LBNL-4183E

ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

EXPERIMENTAL EVALUATION OF INSTALLED COOKING EXHAUST FAN PERFORMANCE

Brett C. Singer, William W. Delp
and Michael G. Apte

Indoor Environment Department
Atmospheric Sciences Department
Environmental Energy Technologies Division

November 2010

Notice about Report and Appendix Availability

This report has been submitted to the California Energy Commission (CEC). It is anticipated that a version of the report – containing the same technical information but potentially differing in presentation based on changes made by CEC technical editors – will be published by the Energy Commission. If published by CEC, the report should be available at the following site: http://www.energy.ca.gov/reports/. The report has an appendix that may be assigned a distinct LBNL report number and, if published, likely will be posted as a separate document on the CEC website. The appendix may be requested directly from the PI, Dr. Brett C. Singer at bcsinger@lbl.gov.

---

[1] Disclaimer included verbatim as required by LBNL RPM Section 5.02.03. United State Government sponsorship refers to the management contract noted in the Acknowledgments. The specific work described in this report was funded by the California Energy Commission through contract 500-05-026.

Abstract

The installed performance of cooking exhaust fans was evaluated through residential field experiments conducted on a sample of 15 devices varying in design and other characteristics. The sample included two rear downdraft systems, two under-cabinet microwave over range (MOR) units, three different installations of an under-cabinet model with grease screens across the bottom and no capture hood, two devices with grease screens covering the bottom of a large capture hood (one under-cabinet, one wall-mount chimney), four under-cabinet open hoods, and two open hoods with chimney mounts over islands. Performance assessment included measurement of airflow and sound levels across fan settings and experiments to quantify the contemporaneous capture efficiency for the exhaust generated by natural gas cooking burners. Capture efficiency is defined as the fraction of generated pollutants that are removed through the exhaust and thus not available for inhalation of household occupants. Capture efficiency (CE) was assessed for various configurations of burner use (e.g. single front, single back, combination of one front and one back, oven) and fan speed setting. Measured airflow rates were substantially lower than the levels noted in product literature for many of the units. This shortfall was observed for several units costing in excess of $1000. Capture efficiency varied widely (from <5% to roughly 100%) across devices and across conditions for some devices. As expected, higher capture efficiencies were achieved with higher fan settings and the associated higher air flow rates. In most cases, capture efficiencies were substantially higher for rear burners than for front burners. The best and most consistent performance was observed for open hoods that covered all cooktop burners and operated at higher airflow rates. The lowest capture efficiencies were measured when a front burner was used with a rear backdraft system or with lowest fan setting for above the range systems that do not cover the front burners.

Keywords: Cooktop, gas burners, indoor air quality, kitchen, oven, nitrogen dioxide, pollutant emissions, range hood, residential, source control, task ventilation

Acknowledgments

The authors acknowledge with appreciation the following contributions to this work. William Fisk of LBNL contributed to the conception of the task and to initial scoping discussions. Tosh Hotchi, Doug Sullivan, Doug Black, Darryl Dickerhoff and Iain Walker contributed to the experimental effort through assistance with equipment and methods.

The authors additionally thank all members of the Project Advisory Committee (PAC) who contributed their time, knowledge, and many specific suggestions to improve many aspects of the work on many tasks of the overall project. Special appreciation is extended to the following members who provided extensive and ongoing technical support and guidance for the work covered in this report: Peggy Jenkins of the California Air Resources Board, Glenn Morrison of the Missouri Technological University, and Jed Waldman of the California Department of Public Health. We thank Tod Bedrosian for coordinating advisory committee meetings.

The authors are particularly indebted to our colleagues and friends who allowed us access to conduct experiments on the equipment installed in their homes.

Direct funding of this research was provided by the California Energy Commission through Contract 500-05-026. Additionally, this work was supported by the Director, Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Table of Contents

List of Figures

List of Tables

Executive Summary

Introduction

Anticipating increasing use of liquefied natural gas in California, the California Energy Commission requested research to assess the potential impacts on combustion appliance performance and pollutant emissions to the environment. Liquefied natural gas typically contains more energy per unit volume compared to the natural gas that has been distributed in California in recent years. This difference has the potential to affect the performance and pollutant emissions of existing natural gas combustion equipment. Lawrence Berkeley National Laboratory and the Gas Technology Institute are working in collaboration to assess these impacts. Lawrence Berkeley National Laboratory is focusing on residential appliances and air quality, while the Gas Technology Institute focuses on industrial burners.

This report presents results of an experimental study of installed cooking exhaust fan performance. Expanding the use of cooking exhaust fans – including devices installed above the cooktop and downdraft systems – could potentially mitigate the effects on indoor pollutant exposures from increased pollutant emission rates when LNG is employed. Prior to this study, there has been a dearth of information about installed pollutant-capture performance of cooking exhaust fans.

Task Purpose and Objectives

The goal of this task was to quantify the performance of a diverse sample of kitchen exhaust fans installed in California residences. Specific objectives included the following:

- Measure airflow rates of installed equipment and compare to product specifications.
- Measure sound levels during installed equipment use.
- Quantify capture efficiency, defined as the fraction of burner-generated pollutants that are removed by the exhaust system during use.

Task Outcomes

On-site performance evaluations were conducted on a diverse sample of 15 cooking exhaust systems installed in California residences. The sample included two downdraft exhaust units, two microwave-over-range (MOR) exhaust fans, three installations of the same model of under-cabinet system with no substantial collection hood and grease screens covering the bottom, and eight units with collection hoods. Comprising these eight were two island chimney units, one wall-mount chimney unit, and five under-cabinet units. These devices span a range of retail price from less than \$100 to \$2900. The sample includes three units installed at the time of building or addition construction, six units installed as part of a major kitchen remodel, two units installed by the current homeowners to replace a previously installed device, and four units installed by current homeowners into a kitchen that did not have an exhaust fan. Eight of the 13 above-the-cooktop devices were installed according to manufacturer specifications (the downdraft systems are incorporated into the cooking appliances).

Measured airflows ranged from 74 to 382 cubic feet per minute at the highest fan settings. The ratio of measured to nominal (nameplate or manufacturer specified) airflow at the highest fan setting ranged from a high of 100% to a low of 28%. Of the six units (four unique models) having airflow ratings certified by the Home Ventilating Institute (using an industry standard test procedure), one had maximum airflow that was only 39% of the rated value, another had a maximum airflow at 71% of its rating and the remaining four (including the three units of the same model) had airflows exceeding 90% of rated values. Of the seven devices with the highest nominal flows, ranging from 550 to 760 cubic feet per minute, none were certified and only two of the seven had measured airflows that exceeded 50% of the nominal value. The nominal airflows for these products appear to be free air delivery, i.e. the amount of air that can be moved by the component fan when not installed in the appliance housing or attached to ductwork that produces pressure resistance and reduces flow. For devices with multiple speed settings, airflows were typically much lower on the lowest speed compared with the highest speed setting; three units had airflows of 50 cubic feet per minute or less at low fan speed.

Sound levels – measured as dB(A) – under background conditions of no fan use and with fan operation varied substantially across locations and installations. Background values were 33 to 49 dB(A) in the kitchens in which evaluations were conducted. Sound levels measured at the position of a cook were 57 to 71 db(A) with fans on highest setting and 40 to 73 dB(A) on lowest fan setting. Fans on high setting caused an increase in sound levels of 18 to 29 dB(A) above background. Interpretation of these results is not straightforward; the measured values are presented primarily for purposes of documentation and reference.

Capture efficiency was determined for each hood for a variety of burner use configurations including single front cooktop burner, single rear cooktop burner, combination of one front and one rear cooktop burner, and oven burner. Capture of cooktop burner pollutants was evaluated with the burners operated on the highest setting and a pot of water placed atop the burner to simulate typical use. Each burner configuration was evaluated at multiple exhaust fan settings as available.

Capture efficiency varied widely across models, installations and conditions. Models with actual collection hoods generally performed better than flat profile (including microwave exhaust fan combination units) and downdraft systems. Microwave-fan combination units were broadly ineffective with capture efficiencies at or below 40% across a range of conditions. Despite achieving maximum airflow rates roughly 230-250 cfm, the three installations of a modestly priced flat bottom under-cabinet model had peak capture efficiencies of only 50-65% and efficiencies below 50% for many burner and fan setting combinations. Capture efficiencies exceeded 70% for one hood and 80% for another across all tested configurations; both of these were high-end models. Among the models with capture hoods, very poor performance was observed for only one of the tested units: an economy model with an exhaust inlet at the same vertical levels as the bottom of the hood (i.e. not situated to draw air from within the hood). For many models, performance varied substantially across conditions. The downdraft systems were generally effective at removing cooking exhaust from the back burners but ineffective for front burners. For most of the above the cooktop models, capture efficiencies were highest for back burner and oven operation, and for the highest fan speed. For devices with multiple fan settings, capture efficiencies were higher at the higher fan settings. Consistent with these effects, the lowest capture efficiencies generally occurred for front burners and lower flow rates. The efficiency results indicate that meeting industry standard guidance on minimum airflow requirements is not sufficient to ensure adequate pollutant capture efficiency.

Benefits to California

This research is helping to lay the groundwork for maintaining a safe and reliable natural gas supply in California. The proactive investigation of potential impacts of new supplies, including LNG, will allow California to better understand the 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 the understanding of the potential value of cooking exhaust fans to mitigate any increases in pollutant emissions resulting from LNG use. The results will further aid in identifying potential performance improvements, and in the analysis of the overall energy and public health implications of cooking exhaust fan use in California. The finding that many installed hoods are much more effective for back burners could enable users to obtain better performance from existing systems. The findings should also help builders and home owners make better choices when selecting kitchen exhaust systems.

1.0 Background

The California Energy Commission's Public Interest Natural Gas Research program has the charge to address significant natural gas issues in the State of California. One of the most important issues is the anticipated growth of new gas supplies—principally including liquefied natural gas (LNG) from Pacific Rim exporters—required to meet growing demand across the Western United States. These new fuels can differ in composition and have higher heating values and Wobbe numbers (energy content delivered through a fixed orifice) compared with recent historical natural gas supplies. These differences raise questions about the potential impacts of using LNG with the existing population of end-use natural-gas combustion equipment. Impacts of concern include safety, performance, service life, and air pollutant emissions.

Lawrence Berkeley National Laboratory (LBNL) and the Gas Technology Institute (GTI) are conducting research to support a broad examination of the potential air quality and end-use device performance impacts of LNG use in California. LBNL and GTI jointly developed a research plan that included experimental burner evaluations, statistical analysis and modeling of results, combustion modeling, outdoor air quality modeling, and indoor exposure modeling assessments. GTI focused on the experimental evaluation of industrial and commercial burners. LBNL focused on residential appliance burners and air quality impacts. This document reports on the work conducted by LBNL as part of Task 15 of the research study. The direct objective of this task was the experimental evaluation of performance of in-used cooking exhaust fans installed in residences. The intent of this task was to advance understanding of the potential for range hood use to mitigate any increase in people's exposures to pollutant emissions resulting from use of LNG on natural gas cooking burners.

There is limited available information about the characteristics and occupant use patterns of cooking exhaust fans installed in residences. The two most substantial source of information relate to California and result from recent studies funded by the California Energy Commission. The first study gathered data from a self-administered survey that was mailed out to 5000 single-family homes built in 2003 [Piazza et al., 2007; Price and Sherman, 2006]. The second study included field measurements of a broad suite of ventilation and indoor air quality parameters in 108 new homes, aged 2-4 years at the time of measurement [Offermann, 2009]. A review of the literature identified only two other surveys conducted in the U.S. during the last two decades [Nagda et al., 1989; Parrott et al., 2003]. Inferences may be made on the presence of venting cooking exhaust fans from broader surveys with an appropriate question included from a study in California [Wilson et al., 1994]

1.1. Purpose of cooking exhaust fans

Effective removal of air contaminants generated inside residences is important to providing good indoor air quality and to protecting the health and safety of occupants. Unvented gas appliances, notably stovetops and ovens, can emit substantial quantities of indoor air pollutants including carbon monoxide, nitrogen dioxide and fine particles [Singer et al., 2009]. Emissions associated with cooking activities (e.g. frying, grilling, and baking) contribute additional pollutants to indoor air [Fortmann et al., 2001]. Venting cooking exhaust fans – either above the cooktop or downdraft systems – can remove burner exhaust and cooking-related pollutants before they mix throughout the kitchen and the residence as a whole. Exhausting pollutants at the source – in this case cooking appliances – can be accomplished with lower overall airflow rates and lower occupant exposures compared to removal by increasing whole-house ventilation rates. Effective removal of pollutants at the source reduces health risks and saves energy. Energy savings result from the reduction in overall ventilation rates that would be required to remove pollutants that have not been removed at the source. Any required or desired thermal conditioning of the ventilation air compounds the energy penalty of increased whole house ventilation for cooking related pollutant removal.

In the context of natural gas interchangeability, venting of residential appliances provides a secondary means to mitigate exposure to potential increases in combustion pollutant emissions associated with fuel changes. The local exhaust fan is thus an important safety feature that can mitigate the effect of increased emissions resulting from changes in distributed natural gas.

1.2. Market penetration

Price and Sherman [2006] identified that in their sample of new homes, nearly all have kitchen range hoods and about 85% of them vent outdoors. Parrott et al [2003] surveyed 78 households (survey date not given) in a non-random sample that the authors characterize as screened to be "demographically representative of the U.S. population." This study found that 92% had mechanical kitchen ventilation systems with at least 55% being vented outside (17% or respondents did not know). In December 1985, Nagda et al (1989) conducted a demographically representative, non-random mail survey of 3000 U.S. residences. In that study 36% of the homes had vented range hood fans and an additional 13% had vented ceiling or wall kitchen fans. Neither of these studies presented data on the prevalence of gas vs. electric cooking appliances in the homes studied.

Wilson et al. (1994) conducted a random survey of indoor air quality (IAQ) in 300 California residences. The survey included questions on the presence of a vented kitchen fan. Based on survey responses, 64.2 percent of the residences had fans that vented outdoors, while 16.7% and 19.1% of respondents said that the fan recirculated kitchen air or that the question was not applicable (e.g., no vent fan), respectively. In this study 48% of the range burners and 52% of the ovens were gas fired while the rest were electric. Kitchen venting stratified by fuel type was not provided in the report.

Although no comprehensive estimate is available, these studies suggest that well over half of the homes in California have a range hood or other fan-powered kitchen vent that exhausts outdoors. Unfortunately, a more precise estimate cannot be made with the data available. The studies cited above include one which is focused on homes built in 2003 (Price and Sherman 2006), another recent study with an insufficient sample size (Parrott et al., 2003), and a demographically representative national study that must now be considered outdated (Nagda et al., 1989; data from 1985). It is not possible from these data to assess the current percentage of homes with gas cooking equipment that have a fan-powered exhaust system. There is also anecdotal evidence, though no solid information on the percentage of homes having poorly-functioning or non-functioning externally venting kitchen exhaust fans.

1.3. Prevalence of use

A venting exhaust system must be operated during cooking for effective pollutant removal. Nagda et al. (1989) reported that fewer than half of the households studied used the vented range hoods regularly and even fewer operated the fans at the start of cooking. Wilson et al. (1994) reported that about 12% of the households always used the range hood when cooking, while 51% and 28% used the fan sometimes and never, respectively. Parrott et al. (2003) report that only 8% of the sampled appliance users utilize their ventilation system "whenever they cook"; 15% use the system once in a while and 8% "almost never" use the system (though it is not stated, it is presumed that the remaining approximately 70% use ventilation at a frequency that falls between "once in a while" and "whenever" they cooked. Price and Sherman (2006) report in their study of new homes that when cooking on the stovetop, 28% always use the range hood, 32% use the hood for odor and humidity control (presumably starting when the problem presents) and 27% sometimes use their hoods. Both Parrott et al. (2003) and Price and Sherman (2006) report much lower hood use for cooking with an oven compared to stovetop cooking. These sparse data indicate that range hood use is inconsistent.

Both Nagda et al. (1989) and Parrott et al (2003) collected data on reasons for use and non-use of the range hood. The most common reasons for use in both studies were removal of smoke or steam and removal of odors (ranges of 23–87%). Removal of heat was important for about 20–25% of users. Many of the people using the hoods for these reasons probably don't turn them on until the problem manifests, i.e. until somewhat long after the range has been in use; this common delay is a key feature of inadequate and improper use of the range hood since waiting may greatly reduce effectiveness.

Improvement of IAQ was the reason for about 10–20% of users. Reasons not to use the range hood are topped by excessive noise (39–48%). Other reasons include "not necessary", "wastes heat and energy," and "don't think about it."

1.4. Airflow ratings and recommendations

The capacity of an exhaust system to move air depends on the performance curve of the fan, flow obstructions (pressure drops) within the appliance, and pressure drops associated with ductwork. Fan performance curves specify air movement in relation to the pressure rise across the fan. For the fans used in cooking exhaust appliances, fan performance data (when available) is typically limited to a single operational point. Airflow at the condition of no pressure drop (fan completely open on either side) is described as free air delivery. The maximum airflow capacity of an exhaust appliance will depend on the internal flow paths and obstructions and resulting pressure drops. When the appliance is connected to ducting, downstream pressure resistance increases and maximum flow decreases. In-use performance may be further impacted by pressure drops resulting from dirty grease filters or a sticky backdraft damper (a flap of sheet metal or plastic designed to open when the fan is on, and remain closed to prevent air from flowing back into the house when the fan is off).

