *Chem. Rev.*, **110**, 2536-2572.

Schwab, M., Mcdermott, A., Spengler, J.D., Samet, J.M. and Lambert, W.E. (1994) Seasonal and yearly patterns of indoor nitrogen dioxide levels - data from Albuquerque, New Mexico, *Indoor Air-International Journal of Indoor Air Quality and Climate*, **4**, 8-22.

Singer, B.C., Apte, M.G., Black, D.R., Hotchi, T., Lucas, D., Lunden, M.M., Mirer, A.G., Spears, M. and Sullivan, D.P. (2010a) Natural Gas Variability in California: Environmental Impacts and Device Performance: Experimental Evaluation of Pollutant Emissions from Residential Appliances, Sacramento CA, California Energy Commission, CEC-500-2009-099.

Singer, B.C., Delp, W.W. and Apte, M.G. (2010b) Natural Gas Variability in California: Environmental Impacts and Device Performance: Experimental Evaluation of Installed Cooking Exhaust Fan Performance, Lawrence Berkeley National Laboratory.

Singer, B.C., Delp, W.W., Price, P.N. and Apte, M.G. (2012) Performance of installed cooking exhaust devices, *Indoor Air*, **22**, 224-234.

Spengler, J., Schwab, M., Ryan, P.B., Colome, S., Wilson, A.L., Billick, I. and Becker, E. (1994) Personal exposure to nitrogen dioxide in the Los Angeles Basin, *Journal of the Air & Waste Management Association*, **44**, 39-47.

Spengler, J.D., Duffy, C.P., Letz, R., Tibbitts, T.W. and Ferris, B.G. (1983) Nitrogen dioxide inside and outside 137 homes and implications for ambient air quality standards and health effects research *Environ. Sci. Technol.*, **17**, 164-168.

Spicer, C.W., Kenny, D.V., Ward, G.F., Billick, I.H. and Leslie, N.P. (1994) Evaluation of NO2 measurement methods for indoor air quality applications, *Journal of the Air & Waste Management Association*, **44**, 163-168.

Stratton, J.C. and Singer, B.C. (2014) Addressing Kitchen Contaminants for Healthy, Low-Energy Homes, Berkeley CA, Laboratory, L. B. N., LBNL-6547E.

Traynor, G.W., Apte, M.G. and Chang, G.M. (1996) Pollutant emission factors from residential natural gas appliances: A literature review, Berkeley, CA, Lawrence Berkeley National Laboratory, LBNL-38123.

Us Epa (2010) Integrated Science Assessment for Carbon Monoxide (Final Report), Washington, DC, U.S. Environmental Protection Agency.

Us Epa (2016) Integrated Science Assessment for Oxides of Nitrogen - Health Criteria (2016 Final Report), Washington DC, U.S. Environmental Protection Agency.

Walker, I.S., Wray, C.P., Dickerhoff, D.J. and Sherman, M.H. (2001) Evaluation of flow hood measurements for residential register flows, Berkeley CA, Lawrence Berkeley National Laboratory, LBNL-47382.

Wallace, L. (2006) Indoor sources of ultrafine and accumulation mode particles: Size distributions, size-resolved concentrations, and source strengths, *Aerosol Sci. Technol.*, **40**, 348-360.

Wallace, L., Wang, F., Howard-Reed, C. and Persily, A. (2008) Contribution of gas and electric stoves to residential ultrafine particle concentrations between 2 and 64 nm: size distributions and emission and coagulation remission and coagulation rates, *Environ. Sci. Technol.*, **42**, 8641-8647.

Wallace, L.A., Ott, W.R. and Weschler, C.J. (2015) Ultrafine particles from electric appliances and cooking pans: experiments suggesting desorption/nucleation of sorbed organics as the primary source, *Indoor Air*, **25**, 536-546.

Wilson, A.L., Colome, S.D., Baker, P.E. and Becker, E.W. (1986) Residential Indoor Air Quality Characterization of Nitrogen Dioxide - Phase I Final Report, Prepared for Southern California Gas Co., Los Angeles CA, Multiple Volumes and Appendices.

Wilson, A.L., Colome, S.D. and Tian, Y. (1993) California Residential Indoor Air Quality Study, Sponsored by Gas Research Institute, P. G. E., San Diego Gas & Electric, Southern California Gas, Integrated Environmental Services, Irvine CA, Multiple Volumes and Appendices.

Singer et al. (LBNL) Pollutants from Gas Cooking Burners

44