The Home Ventilating Institute (HVI) certifies and publishes performance ratings for residential ventilation equipment, including cooking exhaust fans[*HVI*, 2010]. The HVI rating method is described in HVI Publication 916. It requires exhaust appliance performance measurements (airflow and sound) to be conducted with external static pressure of 0.1 inches of water (equivalent to 25 Pascal) to account for a minimal amount of pressure drop in ductwork. Products may additionally be rated at a static pressure of 0.25 inches of water.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard for residential ventilation (Standard 62.2) specifies that vented kitchen "range hoods" (including "appliance range-hood combinations) provide a minimum of 100 cfm at a maximum sound rating of 3 sones as installed or based on testing at 0.25 inches of water.

HVI provides guidance on exhaust hood airflow rates expressed in units of cubic feet per minute of airflow (cfm) per linear foot (lf) of cooking appliance width [HVI, 2008]. Minimum flows are 40 cfm/lf when the appliance is against a wall and 50 cfm/lf for an island installation. Recommended flows are 100 cfm/lf against a wall, and 150 cfm/lf for an island. For a standard 30-inch wide range, these translate to 100 cfm minimum and 250 cfm recommended for a wall-backed installation and 125 cfm minimum, 375 cfm recommended for an island installation.

1.5. Measured airflow rates

Fugler [1989] conducted field inspections of kitchen exhaust fans in 17 houses that they visited across Canada and found that the actual exhaust airflow across 9 models found in the homes was on average only 31% of the rated values with a minimum of 14% and a maximum of 92%. Only 3 of the fans exceeded 50% of the rated flow. Nagda et al. (1989) similarly measured a flow rate of only 56% of the value rated on the range hood used in their Maryland test house.

Differences between installed and rated performance result from several factors. The first is that a hood airflow rating may be based on the performance specification of the fan alone (free air delivery) or based on a test in which the hood is operated without filters or ducts in line. Even when new and clean, these elements will reduce flow. As the filters get dirty with use, resistance to airflow will increase. Similarly, most hood installations contain a back draft flap that is forced open when the fan is operated; grease buildup on this flap can hamper its opening and further restrict flow. Pressure drops resulting from long duct runs, small diameter ducts and/or complex duct installations (e.g. with multiple elbows) can also impair performance.

1.6. Pollutant removal efficiency

Range hoods can reduce indoor pollutant concentrations through two mechanisms: (1) by removing some fraction of locally-emitted pollutants before they have a chance to mix into the bulk air of the room and be transported throughout the residence and (2) by increasing the air exchange rate of the kitchen in particular and of the entire residence overall. The first mechanism directly targets pollutants released from cooking, a cooking appliance, or any other source placed nearby to the hood or other exhaust fan, whereas the second can help mitigate any indoor-generated pollutant. Kitchen exhaust fans therefore can reduce both peak and time-averaged concentrations. Effectiveness, especially for removal of cooking-related pollutants, will be highest if the hood is started prior to, or no latter than the start of the emissions activity.

Revzan [1986] measured the effect of range hood use on room air concentrations in a two-room experimental facility in which sulfur hexafluoride (SF_6) was released from a heated source to simulate the dynamics of pollutants emitted from cooktop burners. Revzan calculated pollutant ventilation efficiency (PVE) as the reduction in well-mixed room air concentrations when using the hood, relative to those that would be expected for generic ventilation at the rate of hood airflow. In other words, Revzan's PVE metric specifically focuses on the first mechanism described above: the effect of exhausting pollutants close to the point of generation to reduce mixing into the bulk air of the room. When hood flow rates were varied from 36 to 216 $m^3 h^{-1}$

(corresponding to air exchange rates of 0.54 to 3.1 h^{-1}), PVE ranged from 16 to 77%. The hood flow rate also affected the degree of mixing between the rooms, which were connected by an open door. At most flow rates studied, SF_6 concentrations measured in the center of the two rooms were comparable. At the highest flow rate, SF_6 concentrations in the room containing the source and range hood were substantially higher than in the second room. This suggests that hood operation can reduce pollutant exposures throughout a residence, but that the largest reduction in exposure may occur in the kitchen.

Nagda et al. (1989) reported that the range hood tested in their research house could reduce peak concentrations of combustion products by about 50% provided the fan was turned on at the beginning of the cooking episode. Traynor et al. (1982) found removal rates from 60% to 87% using hood flow rates ranging from about 150 to 420 $m^3\ h^{-1}$.

Li and Delsante [1996] and others have used the term "capture efficiency" to describe the fraction of generated pollutants that are pulled directly into the range hood before mixing into room air. Equations to calculate capture efficiency as a function of room air and hood exhaust concentrations were derived for steady-state conditions of emissions, ventilation and range hood flow. Li et al. [1997] demonstrated that theoretical capture efficiency is related to the ratio of exhaust system airflow to the volumetric airflow of the thermal plume rising from the cooking appliance.

Combined, the research indicates that although range hoods can be effective in removing some portion of combustion products from gas cooking, the fraction removed is typically below 75%.

1.7. Energy efficiency

The industry standard energy efficiency metric for range hoods is the one used for most air moving equipment, namely the ratio of volumetric air movement (in the U.S. typically expressed as $ft^3\ min^{-1}$ or cfm) to power consumption (typically in units of Watts). This metric is described as fan efficacy and is presented either as W/cfm or cfm/W. It is important to note that this metric should be determined for conditions relevant to actual appliance use and not for fan free air delivery. The actual installed efficiency will vary by installation.

Fan efficacy ratings are not readily available for many cooking exhaust appliances. The Home Ventilating Institute (HVI 2010) provides airflow ratings but does not always provide power consumption for the fans listed in their catalog. In some cases power consumption information is provided in product literature.

The Energy Star® rating (ww.energystar.gov) is granted to kitchen range hoods that meet the following performance requirements, as certified by test procedures of HVI or the Air Movement and Control Association (www.amca.org):

- Maximum airflow of 500 cfm
- Minimum efficacy of 2.8 cfm/W
- Maximum sound level of 2.0 sones

Though characterized as applying to "range hoods" the standard describes the units in a manner that would include downdraft exhaust systems. This standard has been in place since 2001.

Considering the ultimate objective of pollutant removal, an evaluation could be made of the overall energy efficiency of the cooking exhaust system. Narrowly, this could be calculated as the product of pollutant removal efficiency and fan efficacy. More broadly and inclusively, it could include energy required for thermal conditioning of the additional ventilation air. This essentially expands the system being considered to the level of the residence. At that level, the energy used to remove pollutants via the cooking exhaust fan also could logically be compared to the energy that would be required to achieve the same pollutant levels (same indoor air quality) by increasing the air exchange rate of the residence. For the same amount of pollutant removal, almost all cooking exhaust fans will be more efficient than increasing overall air exchange rates.

1.8. Noise

Acoustic noise that is generated by operation of the range hood is an important attribute that determines the device's acceptability and usability. Excessive noise reduces the likelihood that the ventilation system will be operated. As discussed above two survey studies reported that the main reason for not using the range hood was acoustic noise (Nagda et al, 1989; Parrott et al., 2003).

Acoustic noise from range hoods is evaluated in the laboratory using sound pressure measurements in a standard test [*HVI*, 2009]. The standard metric of noise for residential fans is the Sone, a measure of perceived loudness. Environmental measurements are typically measured in A-weighted decibels or dB(A). The doubling of a Sone level is set to be equal to doubling of perceived sound level; this corresponds to an increase in sound level of 10 dB and increasing the sound pressure by $10^{0.5}$.

Fugler (1989) tested sound levels of 17 hoods in the field with manufacturer's Sone ratings from 5 to 7. Field measured sound levels of 62–71 dB(A) were observed with the hood fan on (measurements with the fans off ranged from 20–54 dB(A)).

2.0 Methods

2.1. Overview

The overall goal of this task was to evaluate the effectiveness of cooking exhaust fans as an-exposure mitigation measure in light of possible increases to emissions resulting from fuel variability. Test procedures were designed to study installed range hoods and downdraft ventilation systems under realistic conditions that exist in residences. Experiments focused on quantifying metrics of direct relevance to pollutant removal – including exhaust airflow rate and pollutant removal efficiency – and noise levels during hood use as these may directly impact the likelihood of use. The data obtained in this study can be used to evaluate the potential for externally venting exhaust fans to mitigate exposures to cooking related pollutant emissions, including any increase in pollutant emissions associated with liquefied natural gas use. Detailed descriptions of the methods are provided below.

2.2. Sample selection

Cooking exhaust fan performance was evaluated for an opportunity sample of 15 installed systems that varied in key characteristics. The identification of systems suitable for inclusion in the study was accomplished through inquiries to colleagues and associates. The objective was to capture variations in key parameters such as basic design (downdraft, systems with flat profile above the stove air inlets, and systems using capture hoods), rated airflow, initial price and installation (height; island or wall mount). Summary identifying information is provided in Table 1. Performance and installation specifications and characteristics are provided in Table 2. Both of these tables are presented in the Results section.

2.3. Device and installation characteristics

The make and model number were recorded for each exhaust system. Physical characteristics were recorded on site and performance specifications were obtained for each system from information provided on the nameplate labels attached to the devices and from online product documentation. These included the following: rated or nominal airflow (typically in units of cubic feet per minute), sound rating (sones), rated power or current (watts or amps); and recommended installation height above cooktop (range or maximum, inches).

Characteristics of the installation were observed and documented at the site. These included the following: vertical distance from cooktop surface to bottom of range hood; orientation of exhaust inlet to cooktop surface (downdraft or hood); for systems above the cooktop (range hoods), approximate area of cooktop surface covered by the entire profile of the hood; estimated length and course of ducting from fan to outlet; and soiling of any grease filters. Photographs of each installation are included in the appendix. Several characteristics of the cooking appliance were also recorded for their relevance to the exhaust fan installation. These included firing rates of each cooktop and oven burner (Btu/h) and location of oven vent in relation to exhaust system inlet.

2.4. Airflow rate measurements

Airflow rates were measured using two approaches. Preliminary experiments used a tracer release method that quantifies airflow rate based on measured concentration of the tracer in the exhaust flow. Most of the field measurements were obtained with a calibrated powered-flow hood method. Both are described below. With each method, the fan was operated through all settings, starting with the highest then stepping through to lower settings. The fan was not turned off between experiments.

2.4.1. Tracer method

For the first three systems evaluated (F3, B2, H2), airflow was quantified by a tracer release and measurement approach. (Hood H2 was additionally evaluated with the powered blower method described in the next section.) Sulfur hexafluoride (SF_6) was released at a constant rate into the exhaust intake and concentrations were measured in the downstream exhaust flow. Care was taken to ensure that all of the released SF_6 entered the exhaust flow. With negligible SF_6 in the kitchen air (confirmed through measurements), the volumetric SF_6 emission rate S_{tracer} (mL h^{-1}) and the concentration measured in the downstream exhaust flow C_{tracer} (ppm or mL m^{-3}) were used to calculate the exhaust airflow rate Q_{air} (m^3 h^{-1}) as shown below in Equation 1.

$$Q_{air} = S_{tracer} / C_{tracer} \quad (1)$$

The tracer method for measuring airflows was implemented as follows. Pure and dilute mixtures of SF_6 were conveyed to the study residence in multilayer leak-checked gas-tight bags. Pure SF_6 was used for the release as described above and the dilute mixtures were used to calibrate the analyzer used to measure SF_6 concentrations in the downstream exhaust. Pure SF_6 was transferred from the storage bag to the release point with a peristaltic positive displacement pump at roughly 12 mL min^{-1}. The precise flow rate was measured using a volumetric flow primary standard (bubble flow meter or Gilian Gilibrator 2 by Sensidyne). This flow rate typically was measured both before and throughout the release. The release point was typically very close to the fan inlet, above any grease screens. The dilute SF_6 mixtures were drawn directly from certified standards or created by mixing certified standards (using a gas divider) to concentrations of 0.185, 1.02 and 6.06 ppm. The concentration of SF_6 was measured in the exhaust stream and in the kitchen air using a Bruel & Kjaer 1302 photoacoustic infrared analyzer. The analyzer was calibrated at each site with the dilute mixtures noted above and either pure nitrogen or ultrapure air used as a zero-check.

During airflow measurements the analyzer drew sample air from a location in the exhaust stream that was as far from the inlet as could be achieved. For F3, this location was approximately 2 m above the top of the hood along a straight duct run to the roof; the discharge was roughly 1.5 m above the sample location. Exhaust fan B2 had a duct that extended up for roughly 1 m, followed by a roughly 90 degree bend then a straight run across several meters to an sidewall discharge. Sampling first occurred just before the bend but the sample probe was moved to the discharge where a more steady and consistent reading was achieved. H2 discharged to a back wall behind the hood. Despite the short duct run for this installation, thorough mixing at the sample point was confirmed by repeated sampling at varying locations in the discharge.

2.4.2. Balanced flow hood method

The flow hood method is described in detail by Walker et al. [2001]. The method uses a calibrated and pressure-controlled variable-speed fan (Minneapolis Duct Blaster, Energy Conservatory, www.energyconservatory.com). The Duct Blaster was connected to either the exhaust inlet (preferred approach) or outlet using a customized connector that was fabricated / adapted at each site using cardboard and tape. Using the 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 vs. flow relationship of the Duct Blaster provides the flow through the exhaust fan.

2.4.3. Exhaust duct leakage

The possibility of duct leaks downstream of the fan causing uncontrolled dilution of combustion gases was considered and deemed to not be a likely cause of any bias. When the hood fan is operating, the duct region extending from downstream of the fan to the outside will be at positive pressure. Under this condition any duct leaks would be expected to push exhaust air out of the duct, not into the duct. Under very atypical pressure and flow conditions it may be possible for very small holes in a duct to allow small flow-driven leaks into the system. In all cases, these leaks would by their very nature be small compared with the total flow in the duct, and would not cause an error large enough to be of concern. If the duct leaks are from large holes, no flow-induced entrainment can occur and any leaks will be outward. In no case is a significant dilution from duct leaks expected to occur when the fan is on. Outward leakage would present a problem only if substantial leakage would occur before the exhaust airstream becomes well mixed.

2.5. Sound levels

As it was not possible to conduct the industry standard laboratory-based acoustic test in the field, acoustic field sampling aimed to measured sound levels that could be related to those generally accepted for health and comfort in the residential environment was used.

Sound levels were measured for each fan setting on each system. A-weighted sound levels (dB-A) were measured using an Extech 407736 digital sound level meter. Measurements were made at a standard position in front of the range/oven and at another location likely to be occupied in the kitchen (e.g., at kitchen table or at another food preparation area). The front of range position was 60 inches above the kitchen floor and 12 inches from the front of the range. Sound levels at both locations were measured under background conditions and for the full range of fan settings. Background sound levels were measured with the exhaust fan off and without experimental equipment operating. For some exhaust fans, the sound measurements were made subsequent to airflow and capture efficiency experiments.

2.6. Pollutant removal efficiency

2.6.1. Calculation of capture efficiency

Evaluation of pollutant removal efficiency in actual residences requires a different technique than those used in controlled experimental rooms. Approaches described in the literature (e.g., Revzan, 1986; Li and Delsante, 1996) require a defined well-mixed space of known volume in which concentrations can be measured. In many residences, the kitchen is open to adjoining rooms in a way that precludes sealing it off to establish a well-mixed air volume. Even when an approximately well-mixed volume can be established, approaches that depend on achieving steady-state conditions (e.g. Li and Delsante, 1996) are not suitable for field research in which access to the site is time-limited. In addition, the process whereby one achieves a well-mixed condition, using fans in the space, may bias the results due to altering the local airflows in the vicinity of the exhaust.

In this study, pollutant removal was evaluated with two variations of the steady-state capture efficiency concept: contemporaneous capture efficiency (CCE) and single-pass capture efficiency (SPCE). Single-pass capture efficiency is defined as the potentially time-varying fraction of the pollutant mass emitted from the cooking appliance (range top or oven) that is drawn directly into the exhaust system, i.e., before mixing with the bulk room air. Contemporaneous capture efficiency includes the additional removal of some of the pollutant mass that has mixed into the room air; this is described below.

Both capture efficiency metrics were calculated by considering a mass balance on exhaust gas constituent (P) emitted by the cooking appliance. The concentration of P in the exhaust, $C_{P,h}(t)$ (ppm or mL m^{-3}), can be measured directly and related to other parameters using the mass balance shown below:

$$Q_h \, [C_{P,h}(t) - C_{P,r}(t)] = \eta_D(t) \, E_p \qquad (2)$$

Here Q_h (m^3 min^{-1}) is the airflow rate through the exhaust system; $C_{P,r}(t)$ (mL m^{-3}, or ppm) is the concentration of P in the room air entering the diluted burner exhaust plume; $\eta_D(t)$ is the time-dependent capture efficiency; and E_P (mL min^{-1}) is emission rate of P. The use of a time-varying room air concentration allows for an increase in this value resulting from emitted mass that is not captured on the first pass.

In the experiments conducted for this study, CO_2 was used as the marker for combustion related pollutants. The CO_2 mass emission rate was calculated based on combustion stoichiometry assuming complete combustion, fuel composition and fuel use rates, as described below. The production rate of CO_2 (E_{CO2}) was calculated as follows:

$$E_{CO2} = Q_{fuel} N \tag{3}$$

In this equation, E_{CO2} is the emission rate of CO_2 (mL h^{-1}), Q_{fuel} is the fuel flow rate (mL h^{-1}), and N is the molar fraction of carbon in the fuel (mol C per mol fuel), based on fuel composition. The fuel flow rate for each configuration of burners was checked using the home gas meter – taking care to subtract baseline fuel use for pilot lights, etc. – and when the information was available checked for consistency against the burner firing rates shown on the cooking appliance label. A fixed value of N = 1.0246 was used for all experiments. This value was calculated for a fuel composition of 95% methane, 3% ethane, 0.2% propane, 0.9% carbon dioxide and 0.9% nitrogen; this fuel has a higher heating value of 1022 Btu/scf. For additional details, refer to Singer et al. [2009].

2.6.2. Measurement of CO_2 for capture efficiency calculations

The concentration of CO_2 in the exhaust stream was measured with an EGM-4 infrared analyzer (PP Systems, ppsystems.com) that sampled either from the exhaust discharge or at a point as far downstream from the exhaust inlet as could be achieved. Specific sampling locations for each exhaust system are noted in the appendix. The analyzer has a rated accuracy of better than 1% of the span concentration over the calibrated range. The instrument has an automated zero check. The span calibration was checked at each experimental site with a verified standard mixture of 2532 ppm CO_2.

The concentration of CO_2 in room air ($C_{P,r}$ in Equation 2) was determined from measurements in the exhaust air before and just after each burner firing. Airflow rates were determined as described in the previous section. With all other parameters in Equation 2 either measured directly or calculated from other measurements, the capture efficiency η_D was calculated.

The difference between single-pass and contemporaneous capture efficiency is illustrated in Figure 1, which shows data for exhaust system H1. The points are CO_2 concentrations measured in the exhaust duct and recorded every 2 seconds. The bottom of the red wedge is the CO_2 concentration at the start of burner operation; the concentration measured at this time characterizes the room air entering the hood before CO_2 is added from combustion. The CO_2 concentration rises sharply as much of the exhaust plume is captured by the exhaust system. The point at the top of the right side of the wedge characterizes room air entering the hood after burner operation has ceased. At this time, the air entering the exhaust system – now the background room air – has a slightly higher concentration of CO_2 compared with the pre-experiment condition. Excluding the wedge provides a calculation for single-pass capture efficiency; inclusion of the wedge provides contemporaneous capture efficiency (CCE).

Calculated values of SPCE and CCE were generally very close to one another; they diverged as the capture efficiency decreased and room air concentrations of CO_2 increased over the course of an experiment.

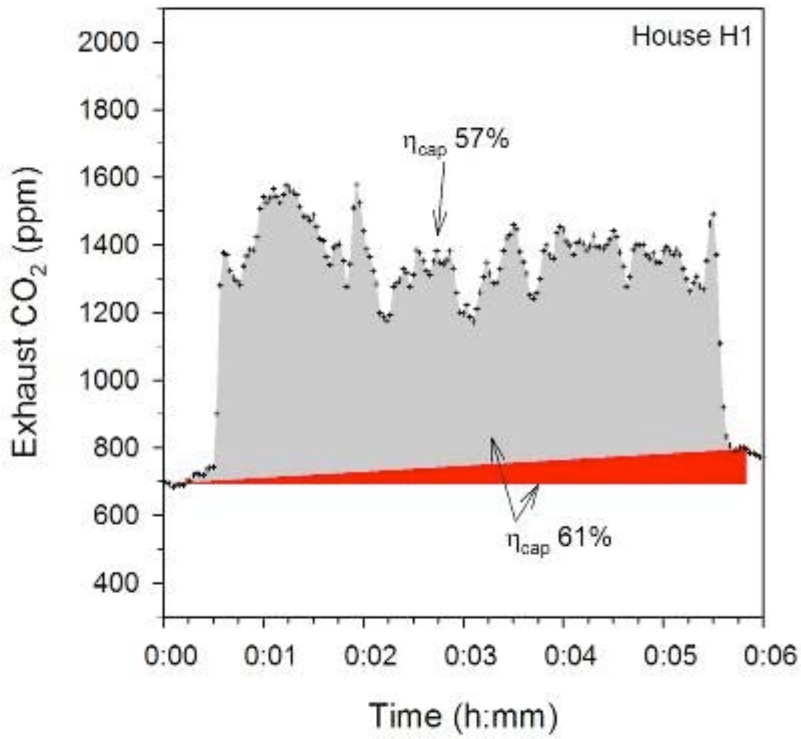

Figure 1. Example of carbon dioxide levels in exhaust air and calculation of capture efficiency.

2.7. Implementation of experimental protocols at field sites

2.7.1. Most experiments conducted on equipment as found

In all but one case, airflow measurements and capture efficiency experiments were conducted on the exhaust systems as found, i.e. without cleaning or replacement of grease screens. Three of the systems had no inline grease screens by design, relying instead on impaction for grease collection. Of the systems containing grease screens, most were lightly soiled with loading rates that were not deemed to present a substantial impairment to airflow. For exhaust system F2 (a microwave exhaust fan), the grease screen was found with a thick mat of accumulated grease and dust. The field researcher assessed that data collected under these conditions may have been more reflective of soiling than equipment and configuration, and thus would not provide data to compare the performance of F2 to other exhaust systems. The grease screen for this system was cleaned by the researcher using dish soap and hot water and replaced in the hood.

2.7.2. Order of data collection

In all cases, airflow measurements were made prior to capture efficiency experiments. This allowed time for the CO_2 analyzer to warm up prior to use. Sound measurements were collected either prior to the start or following completion of airflow and capture efficiency experiments.

2.7.3. Protocols for capture efficiency experiments

For each system, capture efficiency experiments were conducted for a variety of burner combinations and exhaust fan settings.

All cooktop experiments were conducted with a 9-inch diameter, 5-L stainless steel pot filled with 3-4 L of room temperature water placed on each burner that was being used. The pots had been previously used to conduct emission experiments on cooktops as described in Singer et al. (2009). Pots were utilized to incorporate the effect of a physical barrier on plume spread above the flame and the temporal effect of heat removal on plume momentum. Between experiments, pots were cooled back to or slightly above room temperature by exchanging water and through rotation. The oven was set to a temperature of 450 F to ensure that the burner would remain on for the duration of the experiment. Each experiment included at least 5 min of burner operation.

Capture efficiency experiments were conducted first at the highest fan setting then at decreasing fan settings. The intent was to minimize the buildup of background CO_2 in the room air resulting from incomplete capture. If background concentrations were observed to increase, experiments were delayed and efforts were made to promote air exchange with other rooms and outdoors. These efforts excluded the use of mixing fans or windows that through proximity could directly impact flow between burners and the exhaust system inlet. The fan generally remained on throughout the experiments.

Experiments were conducted with one of four burner configurations: oven only, single front cooktop burner, single rear cooktop burner, combination of one front and one rear cooktop burner. In almost all cases, the two-cooktop burners were diagonally opposed. In most cases, all four of these configurations were evaluated at both the lowest and highest fan settings and at least one configuration was duplicated. A limited set of configurations was evaluated at intermediate fan settings. The appendix includes a series of tables that list the order of experimental configurations (burner and fan settings) evaluated on each exhaust system.

2.7.4. Effect of airflow around cooktop

In most experiments, there was an attempt to minimize external (other than the exhaust fan) drivers of airflow in the vicinity of the cooking appliance. Adjacent windows were closed and almost all experiments were conducted without any actual or simulated human presence or activity nearby to the cooktop. In a few experiments, the field researcher explored the effect of human activity by walking up to the cooktop once per minute, standing and stirring the pot of water for 30 seconds, then walking away. Experiments including this activity are noted in appendix tables.

3.0 Results and Discussion

3.1. Exhaust fans evaluated

Figures 2-7 present photographs showing the installed exhaust devices evaluated in this study. Following these photographs are tables that provide summary information including hood make, model and performance specifications. The systems are organized by design and within each design, by the measured maximum airflow.

The sample includes 3 units (D1-D2, F2) installed at the time of construction, 6 units (H1-H2, B3-B6) installed at the time of a major kitchen remodel, 2 units (F1, B2) installed by the current homeowners to replace a previously installed device, and 4 units (F3-F5, B1) installed by current homeowners into a kitchen that did not have a venting hood installed at the time.

3.1.1. System designs

The evaluated systems are divided into 4 basic design categories. The most substantial distinction is between downdraft and above the range systems. Above the range devices are subdivided into units that feature a true capture hood (identified as B1-B6), devices that provide minimal or no capture volume (identified as F1-F5) and "hybrid" devices with a substantial capture volume above grease screens that cover the bottom inlet (H1-H2). The grease screens at the bottom of the hybrid units can present a non-negligible impediment to vertical airflow when clean and have the potential to significantly impede airflow when coated with grease and dust. The same impediment can occur at the air inlets of "B" units, which also are covered with grease screens. Devices F1-F2 are combination exhaust fan and microwave appliances, commonly referred to as microwave over range (MOR) units. Devices D1 and D2 are variations of the same basic design and nameplate. Exhaust fans F3-F5 are the same basic equipment. Readers should note that for marketing purposes, cooking exhaust systems are organized into the following categories: under-cabinet (largest and broadest category); microwave exhaust combination units (typically marketed as microwaves but designed for under-cabinet installation); chimney – wall; and chimney – island. The tested devices are mapped to this organization in Table 1 below.

Figure 2. Rear downdraft exhaust systems D1 and D2.

Figure 3. Microwave over range exhaust systems F1 and F2.

Figure 4. Flat-profile exhaust systems F3-F5.

These are three installations of same model. Right panel (F5) shows aperture covered by grease screens; recirculation air is provided at strip just forward of lights.

Figure 5. Exhaust hoods with grease screens across bottom opening, H1-H2.

Figure 6. Exhaust systems with open capture hoods B1-B3.

Figure 7. Exhaust systems with open capture hoods B4-B6.

Table 1. Description of exhaust systems evaluated in this study.

ID	Nameplate make	Model	Design category	Installation notes	Width (in.)	Depth (in.)	Cooktop width (in.)
D1	Thermador	RDDS30	Downdraft	Behind rear burners	30	n/a	30
D2	Dacor	RV30/CABP3	Downdraft	Behind rear burners	30	n/a	30
F1	Kenmore	721.636523	Microwave over range	Between cabinets	30	13	30
F2	GE	JVM1850	Microwave over range	Between cabinets	30	13	30
F3	Broan	Allure QS2	Under cabinet	Wall, no cabinets	36	20	39
F4	Broan	Allure QS2	Under cabinet	Cabinet on one side	30	20	30
F5	Broan	Allure QS2	Under cabinet	Between cabinet, refrigerator	30	20	30
H1	Kobe	RA9430SQB	Wall chimney	Wall, space to cabinets	30	20.5	30
H2	Bosch	DAH93	Under cabinet	Between cabinets	30	22	30
B1	Broan	42,000F	Under cabinet	Between cabinet, open aisle	30	17.5	30
B2	Dacor	IVS1	Under cabinet	Between cabinets	42	16.5	36
B3	Vent-A-Hood	PYD-18	Island chimney	Island	48	27	36
B4	Kenmore	233.5234059	Under cabinet	Between cabinets	30	20	30
B5	Vent-A-Hood	NP9-236	Under cabinet	Between cabinets	36	20.5	36
B6	Vent-A-Hood	PYD-18	Inland chimney	Island	42	27	34

3.1.2. Characteristics of exhaust devices and installations

Table 2 below provides additional information about the evaluated systems. The evaluated units spanned a wide range of prices and nominal airflows. The sample included one low cost hood (B1) and two microwave over-the-range (OTR) units that represent the lower quality exhaust devices present in many existing homes and installed in many new homes. While the total cost of the microwave OTR units is listed as $300, it is important to note that this cost includes a microwave oven; the exhaust fan component of this appliance typically is of low quality. The nominal airflows for these microwave OTR units were not certified by HVI. The sample included several high-end units (estimated cost >$800) including the two downdraft systems, the stainless steel against the wall chimney hood H1, the island chimney units B3 and B6 and the wide, high nominal flow units B2 and B5. While these units all had nominal airflows of 550 cfm or above, none were HVI rated. Units B3, B5 and B6 all contain the same fan unit (described as B-200 dual blower unit in product literature).

Table 2. Characteristics of cooking exhaust fans evaluated in this study.

Device Characteristics (NA = not available; NR = not relevant)								Installation	
ID	Age (y)	Est. Cost [a]	Nominal airflow (cfm) [b]	Number of fan settings	Sound (sones) [b]	Rated power (W) [b]	Rec. height (in) [b]	Installed Height (in)	Coverage [c]
Downdraft									
D1	10	$1,350	600 [d]	4	NA	NA	NR	NR	NR
D2	15+	$1,350	600 [d]	3	NA	460	NR	NR	NR
Flat (No capture hood)									
F1	4	$250	300 [d]	5	NA	NA	>14	22.5	<50%
F2	4	$250	300 [d]	5	NA	NA	>14	19	50-75%
F3	9	$275	250	3	3.5	228	16-23	39	50-75%
F4	6	$275	250	3	3.5	228	16-23	25	<50%
F5	5	$275	250	3	3.5	228	16-23	27	>75%
Hybrid (Capture volume above bottom grease screens)									
H1	3	$825	760 [d]	4	4.5	215	27-30	32	>75%
H2	5	$450	360	3	NA	528	30-36	30	>75%
Open (Bowl)									
B1	15+	$75	190	2	6	300	18-24	23	50-75%
B2	15	$950	600 [d]	Variable [e]	NA	410	25	24	>75%
B3	6	$2,900	550 [d]	1	6	333	30	27	>75%
B4	8	$300	360	Variable [e]	5.5	540	13-21	27.25	>75%
B5	3	$1,250	550 [d]	2	6.5	333	27	27	>75%
B6	6	$2,900	550 [d]	1	6	333	30	25.75	50-75%

[a] Estimated retail prices based on review of web-based retailers conducted in late 2009.
[b] Nominal (maximum) airflow, rated apparent power (watts = voltage * amps), sound rating and recommended installation height (inches) based on product literature.
[c] Fraction of cooktop covered by range hood.
[d] NA = not available; NR = not relevant to product design.
[d] Fan free air delivery.
[e] Knob or control without any set levels.

Table 2 lists for each hood both the recommended and actual installation height above the cooktop. Most of the units were installed within or just slightly above the recommended ranges. The largest deviation between recommended and actual was observed for F3 (installed height of 39 in. compared with recommended range of 16-23 in.). It is interesting to note the variation in recommended installation height from the lowest range of B4 (13-21 in.) to the range of 30-36 in. specified for H2. In general, the larger open hoods (B3, B5, B6) and "hybrid" units with large collection hoods above the bottom grease screens allowed higher installations. A higher installation has less potential to interfere with cooking. Microwave-over-range units balance the objectives of mitigating obtrusiveness (e.g. through limited projection over front burners) and convenient access to the microwave (requiring that the appliance not be too high above the range).

Table 2 additionally provides information about the fraction of the cooktop covered by exhaust fans above the cooktop. Coverage exceeded 75% of the cooktop burner area for 7 of the units, was in the range of 50-75% for 4 units and was <50% for 2 installations. Interestingly, the sample includes examples of the same exhaust hood installed at similar heights but with very poor (F4) and very good (F5) coverage. Seven of the nine hoods and hybrid systems had coverage >75%. In all cases of incomplete coverage it was the front burners that were not completely under the device containing the exhaust fan.

3.2. Measured airflow and sound levels

Measured airflows at various fan settings are presented in Table 3. The actual airflow rates as well as the ratio of airflows across settings varied substantially across the units evaluated. The lowest cost exhaust fans – F1, F2 and B1 – had the lowest airflows. In general higher-cost units had higher airflows. However, the modestly priced F3-F5 and B4 (under $300) all had flows in the range of 230-250 cfm and H2 ($450) had among the highest airflows, moving about 150 cfm on low and about 360 cfm on high setting.

Table 3 also presents summary results for measured sound levels for 13 of the 15 installations. Background sound levels varied from 34 to 49 dB(A) at the cooktop location and from 33 to 44 at other kitchen locations. With fans on high speed, sound levels varied from 57 to 71 dB(A) at the front of the cooktop and from varied from 50-59 at other kitchen locations. Sound levels at kitchen locations away from the cooktop were lower than but closely correlated with sound levels at the cooktop.

Sound levels generally increased with fan setting and airflow for each fan but the relationship between airflow and sound varied across devices and installations. Comparing performance among devices of the same or similar design indicates the importance of installation. Whereas F1 and F2 had roughly similar increments in sound above background, absolute sound levels for F2 were substantially higher than F1. Despite similar background sound levels and similar actual airflow rates, F5 was substantially louder than F3 as installed. As a pair, F3 and F5 produced substantially less of a sound increment while moving much more air compared with F1 and F2. This model (of F3-F5) is compliant with ASHRAE 62.2 sound requirements and with an HVI rating of 0.9 sones at low speed and 3.5 sones on high speed is considered to have good, but not the best available sound performance. The sound versus airflow performance of D2 was roughly similar to F3 even though this device is not rated for sound. Consistent with its poor sound rating (high sones) the economy hood B1 was relatively loud despite producing only a fraction of the airflow of other fans; this fan was very loud while moving very little air at the low speed fan setting. B2-B4 had similar sound performance to each other with some variation in airflow. Despite similar background and air movement, B5 at low setting was substantially louder than F3 at high setting. At high setting, this unit was much louder despite producing much lower airflow compared with B6.

Table 3. Measured airflows and sound at various fan settings.

Hood ID	Measured airflow (cfm)[a]			Measured sound (dBA)[a] At front of cooktop				Other kitchen location			
	Low	Med	High	Off	Low	Med	High	Off	Low	Med	High
D1	213	233	242	45	64	66	67	45	55	57	58
D2	NM	255	289	36	NM	55	58	36	NM	48	50
F1	29	56	85	43	51	56	61	43	49	49	53
F2	73	91	96	49	63	66	66	39	50	54	53
F3	50	157	229	36	40	47	57	37	38	45	54
F4	85	NM	246	NM	NM	NM	NM	NM	NM	NM	NM
F5	88	164	248	34	42	53	63	33	40	47	57
H1	180	200	225	42	62	64	67	42	53	54	57
H2	152	235	361	44	53	56	66	44	45	48	59
B1	45	NA	74	45	73	NA	65	42	56	NA	58
B2	159	165	181	43	71	69	68	43	58	59	59
B3	NA	NA	223	42	NA	NA	67	41	NA	NA	54
B4	88	205	254	41	45	60	65	43	45	54	59
B5	255	NA	314	37	67	NA	71	37	55	NA	58
B6	NA	NA	382	34	NA	NA	62	35	NA	NA	57

[a] Values shown are means of all measurements recorded. For devices with more than 3 settings, airflow and sound were measured at highest, lowest and one intermediate setting. For fans with fewer than 3 settings, some entries are not applicable (NA). Airflow not measured (NM) for lowest setting of D2 and for medium setting of F4. Sound levels not measured for F4.

Presented below in Table 4 are the nominal maximum airflows from product nameplate or literature, the ratio of the measured to nominal maximum airflow, and whether or not the nominal airflow is HVI rated. The HVI rated airflows are measured at 0.1 inches of water static pressure whereas the non-rated values may be based on free air delivery (no static pressure) of the unit or of a component fan.

Four of the six HVI-rated units (representing two models, as F3-F5 are all the same model) had maximum airflows within 90% of the nominal values with a fourth at 71% and only one unit below 50%. The lowest performing of the HVI-rated systems was an older (>15 years) economy hood (B1). The discrepancy between actual and rated could result because the pressure drop in the duct system is much larger than the 0.1 inches of water specified for HVI ratings. Of the nine units that were not HVI-rated, only two had maximum airflows that were greater than 50% of the nominal values and both of these were high-end products costing above $1000. Whereas the low airflow performance values for the fans on F1-F2 are consistent with their low cost, the substantially more expensive B2 and B3 had similarly poor performance relative to the expected (nominal) values. The nominal airflows noted for D1 and D2 were taken from the product literature for the fans installed in these units; this value appears to represent fan free-air delivery and does not even account for the pressure drop that results when the fan is installed into the downdraft appliance.

Table 4. Airflow performance and efficacy at various fan settings.

Hood ID	Nominal airflow (High)	Measured airflow (cfm)[a] Low	Med	High	Ratio of measured to nominal High	HVI rated	Fan efficacy: measured flow / rated power (cfm/W)
D1	600	213	233	242	40%	No	NA
D2	600	NM	255	289	48%	No	0.6
F1	300	29	56	85	28%	No	NA
F2	300	73	91	96	32%	No	NA
F3	**250**	**50**	**157**	**229**	**92%**	**Yes**	1.0
F4	**250**	**85**	**NM**	**246**	**99%**	**Yes**	1.1
F5	**250**	**88**	**164**	**248**	**99%**	**Yes**	1.1
H1	760	180	200	225	30%	No	1.0
H2	**360**	**152**	**235**	**361**	**100%**	**Yes**	0.7
B1	**190**	**45**	**NA**	**74**	**39%**	**Yes**	0.2
B2	600	159	165	181	30%	No	0.4
B3	550	NA	NA	223	40%	No	0.7
B4	**360**	**88**	**205**	**254**	**71%**	**Yes**	0.5
B5	550	255	NA	314	57%	No	0.9
B6	550	NA	NA	382	69%	No	1.1

[a] Values shown are means of all measurements recorded. For devices with more than 3 settings, airflow was measured at highest, lowest and one intermediate setting. For fans with less than 3 settings, some table cells are not applicable (NA). Airflow not measured for low setting of D2 and medium setting of F4.

Table 4 presents results for fan efficacy based on measured maximum airflows and nominal power ratings, as available. These results should be regarded with caution as they combine a measurement of airflow under installed conditions and a power rating that may not be directly relevant to the measured condition. With these caveats, it may be noted that the calculated fan efficacy values are well below the Energy Star requirements.

3.3. Measured capture efficiencies

3.3.1. Overview of capture efficiency results

A complete record of conditions and results – including burner configurations, measured CO_2 concentrations (primary results) and calculated contemporaneous capture efficiencies – is presented in the appendix for all experiments. The capture efficiency results are summarized in Figure 8. In this figure, the data for each device is plotted above the device ID; as in previous tables, devices are grouped by basic design and ordered by measured airflow. The top panel of this figure displays the measured airflow rates across the available fan speed settings. Fan speeds are listed in order of lowest to highest available settings; if only one setting is available (e.g., single fan on-off switch), it is shown as a "1". Also shown in the top panel are HVI recommended and minimum airflows based on cooktop width and location [HVI, 2008]. In the lower panel, each plotted point represents results for a single experiment. Burner conditions are indicated by color and the fan setting is indicated by symbol shape; these shapes correspond to symbols and airflow values show in the top panel.

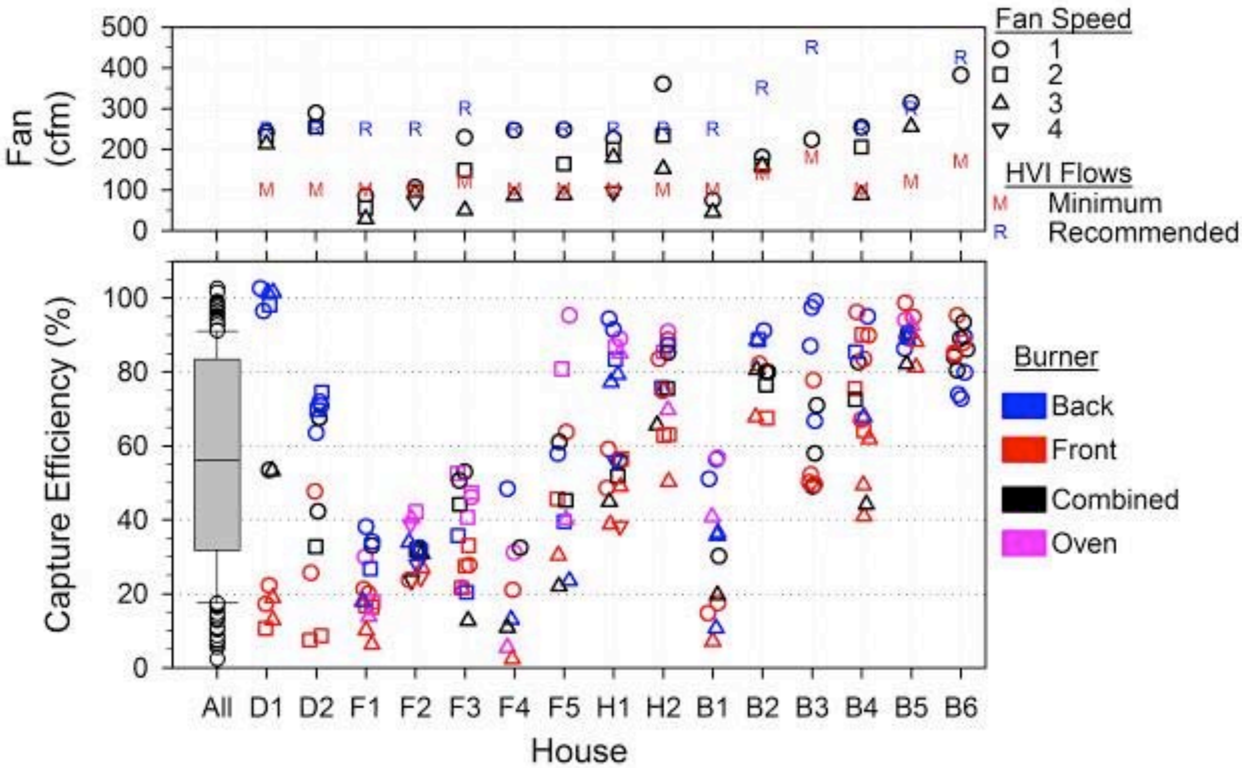

Figure 8. Summary results from capture efficiency experiments.

Overall these results indicate that cooking exhaust fan performance varies widely across models, installations and conditions. Across designs, the units with actual collection hoods (H and B series) generally performed better than the flat bottom (F) and downdraft systems. The microwave-over-range units F1-F2 were broadly ineffective with capture efficiencies at or below 40% across a wide range of operating conditions. Despite achieving maximum airflow rates roughly 230-250 cfm, the modestly priced F3-F5 had peak capture efficiencies of only 50-65% and efficiencies below 50% for many burner and fan setting combinations. Capture efficiencies were 40-100% for H1 and B4 and 50-100% for H2 and B3. Capture efficiencies exceeded 80% for B5 and 70% for B6 (both high-end units) across all assessed conditions. Among the H and B units, very poor performance was observed only for the economy unit B1.

For many of the devices, performance varied substantially across conditions. Downdraft unit D1 was very effective at removing cooking exhaust fumes from the back burners and ineffective for front burners. A similar though less pronounced trend was observed for downdraft unit D2. For most of the exhaust appliances installed above the cooktop (F, H and B series), capture efficiencies were highest for back burner (blue symbols) and oven (pink symbols) operation, and for the highest fan speed (circles). Effective capture of oven exhaust likely resulted from the oven exhaust being located near the rear part of the range. Consistent with these effects, the lowest capture efficiencies generally occurred for front burners (red) and lower flow rates (triangles).

As expected, fan setting had a substantial effect on capture efficiency for many of the units. While varying in the overall range of capture efficiencies, units F3-F5 all had much higher capture efficiencies at the highest fan setting (229-248 cfm) compared with low (50-88 cfm) or medium (157-164 cfm) fan settings. For example, unit F5 achieved capture efficiencies of 58-64% on high speed compared with 40-46% on medium and 22-30% on low speed for various cooktop burner configurations. Excluding experiments that included simulated cook movement, the moderately priced units H2 ($450) and B4 ($300) both achieved capture efficiencies exceeding 80% when operated on the highest fan setting for all cooktop experiments.

The importance of installation is demonstrated by the variability in results among F3, F4 and F5, three installations of the same basic equipment. The most effective of these was an under cabinet installation in which an adjacent refrigerator may have the effect of helping to direct airflow into the hood to improve capture efficiency.

Results indicate that meeting industry standard minimum airflow requirements is not sufficient to ensure consistently high capture efficiencies across usage conditions. For example, devices F2 through F5 each achieve the minimum guidance for airflow yet they still do not capture a high fraction of cooking burner exhaust.

3.3.2. Effect of cook movement in front of cooktop

Experiments to assess the impact of cook activity on capture efficiency were conducted at four of the fifteen field sites. The hypothesis is that the presence and movement of a cook standing in front of the cooktop may interfere with airflow fields and affect capture efficiency. T below provides summary list of these experiments along with results for experiments conducted with the same burner configuration and fan setting without simulated cook activity. These results indicate a small effect on capture efficiency for two of the four units on which experiments were conducted. Units B3 and B4 had lower capture efficiencies, on average, for experiments with simulated cook activity compared with the same burner and fan settings without the activity. We note, however, that the effect is small and within the variability observed for some replicates of the same conditions (see second row of B3 experiments below). Results for B1 and B6 suggest no overall effect of cook movement on capture efficiency for these installations.

While simulated cook activity affected the calculated capture efficiencies on only two of the four installations, the measured CO_2 concentrations in the exhaust stream suggest that the movement in front of the cooktop interfered with the temporal consistency of capture during experiments. Figure 9 below presents results for three experiments with unit B6; in the first two, there was no movement in front of the cooktop, in the rightmost experiment, the field researcher approached to open and stir each pot for a total of 30 seconds during each minute of the experiment. This plot indicates sharp temporal variations in the CO_2 concentration and thus the capture efficiency during this experiment. It should be noted that carbon dioxide is emitted (exhaled) by an adult human at a rate that is on the order of 10% or less than the emission rate for a single cooktop burner on high. Exhaled CO_2 from the researcher introduces a small bias that gives the appearance of slightly higher capture efficiency as it contributes to mass flow in the exhaust but is not counted in the mass emission in the denominator of the capture efficiency equation.

Table 5. Experiments examining impact of simulated cook activity on capture efficiency.

ID	Burner	Fan	Airflow	Exp ID		Measured capture efficiency	
			(cfm)	No cook	Simulated cook	No cook	Simulated cook
B1	LF	High	74	2	6	17%	15%
	LF	Low	45	10	12	7%	11%
B3	LR	High	223	1, 6	10	99, 97%	87%
	LF	High	223	4, 8	11	78, 50%	50%
B4	RF	High	254	1, 5	6	90, 83%	67%
	RF	Med	235	9	11	75%	64%
	RF	Low	88	13	15	49%	41%
B6	LR	High	382	3, 10	12	80, 74%	73%
	RF	High	382	6, 11	13	85, 85%	88%

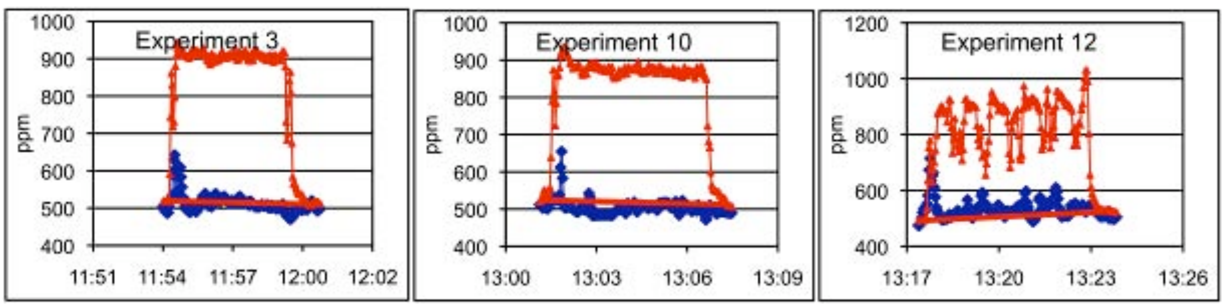

Figure 9. CO_2 concentrations in exhaust duct and kitchen air for unit B6.

The left rear burner was operated on full power in all experiments.
Experiment 12 featured simulated cooking activity.

3.4. Analysis: thermal plume airflow and capture efficiency

This section employs thermal plume dispersion theory to examine the interactive effects of exhaust airflow, exhaust fan height and exhaust system orientation relative to the burners. It uses the conceptual approach of Li et al. [1996] to examine the ratio of exhaust flow to plume airflow and the relationship of this ratio to capture efficiency.

Thermal plume theory predicts the size of an evolving plume over a fixed heat source. As the plume rises above the heat source it entrains surrounding air and increases in both horizontal spread and volumetric flow. Kosonen et al. [2006] present the following equation for plume airflow, Q_p:

$$Q_p = k \cdot \left(z + aD_h\right)^{5/3} \cdot \Phi_{conv}^{1/3} \tag{4}$$

The symbols in this equation represent the following parameters:

Q_p is the airflow in the convective plume above the cooking surface
k is an empirical coefficient
z is the height above the cooking surface
a locates the virtual source below the cooking surface
D_h is the hydraulic diameter of the cooking appliance
Φ_{conv} is the convective power, driven by heat generation at the burners.

This equation indicates that the volumetric airflow associated with the thermal plume increases with the burner rating (typically in Btu/h) raised to the 1/3, and increases with height above the plume raised to the 5/3. For a generic hood, Kosonen et al. suggest $k = 0.005$. For a gas burner, the virtual source parameter $a = 1.2$, and it is estimated that 40% of the fuel energy contributes to convective power.

Using this equation, we calculated the ratio of exhaust fan airflow to estimated plume airflow at the height of the exhaust system inlet. Logically, the exhaust volumetric airflow must be at least as large as the plume airflow to achieve a high percentage of capture.

In the figure below, the capture efficiency calculated for each experiment is plotted against the ratio of exhaust fan flow to plume flow. Data are grouped by the degree to which the exhaust system covered the burners used for the experiment. Coverage was considered "Full" if the burner was entirely underneath the projected area of the hood. Fair coverage was between 50 and 100%, and poor coverage was less than 50%. Thus, an exhaust hood that completely covered the two back burners and completely did not cover the front burners would be marked with full coverage for experiments with back burners only, fair coverage for experiments with one front and one back burner, and poor coverage for front burner only experiments.

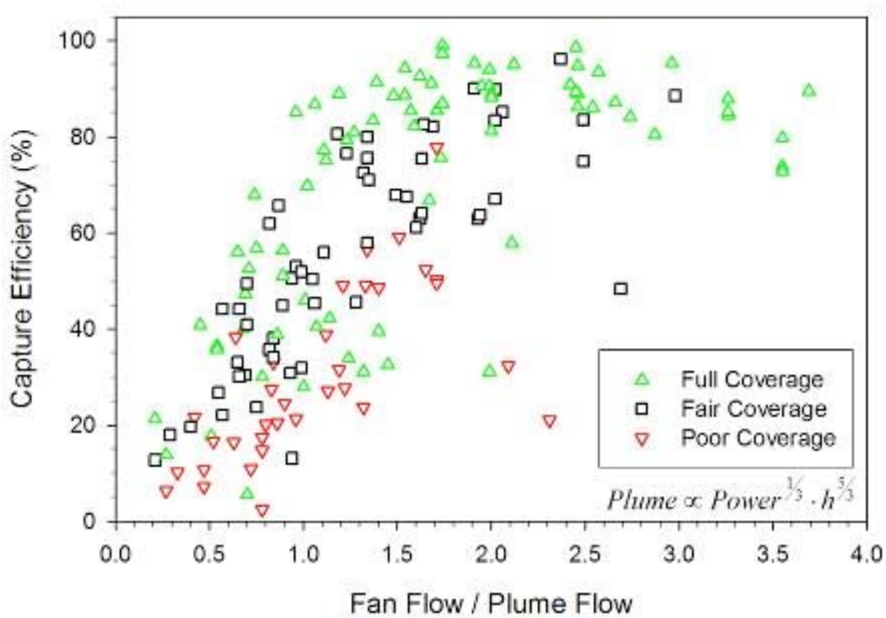

Figure 10. Ratio of measured fan flow to thermal plume flow at height of exhaust inlet.

This analysis and Figure 10 elucidate the impact of exhaust inlet height and fan flow rates. At low values of the fan to plume airflow, capture efficiency is very low. As exhaust airflow increases relative to plume flow, the capture efficiency tends to increase. When fan flow substantially exceeds plume flow (e.g. by a factor of 2), capture efficiency is consistently above 70%. This figure additionally affirms the importance of having the exhaust system installed to cover the cooktop burners. At a given value of the fan flow to plume flow ratio, capture efficiency is reduced for burners not covered by the exhaust hood.

There are a few additional points to consider in relation to this analysis. First, the functional relationship used for predicting the plume flow is semi-empirical. The actual parameters will be installation dependent. The use for this analysis of a single set of parameters for all installations is a suitable simplification that should not greatly impact the trends observed. Second, as shown in Equation 4, plume flow is dependent on burner power to the 1/3 power and dependent on installation height to the 5/3 power. The primary balance is therefore between height and fan power. Variations in heat release rates of residential cooking burners could cause large variations in the fan to plume flow ratio. For residential cooktops, individual burners can vary from about 5000 Btu/h for a small simmer burner (typically in the rear location for 4-burner cooktop or center location for a 5-burner cooktop) to 16000 Btu/h for a power burner, which is typically in the front. If the exhaust system adequately covers all burners, these variations may be accommodated by use of different fan settings if the overall fan flow is adequate.

This analysis extends the findings of Li et al. [1996] to installed physical devices. In that earlier study, the authors used computational fluid dynamics to quantify capture efficiency for the idealized configuration of a capture hood centered over a single heat source. The current analysis includes the effects of incomplete coverage, off-centered and in some cases multiple heat sources, variations in exhaust inlet geometry, etc.

3.5. Selection and use of cooking exhaust fans to mitigate exposures

The results presented above provide some insights about the potential for using exhaust fans to remove pollutants generated by natural gas cooking burners. Overall the results indicate that exhaust system performance can vary widely with equipment, installation and with specific conditions of use.

The limited results of this study suggest that designs that include a large capture hood and a robust fan that provides airflows at industry recommended levels (based on appliance width) are the most effective. While the most broadly effective hoods (B5 and B6) are prohibitively expensive for most building owners, the more moderately priced hoods H2 and B4 had high capture efficiencies under almost all conditions. The flat bottom under-cabinet model represented by F3-F5 (under $300) produced the advertized airflow but captured a relatively low fraction of emitted pollutants. The observed poor performance of this model is likely due in part to installation issues and partly related to the fundamental design, which does not extend over the front burners. The importance of installation is indicated by the widely varying results observed for F3, F4, and F5. Microwave over ranges performed especially poorly even though they were installed at recommended heights.

Another finding of this work is that capture efficiencies can vary substantially between front and back burners. For many of the under-cabinet and wall mount units, and certainly for the back mounted downdraft systems, capture efficiencies were much higher on back as compared with front burners. This is a largely intuitive result: capture is more efficient when the fan is over or adjacent (for downdraft) to the burners.

This research provides some findings to be considered by buyers and users of kitchen exhaust fans. For buyers, it is important to recognize that cooking exhaust systems are not all equally effective or appropriate to all installations. Some manufacturers advertize airflow rates that are in fact the fan free air delivery; airflow rates for the exhaust appliances will be much lower. Some manufacturers submit their appliances for airflow and sound performance certification using industry standard test procedures. Our results show that installed airflows may be below even certified values (likely because duct pressure drops are higher than the conditions in the industry standard test). When selecting a design, buyers should consider whether the hood can be installed at the site according to manufacturer recommendations and should consider whether the hood will cover most or all of the cooktop burners. The potential to achieve complete coverage may be limited since many of the available under-cabinet and wall mount hoods are not deep enough to cover front burners. This target is further complicated when the cooktop or stand-alone range is not flush against the back wall. Our results suggest – though do not conclusively establish – that models with actual collection volumes (hoods) are more effective than flat profile designs.

Users – including renters and those who cannot afford to purchase replacement units or alter installations – can operate available units to maximize effectiveness. Fans should be activated before burners are started and remain on beyond the end of cooking. Since most of the installed units are likely of the budget or modestly priced varieties tested here, most people should use the highest fan settings with a tolerable noise level. Switching from front to back burner cooking can in many cases improve capture and reduce pollutant exposures.

3.6. Recommendations for future work

The results of this study provide an important part of the data basis that is needed to assess the current and possible implications of kitchen exhaust fan use on energy, indoor air quality and public health in California.

Three groups of research and analysis activities are required to advance these goals:

- Additional research to identify and understand the key factors affecting installed performance.
- Characterize current stock of installed exhaust fans and usage patterns.
- Analyze energy and IAQ implications of exhaust fan use for current stock and potential benefits of improving fan energy and capture efficiency.

While the current study provides a valuable data set to assist in this objective, a more extensive set of controlled experiments are needed to explore some of the factors that impact capture efficiency. For example, laboratory experiments could facilitate assessment of effect of installation location (height, coverage), airflow, and downstream pressure drops (from ductwork) on capture efficiency for various hood designs.

There are several important research needs related to stock characterization. The first task is to characterize (e.g., by analysis of existing or collection of new data) the distribution of basic equipment designs and quality in existing and new California homes. A second task is to obtain information on the pressure drop in installed exhaust fan ductwork. Finally, there is a need for additional performance data for exhaust fans and ductwork installed in current and recently new homes, and for measurements of power consumption and fan efficacy in installed units.

Quantification of the impacts of improving fan and capture efficiency and exhaust fan use can be achieved – at least conceptually – through three types of analyses. The initial analysis should seek to quantify energy and indoor air quality (pollutant concentrations) associated with the current equipment stock and use patterns. A second analysis would examine the energy and indoor air quality ramifications of widespread use (as recommended) of currently installed equipment. This scenario likely would result in a higher energy consumption and greatly improved indoor air quality. The third and final analysis would consider energy and indoor air quality implications of improved hood designs along with universal usage.

Perhaps most importantly, research is also needed to guide efforts to increase use of range hoods. The literature summarized in the Introduction indicates reasons that hoods are not used, yet we identified no research focused on actually increasing use. Elements that should help are education about the hazards associated with pollutants generated in natural gas flames and from cooking (food preparation), and reducing the noise associated with exhaust fan operation. The potential benefits of such measures should be explored and quantified.

4.0 Summary and Conclusions

This study provides an important updating of data about the performance of installed cooking exhaust systems. Assessments were conducted on fifteen installed exhaust appliances; the units spanned a wide range of prices and included various common designs. Performance was assessed based on actual airflows, comparison of actual to advertized airflows, sound performance, and capture efficiency of pollutants generated by the natural gas cooktop and oven burners.

The sample of exhaust systems varied in price, design and performance specifications. The tested systems range in purchase costs (for the exact or similar models) from $75 to $2900. The systems included two downdraft systems, two exhaust fans combined with microwave over the range units, three installations of the same model of flat profile under-cabinet hood, several under cabinet collection hoods and several wall or island chimney capture hoods. Nominal maximum airflows – according to manufacturer product literature – varied from 190 to 600 cubic feet per minute.

Measured airflows were substantially lower than the rates claimed in product literature for most of the fans evaluated. Only two of the 13 independent models (three installations were same model) had actual airflows that are 90% or greater of the advertized values. Measured maximum airflows (highest fan settings) ranged from 74 to 382 cfm, with three units achieving less than 100 cfm. Of the thirteen units that had lower fan settings, seven had measured airflows below 100 cfm at these lower settings. Measured sound levels varied widely across installations and for some but not all units, sound levels varied substantially with fan speed.

Pollutant capture efficiency varied by basic system design, across models having similar designs, across different installations of the same model, and with the burners used. Across designs, the units with actual collection hoods (H and B series) generally performed better than the flat bottom (F) and downdraft systems. Exhaust fan and microwave combination units had capture efficiencies of 40% or less across a wide range of operating conditions. A common flat bottom model had peak capture efficiencies of only 50-65% and efficiencies below 50% for many burner and fan setting combinations across 3 installations. Capture efficiencies exceeded 80% for B5 and 70% for B6, both high-end units with capture hoods, across all assessed conditions. Among the H and B units, very poor performance was observed only for the economy unit B1.

Performance generally varied with the burner used. The rear downdraft units were effective for combustion exhaust from back burners and ineffective for front burners. For exhaust appliances installed above the cooktop, capture efficiencies generally were higher for back burner and oven burner use and for the highest fan speed.

Fan setting had a substantial effect on capture efficiency for many of the units. For example, unit F5 achieved capture efficiencies of 58-64% on high speed compared with 40-46% on medium and 22-30% on low speed for various cooktop burner configurations. The importance of installation is demonstrated by the variability in results among F3, F4 and F5, three installations of the same basic equipment. The most effective of these was an under cabinet installation in which an adjacent refrigerator may limit leakage and improve capture.

The efficiency results indicate that meeting industry standard minimum airflow requirements is not sufficient to provide high rates of pollutant capture. For example, devices F2 through F5 each achieve the minimum guidance for airflow yet they still do not capture a high fraction of cooking burner exhaust.

The "real world" implications of these results may be profound. The population of existing devices likely includes many more installations of the low to moderate cost models B1 and F3-F5 and the microwave exhaust fans F1-F2 than the high-end units with large capture hoods. The range of potential capture efficiency – as a function of burner and fan setting use – is therefore likely to be in the 30-70% range for many installed units. Survey evidence that exhaust fan use is limited by noise concerns suggest that fans often may be operated at lower speeds to minimize noise; in-use performance may thus reflect some of the lower capture efficiencies reported here.

In summary, while cooking exhaust fans can be effective at removing pollutants, many installed devices likely result in low capture efficiencies as used in practice. An assessment of the overall indoor air quality and energy costs, benefits and opportunities associated with kitchen exhaust fans requires research on stock characterization, additional experimental assessments in field and laboratory setting, and simulation analyses.

5.0 References

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

Fugler, D. W. (1989), Canadian research into the installed performance of kitchen exhaust fans, ASHRAE Transactions, 95(1), 753-758.

HVI (2008), HVI Range Hood Brochure, edited by H. V. Institute, Wauconda IL.

HVI (2009), HVI Loudness Testing and Rating Procedure, HVI Publication 915, Home Ventilating Institute, Wauconda IL.

HVI (2010), Certified Home Ventilating Products Directory, Home Ventilating Institute, Wauconda IL.

Kosonen, R., H. Koskela, and P. Saarinen (2006), Thermal plumes of kitchen appliances: Cooking mode, Energy and Buildings, 38(10), 1141-1148.

Li, Y., and A. Delsante (1996), Derivation of capture efficiency of kitchen range hoods in a confined space, Building and Environment, 31, 461-468.

Li, Y., A. Delsante, and J. Symons (1997), Residential kitchen range hoods - Buoyancy-capture principle and capture efficiency revisited, Indoor Air-International Journal of Indoor Air Quality and Climate, 7(3), 151-157.

Nagda, N. L., M. D. Koontz, R. C. Fortmann, and I. H. Billick (1989), PREVALENCE, USE, AND EFFECTIVENESS OF RANGE-EXHAUST FANS, Environment International, 15(1-6), 615-620.

Offermann, F. J. (2009), Ventilation and Indoor Air Quality in New Homes, CEC-500-2009-085, California Energy Commission and California Air Resources Board, Sacramento, CA.

Parrott, K., J. Emmel, and J. Beamish (2003), Use of Kitchen Ventilation: Impact on Indoor Air Quality, in The Forum for Family and Consumer Issues, edited, NC State University, Raleigh NC.

Piazza, T., R. H. Lee, M. Sherman, and P. P. (2007), Study of Ventilation Practices and Household Characteristics in New California Homes. , CEC-500-2007-033, California Energy Commission and California Air Resources Board, Sacramento, CA.

Price, P. N., and M. H. Sherman (2006), Ventilation Behavior and Household Characteristics in New California Houses, LBNL-59620, Lawrence Berkeley National Laboratory, Berkeley CA.

Revzan, K. L. (1986), Effectiveness of local ventilation in removing simulated pollution from point sources, Environment International, 12, 449-459.

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

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

Wilson, A. L., S. D. Colome, and Y. Tian (1994), California Indoor Air Quality Study, Multiple Volumes and Appendices, Integrated Environmental Services, Irvine CA.

Appendix A

Introduction

This document is an appendix to an interim project report for California Energy Commission Contract 500-05-026, *Natural Gas Variability in California: Experimental Evaluation of Installed Cooking Exhaust Fan Performance*. The full interim project report caries the same base report number as this document and should be cited as the primary source of information about the work described in this appendix. As its title suggests, the main report describes objectives, methods, primary results and analysis related to the experimental evaluation of exhaust fans installed for the purpose of removing contaminants generated during cooktop or oven use. The goal was to acquire information that would inform consideration of the potential for exhaust fans to mitigate any increase in emissions resulting from use of liquefied natural gas. Of course this information is also relevant to the removal of pollutants generated from any fuel use and for contaminants associated with actual cooking of food.

This appendix provides a record of notes and primary data from experiments conducted to quantify pollutant capture efficiency for installed kitchen exhaust fans. The material is organized by exhaust system. Each section is labeled with the exhaust system identifier used in the main body of the final report. Information about the systems is presented in the main report. For each fan system, there is first a presentation of special notes recorded by the field researcher, then photographs of the system. Experimental apparatus is visible in some photographs.

Presented for each fan system is a table of experiments and summary results, followed by a series of figures providing the time-resolved CO_2 that is part of the the primary data record. In all of the figures, the light red line with markers presents CO_2 concentrations quantified from a sample located at the outlet of the exhaust ductwork. This measurement was used along with airflow rate to determine the mass of CO_2 exhausted by the hood. The calculation is described in the main body of the report. In many figures, a blue line present data measured using a second CO_2 analyzer located in the kitchen. During some experiments the kitchen sample location was moved to determine if CO_2 was 'pooling' near the ceiling. If the background sample location was moved it is reported in the following experimental descriptions. The heavy red line represents the background concentration for the integration procedure. Unless otherwise noted all flow measurements were made inside with a powered flow hood.

Exhaust System D1

This house had an integrated downdraft exhaust hood built into the range/oven combination (Dacor model RDDS30). This is a 'dual-fuel' unit with a gas range and an electric oven. The unit was approximately 10 years old. The exhaust was sampled approximately 3m downstream as left the house. The background sample was not moved, the blip in experiment 5 was likely due to someone standing too close to the sample inlet.

Figure A-1. Downdraft exhaust system D1, placement within kitchen.

Figure A-2. Downdraft exhaust system D1.

Table A-1. Summary of experiments and results for D1.

Exp	Burners	Fan Setting	Fan (cfm)	Burner Fire Btu/hr	Fan/Plume	Eff
1	RR	High	242	9,100	1.5	103%
2	LR	High	242	11,000	1.4	96%
3	LF	High	242	9,100	1.5	22%
4	RF	High	242	11,000	1.4	17%
5	RF LR	High	242	22,000	1.1	53%
6	LR	Med	233	11,000	1.4	98%
7	RF	Med	233	11,000	1.4	11%
8	LR	Low	213	11,000	1.2	102%
9	RR	Low	213	9,100	1.3	102%
10	LF	Low	213	9,100	1.3	19%
11	RF	Low	213	11,000	1.2	13%
12	RF LR	Low	213	22,000	1.0	53%

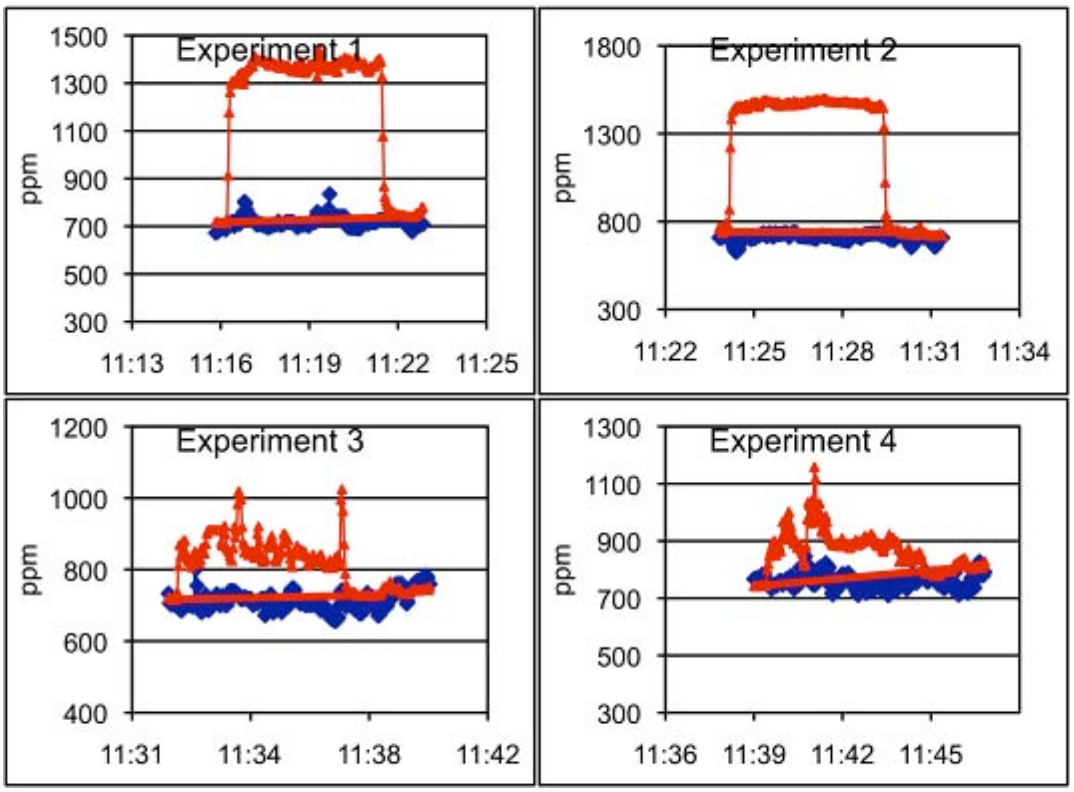

Figure A-3. Measured CO_2 in exhaust system D1, Exps. 1-4.

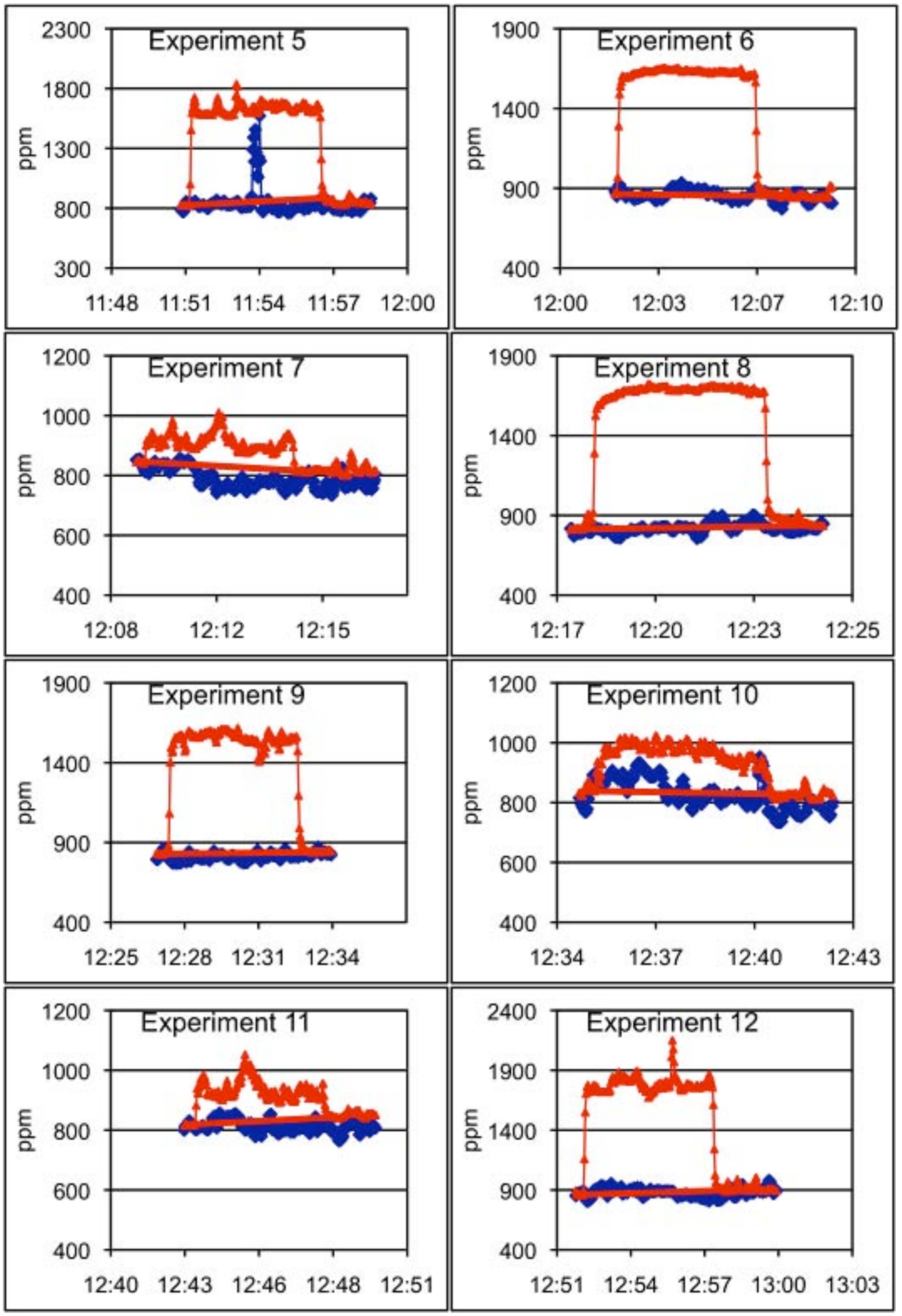

Figure A-4. Measured CO_2 in exhaust system D1, Exps. 5-12.

Exhaust System D2

This house had a DACOR model RV30/CABP3 downdraft hood/blower. The exhaust served a gas range only. The unit was at least 15 years old. The exhaust was sampled 10+m downstream in a straight section of duct. During experiment 1 the background sample location was moved around the island looking for a representative location. For experiments 11 and 12 the background sample was moved to ~3m above the island (the house has a vaulted ceiling), pooling near the ceiling is evident in this figures. This was identified in original project notes as House E.

Figure A-5. Downdraft exhaust system D2, location in kitchen.

Figure A-6. Downdraft exhaust system D2.

Table A-2. Summary of experiments and results for D2.

Exp	Burners	Fan Setting	Fan (cfm)	Burner Fire Btu/hr	Fan/Plume	Eff
1	RR	High	289	10,300	1.5	72%
2	LF	High	289	14,200	1.4	26%
3	LR	High	289	12,700	1.4	64%
4	LF RR	High	289	24,500	1.1	42%
5	LR RR	High	289	23,000	1.2	68%
6	RR	High	289	10,300	1.5	71%
7	LF	High	289	14,200	1.4	48%
8	LF	Med	255	14,200	1.2	9%
9	RR	Med	255	10,300	1.3	75%
10	LR	Med	255	12,700	1.2	70%
11	LF	Med	255	14,200	1.2	8%
12	LF RR	Med	255	24,500	1.0	33%

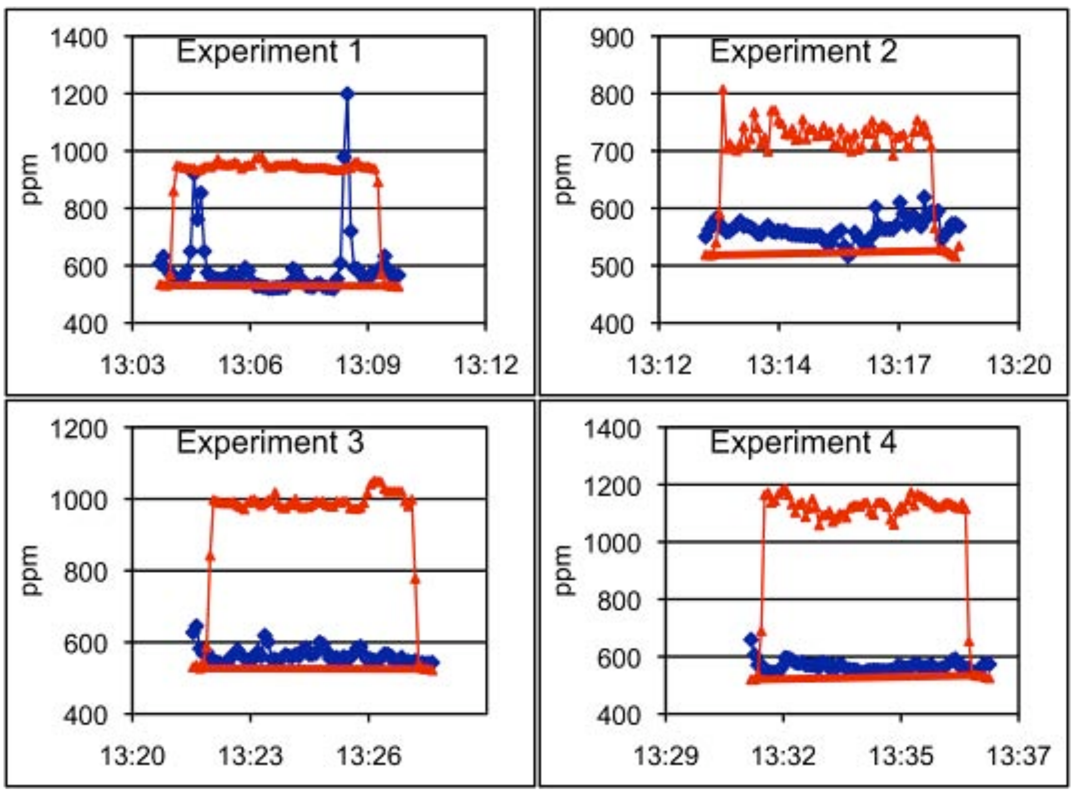

Figure A-7. Measured CO_2 in exhaust system D2, Exps. 1-4.

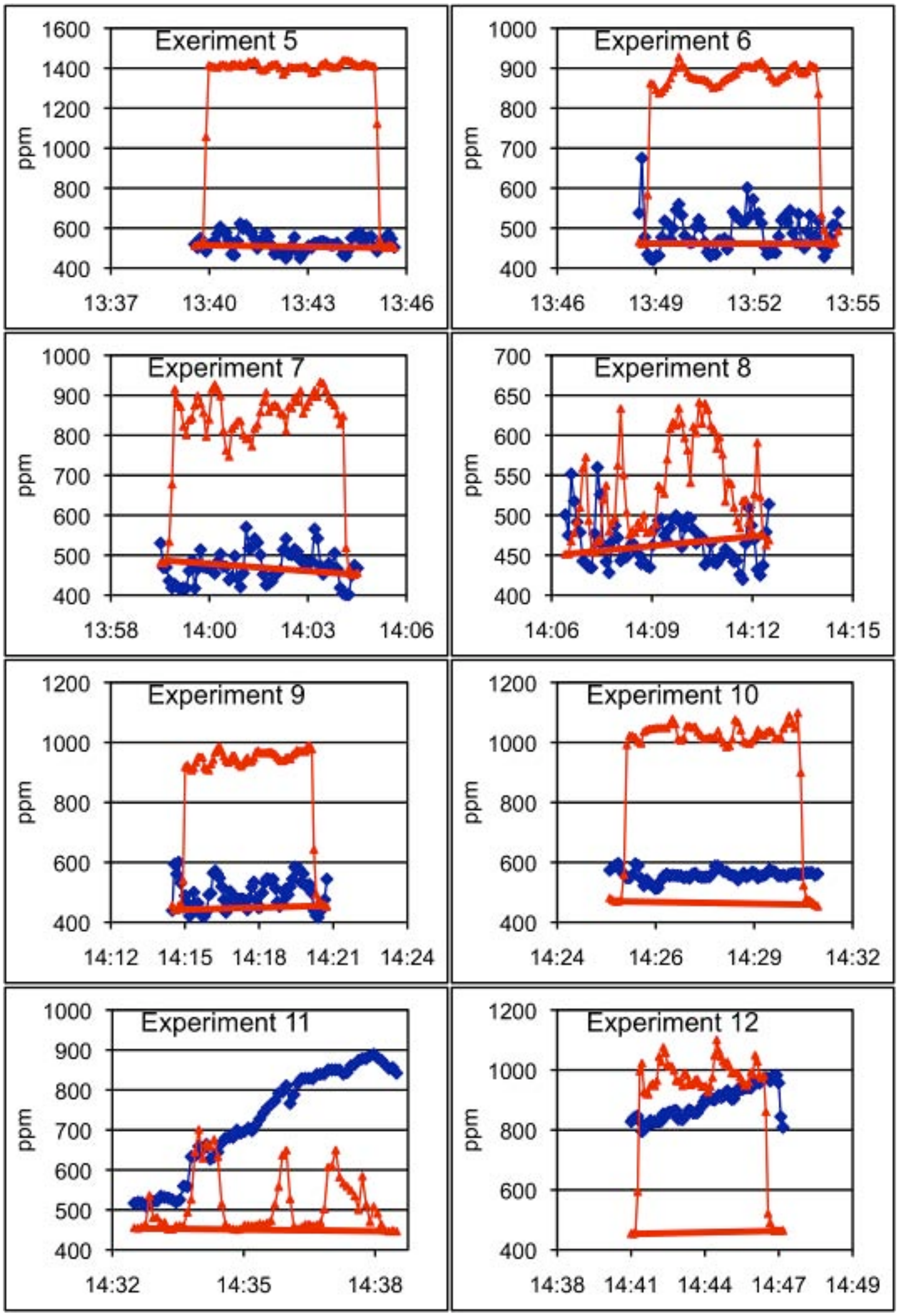

Figure A-8. Measured CO_2 in exhaust system D2, Exps. 5-12.

Exhaust System F1

This house had an integrated exhaust hood/microwave KENMORE model 721.63652300. The exhaust served a range/oven combination. The unit was 4 years old. The exhaust was sampled ~1.5 m downstream past 2 elbows in a straight section of duct. The background sample was not moved during the experiments. This was identified in original project notes as House K.

Figure A-9. Microwave over range; exhaust system F1, location in kitchen.

Figure A-10. Top view showing coverage of exhaust system F1 over cooktop.

Table A-3. Summary of experiments and results for F1.

Exp	Burners	Fan Setting	Fan (cfm)	Burner Fire Btu/hr	Fan/Plume	Eff
1	RF	High	85	16,900	0.5	20%
2	LR	High	85	14,400	0.5	38%
3	Oven	High	85	17,800	0.5	30%
4	LF	High	85	9,700	0.6	21%
5	LR RF	High	85	31,300	0.4	33%
6	Oven	Med	56	17,800	0.3	18%
7	LR	Med	56	14,400	0.3	27%
8	RF	Med	56	16,900	0.3	17%
9	LF	Med	56	9,700	0.4	16%
10	Oven	Low	29	17,800	0.2	14%
11	LR	Low	29	14,400	0.2	18%
12	RF	Low	29	16,900	0.2	6%
13	LF	Low	29	9,700	0.2	10%
14	LR	High	85	14,400	0.5	34%

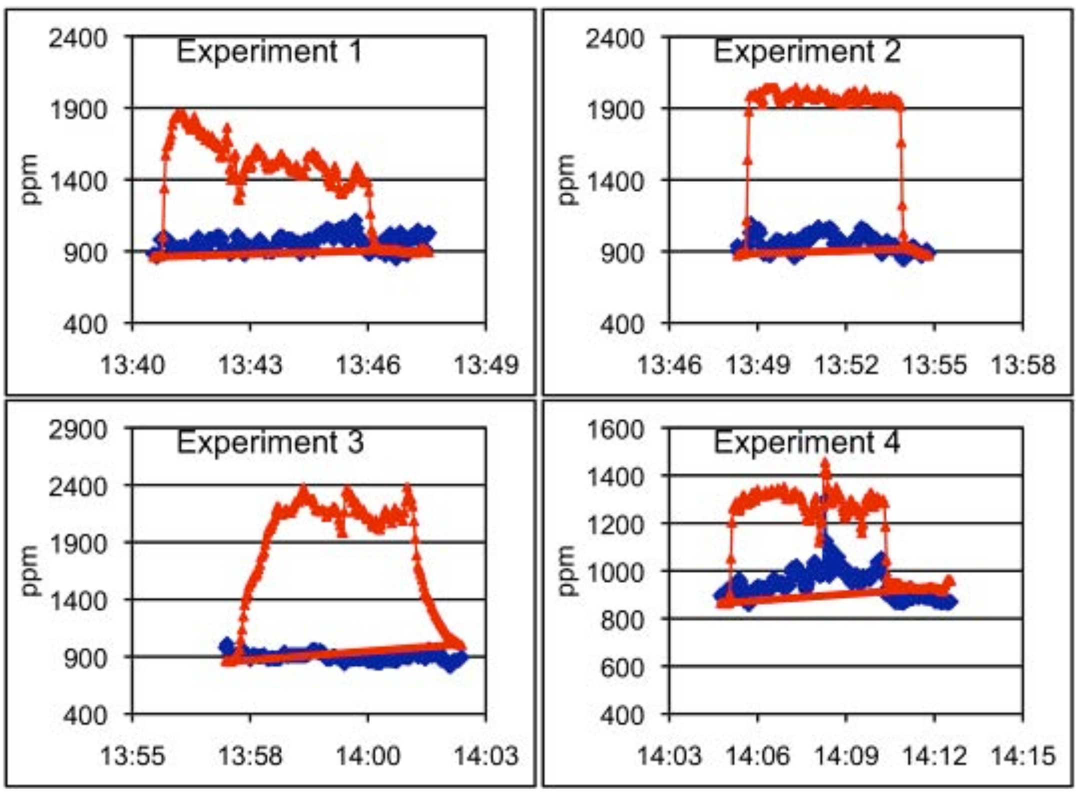

Figure A-11. Measured CO_2 in exhaust system F1, Exps. 1-4.

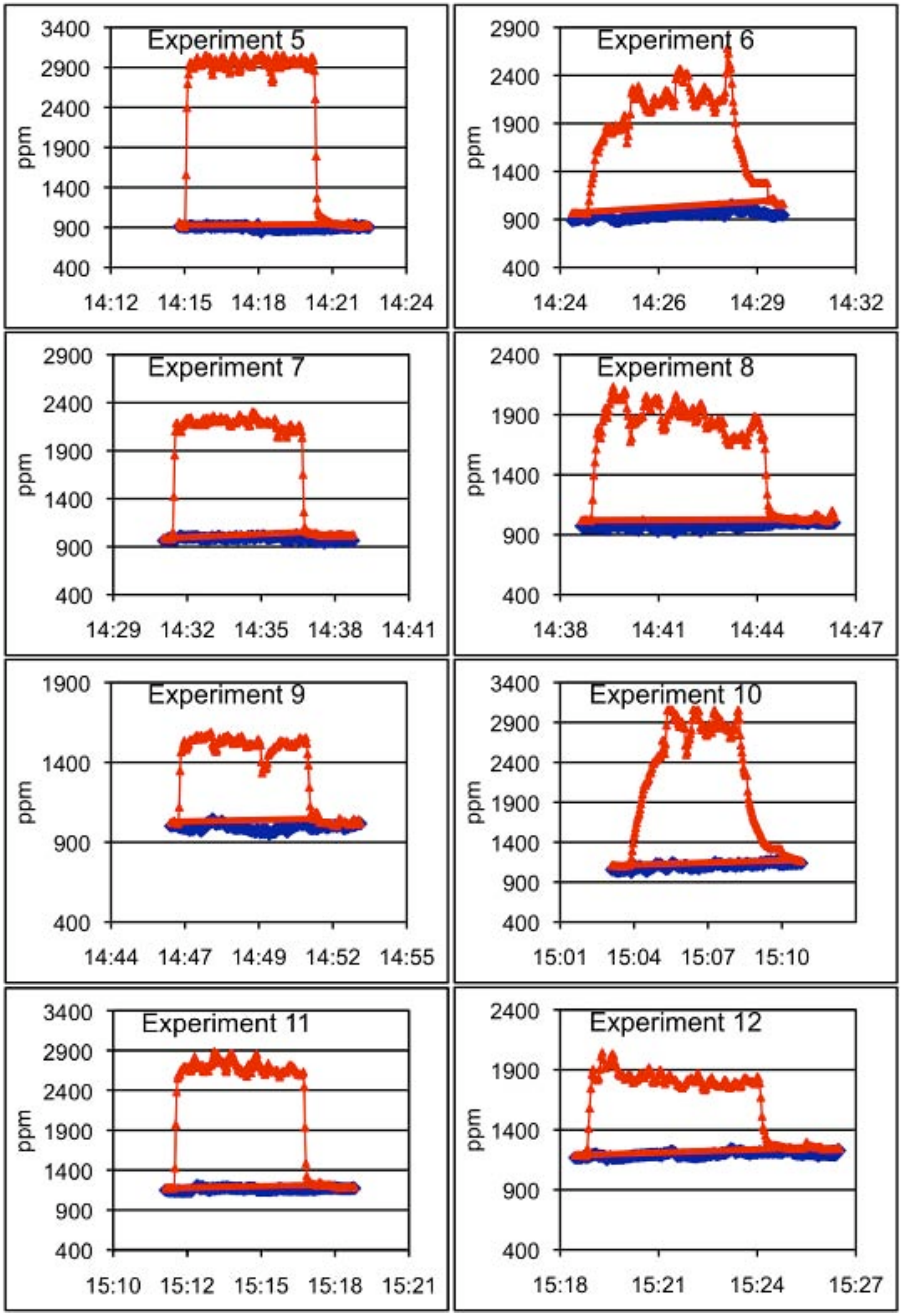

Figure A-12. Measured CO_2 in exhaust system F1, Exps. 5-12.

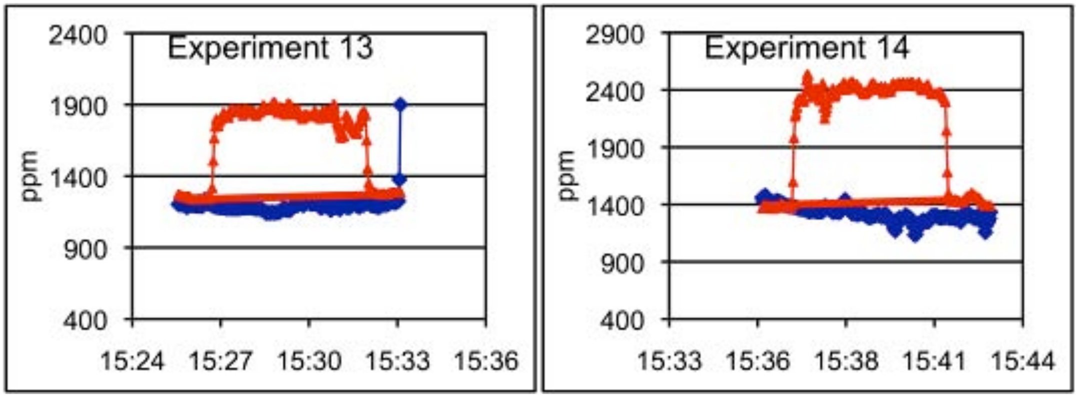

Figure A-13. Measured CO_2 in exhaust system F1, Exps. 13-14.

Exhaust System F2

This house had an integrated exhaust hood/microwave GENERAL ELECTRIC model JVM1850. The exhaust served a range/oven combination. The unit was 4 years old. The exhaust was sampled ~1.5 m downstream by inserting a piece of copper tubing as far up into the duct above the unit as possible. The background sample was not moved during the experiments. The filter was initially plugged solid, and the researcher felt it needed cleaning before any testing was performed. This was identified in original project notes as House L.

Figure A-14. Microwave over range; exhaust system F2, location in kitchen.

Figure A-15. Microwave over range; exhaust system F2, side view.

Table A-4. Summary of experiments and results for F2.

Exp	Burners	Fan Setting	Fan (cfm)	Burner Fire Btu/hr	Fan/Plume	Eff
1	LR	High	96	9,300	0.8	31%
2	RF	High	96	12,400	0.7	32%
3	Oven	High	96	14,300	0.7	42%
4	LR RF	High	96	21,700	0.6	32%
5	LR	Med	91	9,300	0.7	34%
6	Oven	Med	91	14,300	0.6	40%
7	RF	Med	91	12,400	0.7	27%
8	LR RF	Med	91	21,700	0.6	31%
9	Oven	Low	73	14,300	0.5	39%
10	LR	Low	73	9,300	0.6	28%
11	RF	Low	73	12,400	0.5	24%
12	LR RF	Low	73	21,700	0.5	24%
13	LR	Boost	106	9,300	0.9	32%
14	RF	Boost	106	12,400	0.8	24%

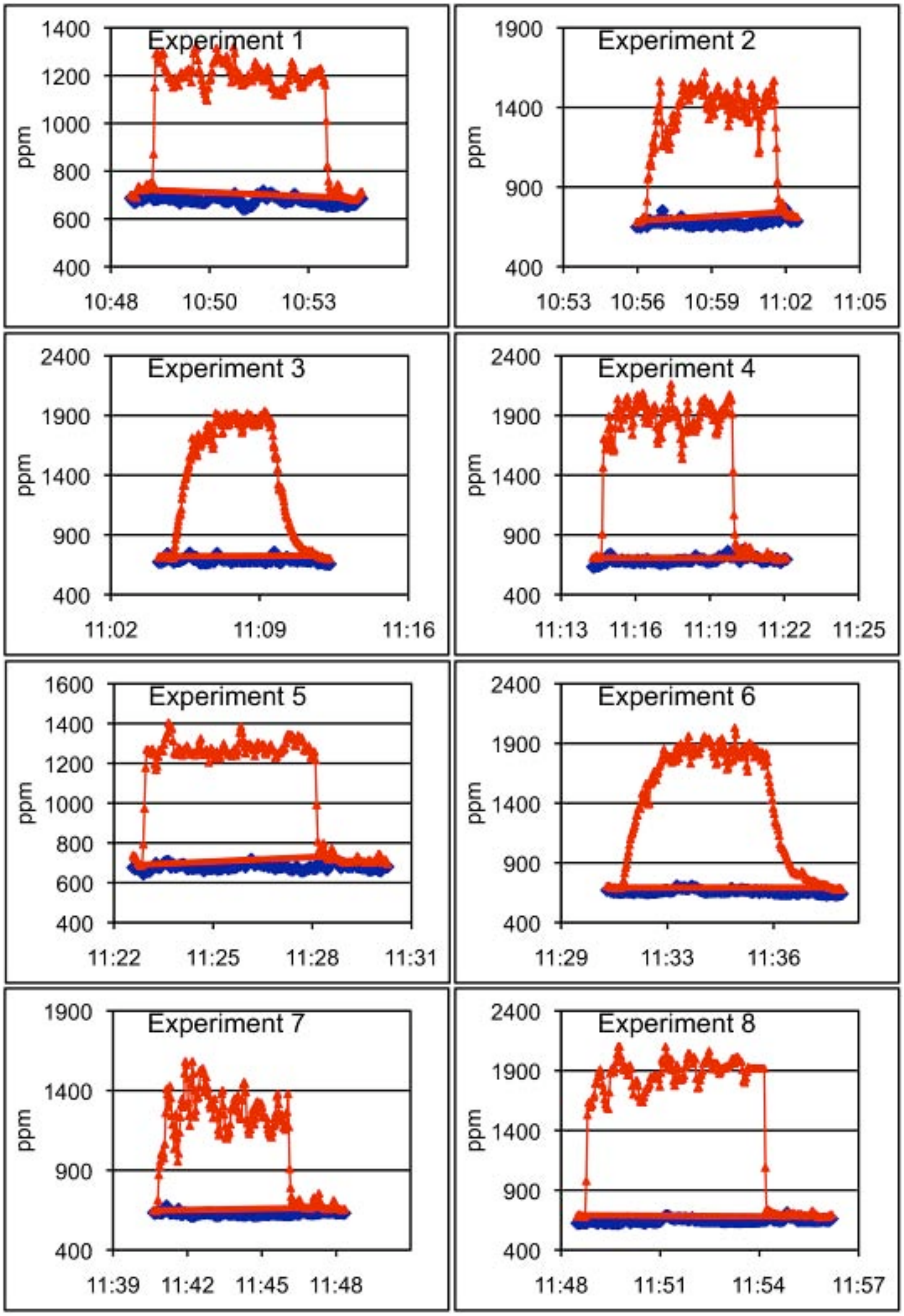

Figure A-16. Measured CO_2 in exhaust system F2, Exps. 1-8.

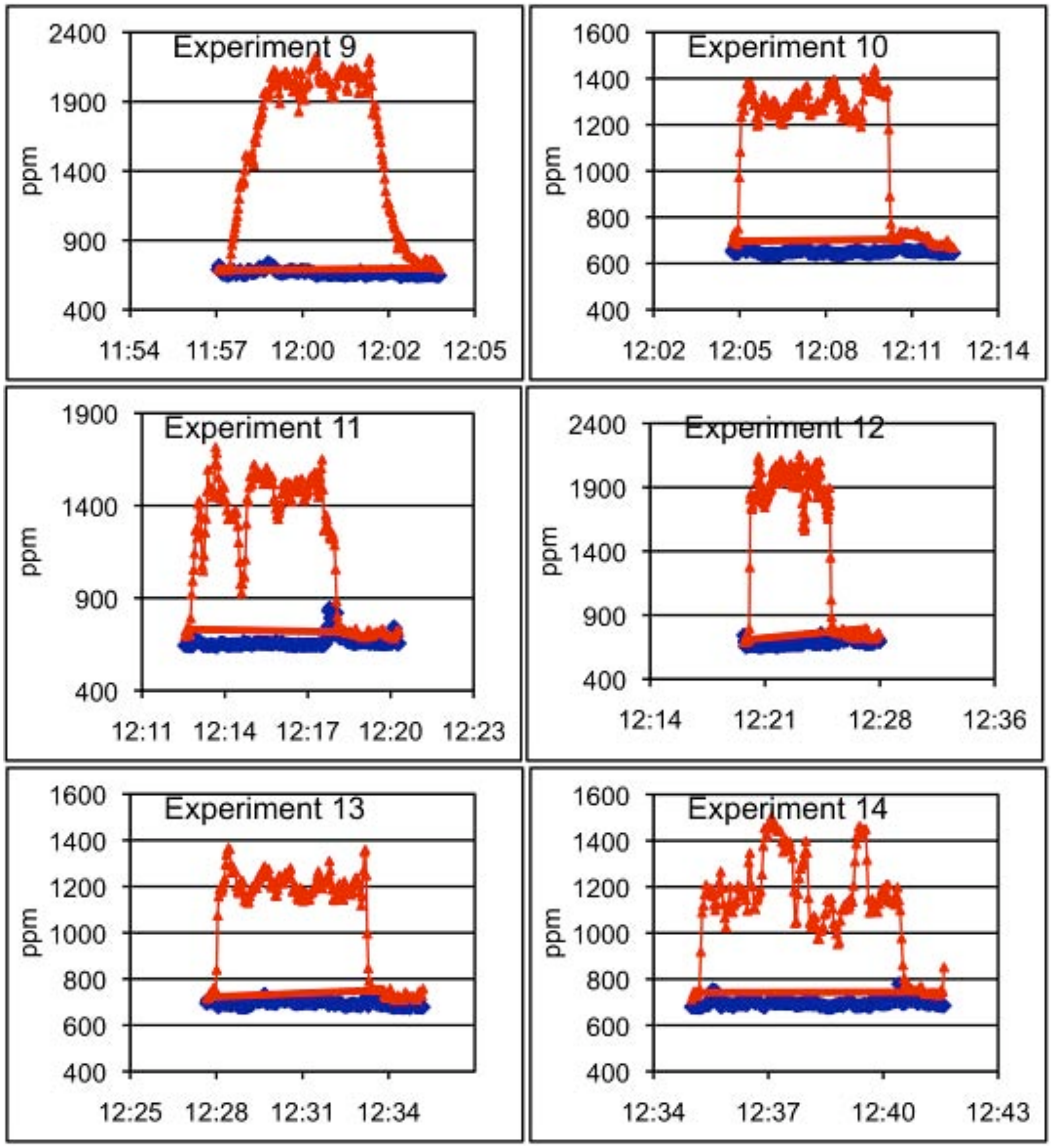

Figure A-17. Measured CO_2 in exhaust system F2, Exps. 9-14.

Exhaust System F3

The house had a BROAN model Allure QS2. The exhaust served a range/oven combination. The unit was 9 years old. The exhaust was sampled ~2m above the hood in a straight section of duct in the attic. The background sample was not moved during the experiments. Fan flow measurements were made with the SF6 tracer method only. This was identified in original project notes as House A.

Figure A-18. Exhaust system F3, location in kitchen.

Figure A-19. Exhaust system F3, side view.

Table A-5. Summary of experiments and results for F3.

				Burner Fire		
Exp	Burners	Fan Setting	Fan (cfm)	Btu/hr	Fan/Plume	Eff
1	LF RR	High	229	27,100	0.5	53%
2	L Oven	High	225	22,000	0.8	46%
3	LF RR	Low	51	27,300	0.1	13%
4	L Oven	Low	49	24,700	0.2	21%
5	LF	Med	79	13,000	0.3	22%
6	RR	Med	161	14,700	0.7	36%
7	L Oven	Med	156	22,600	0.6	41%
8	LF RR	Med	158	27,100	0.3	44%
9	L Oven	Med	153	21,600	0.6	47%
10	LF	Med	157	13,100	0.7	33%
11	RF	Med	157	11,900	0.7	20%
12	R Oven	Med	155	20,300	0.6	53%
13	LF	Med	159	13,700	0.7	27%
14	RF	High	231	13,400	1.0	28%
15	LF RR	High	230	29,200	0.5	51%

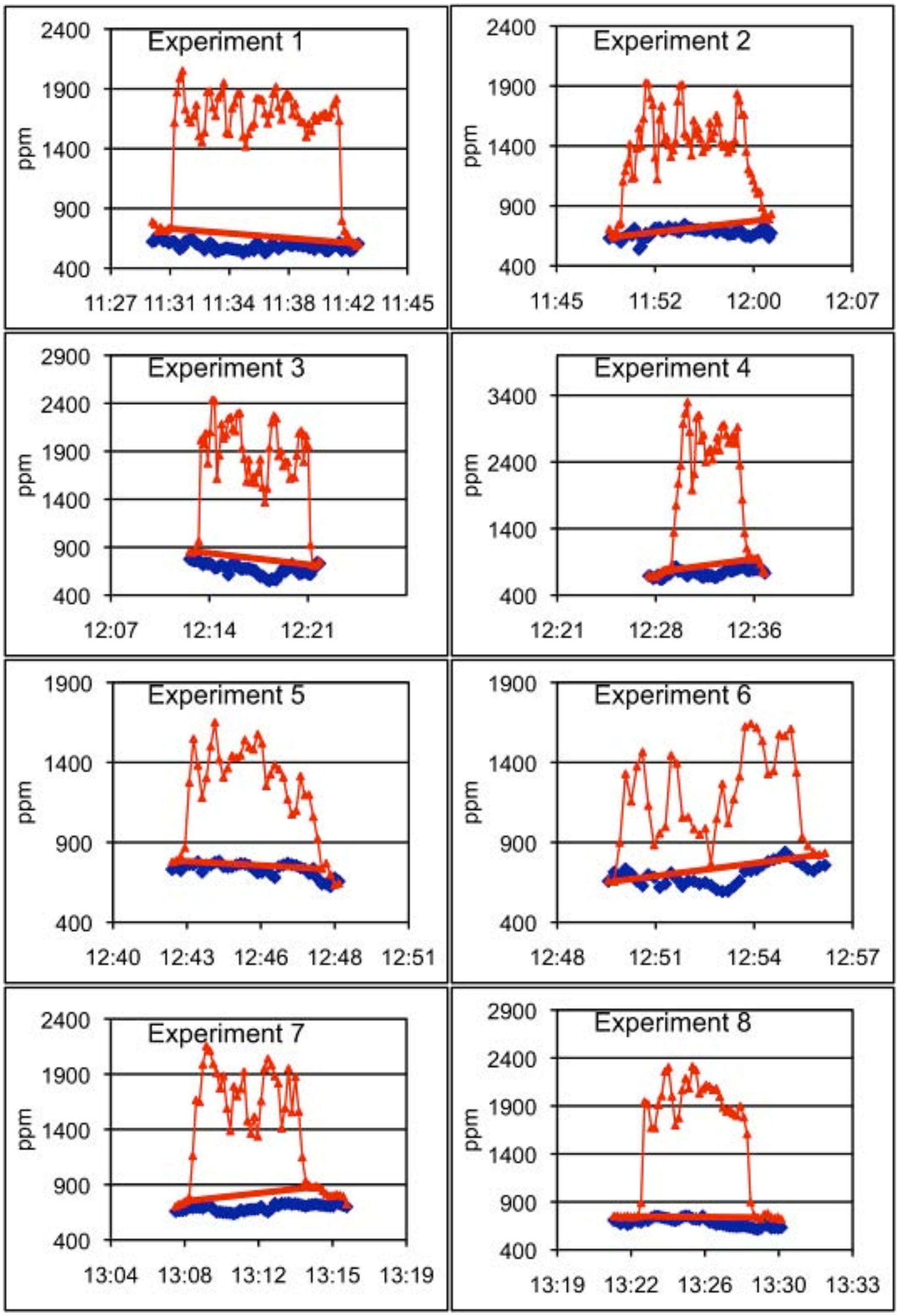

Figure A-20. Measured CO_2 in exhaust system F3, Exps. 1-8.

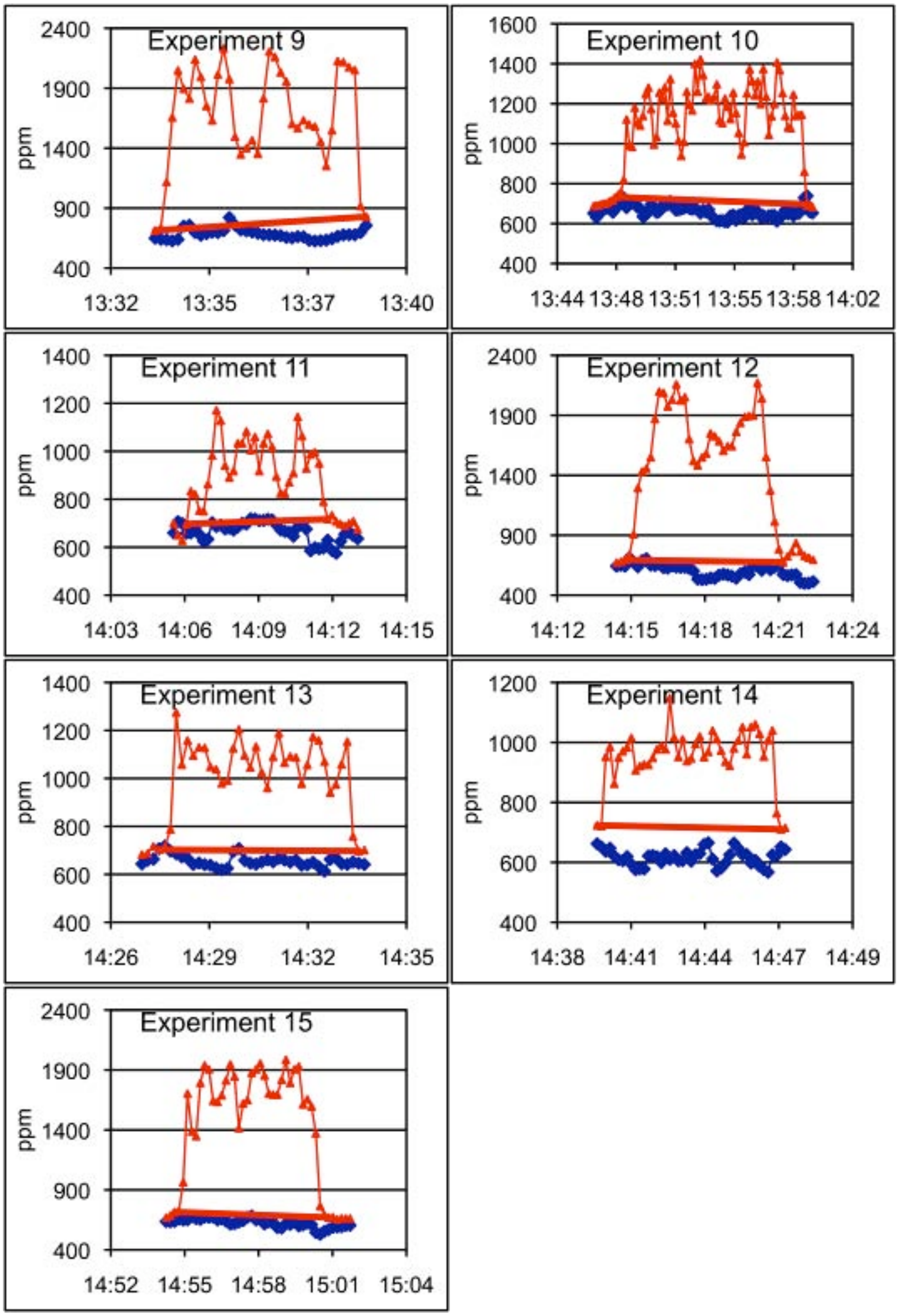

Figure A-21. Measured CO_2 in exhaust system F3, Exps. 9-15.

Exhaust System F4

The house had a BROAN model Allure QS2. The exhaust served a range/oven combination. The unit was 6 years old. The discharge was directly out of the back of the hood on the outside wall. Due to mixing concerns the exhaust was sampled at the outlet of a powered flow hood mounted outside the house. The background sample was not moved during the experiments. The range was set back from wall, while the hood was mounted directly on the wall. This was identified in original project notes as House D.

Figure A-22. Exhaust system F4, side view.

Figure A-23. Installation of flow hood to exhaust of system F4.

Table A-6. Summary of experiments and results for F4.

Exp	Burners	Fan Setting	Fan (cfm)	Burner Fire Btu/hr	Fan/Plume	Eff
1	O	Low	88	19,200	0.4	9%
2	RF	Low	83	11,600	0.5	2%
3	RR	Low	85	7,300	0.6	13%
4	LF RR	Low	86	16,200	0.4	11%
5	RF	High	244	11,600	1.4	21%
6	RR	High	244	7,300	1.6	48%
7	O	High	250	19,200	1.2	31%
8	LF RR	High	247	16,200	1.3	32%

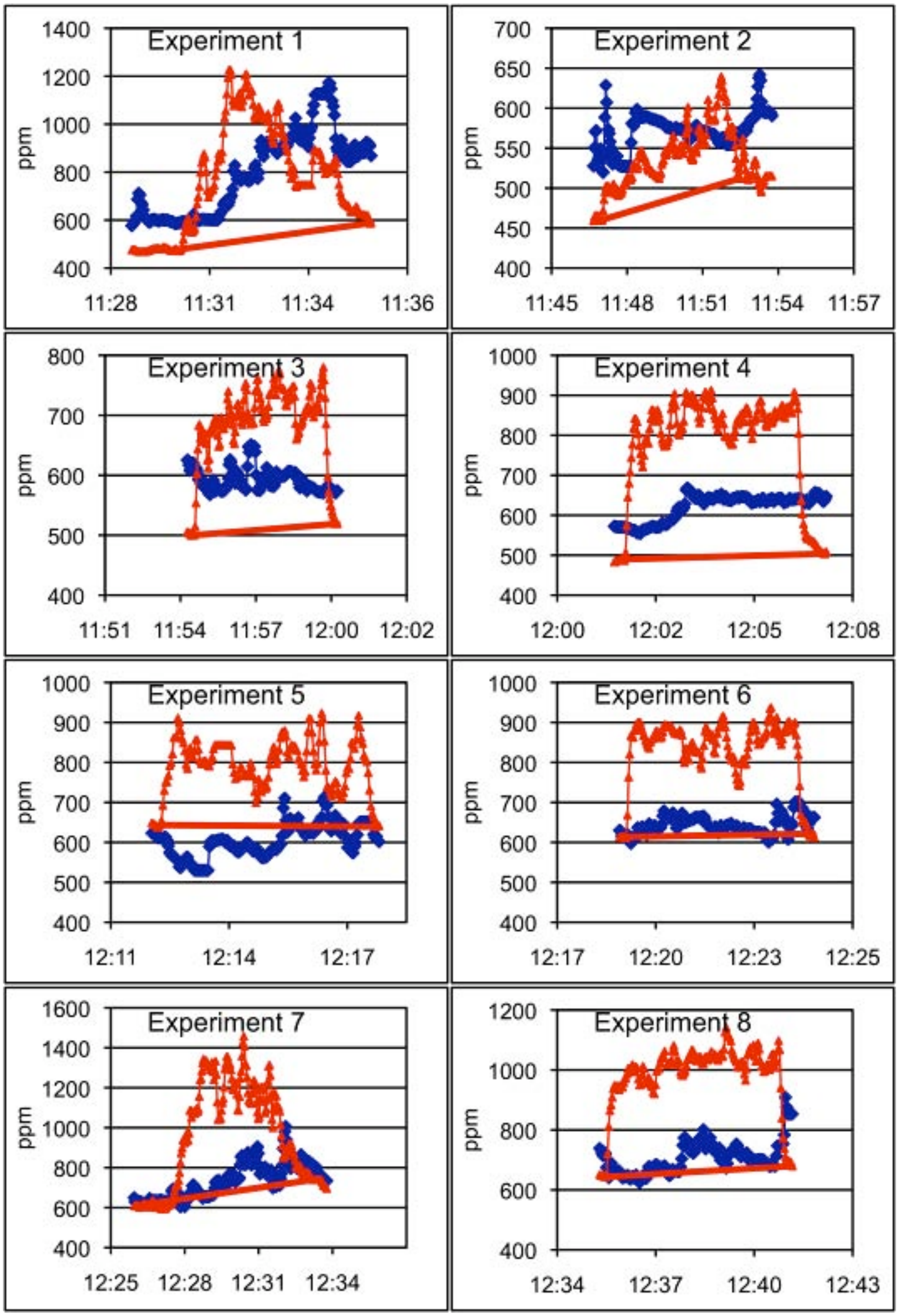

Figure A-24. Measured CO_2 in exhaust system F4, Exps. 1-8.

Exhaust System F5

The house had a BROAN model Allure QS2. The exhaust served a range/oven combination. The unit was 5 years old. The exhaust was sampled ~1.5 m downstream by inserting a piece of copper tubing as far up into the duct above the unit as possible. The background sample was moved during experiments 4-6 and 8-11. This was identified in original project notes as House F.

Figure A-25. Exhaust System F5 with cabinets and refrigerator on sides.

Figure A-26. Exhaust System F5 showing profile at bottom.

Table A-7. Summary of experiments and results for F5.

Exp	Burners	Fan Setting	Fan (cfm)	Burner Fire Btu/hr	Fan/Plume	Eff
1	LR	High	248	12,100	1.3	58%
2	RF	High	248	15,600	1.2	64%
3	O	High	248	16,400	1.2	95%
4	RF LR	High	248	27,800	1.0	61%
5	LR	Med	164	12,100	0.8	40%
6	RF	Med	164	15,600	0.8	46%
7	O	Med	164	16,400	0.8	81%
8	LR	Low	88	12,100	0.5	24%
9	RF	Low	88	15,600	0.4	30%
10	RF LR	Med	164	27,800	0.6	45%
11	RF LR	Low	88	27,800	0.3	22%
12	O	Low	88	16,400	0.4	40%

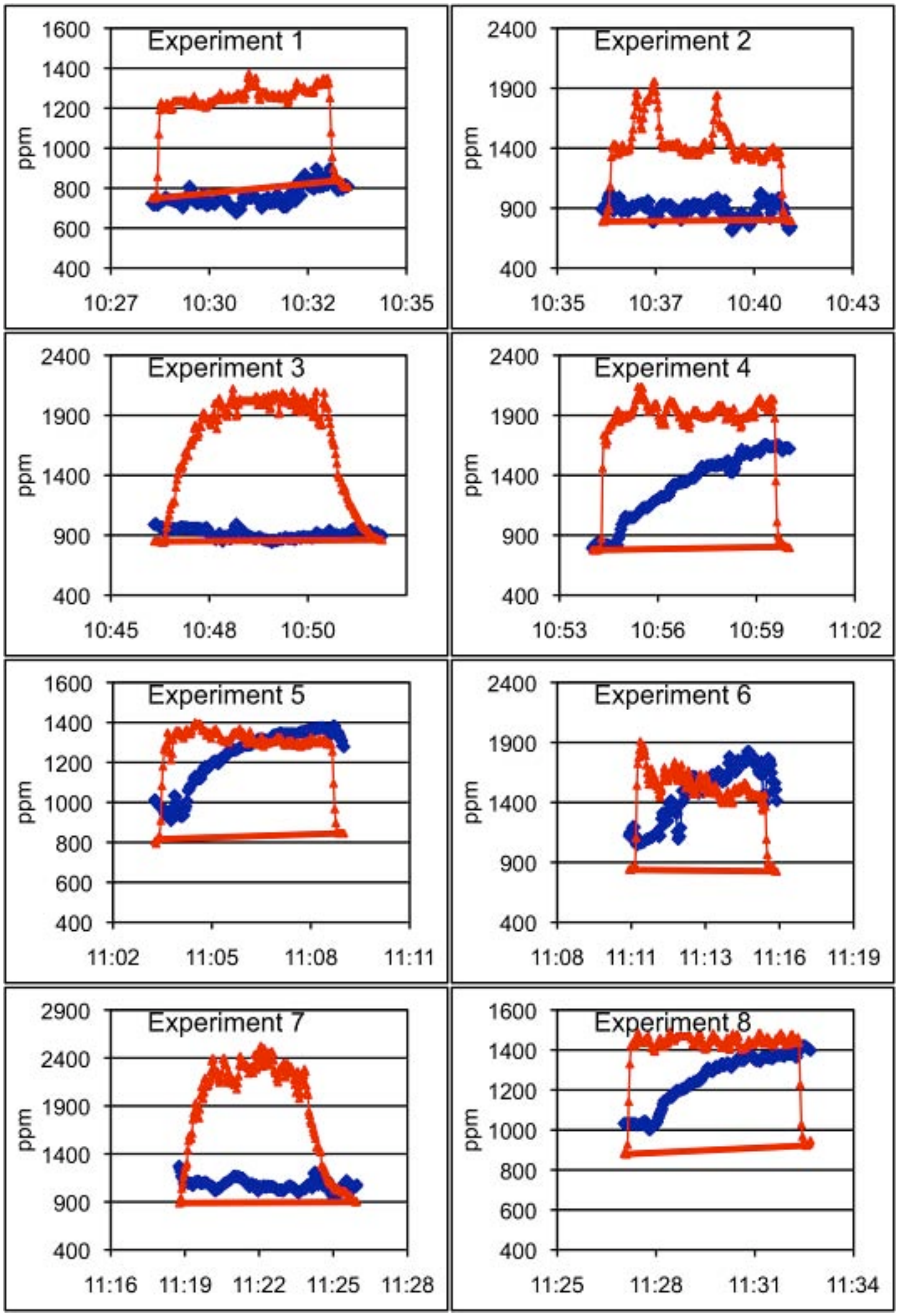

Figure A-27. Measured CO_2 in exhaust system F5, Exps. 1-8.

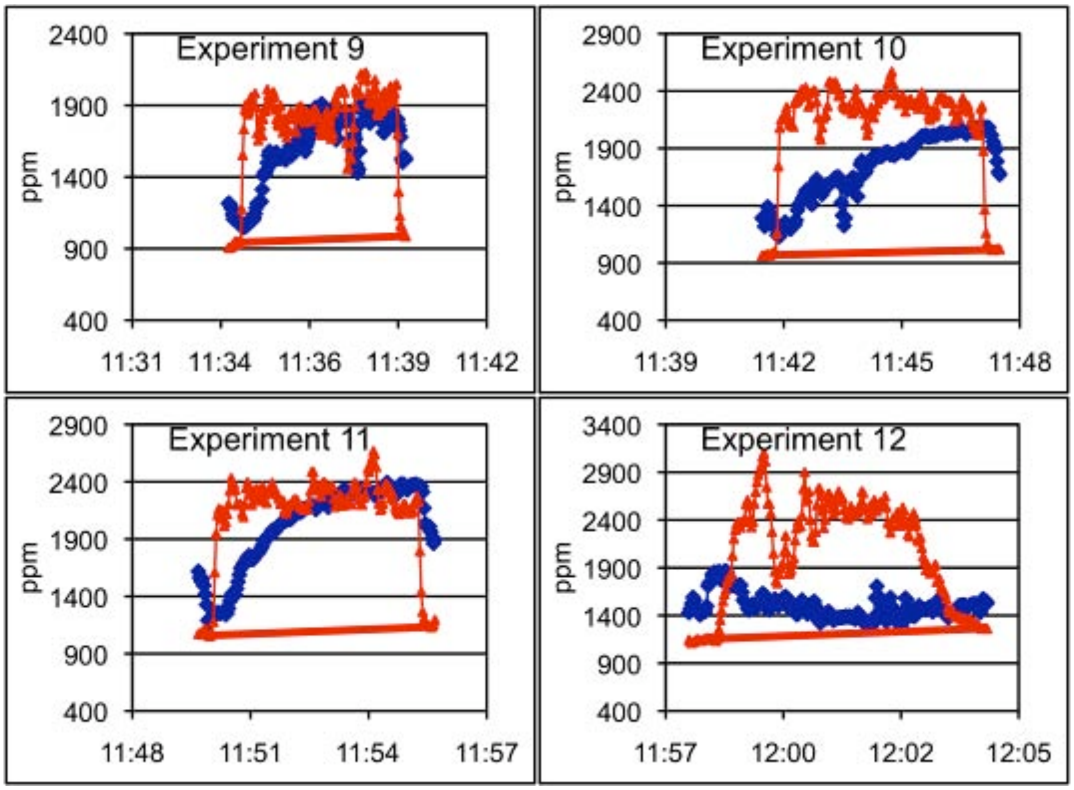

Figure A-28 Measured CO_2 in exhaust system F5, Exps. 9-12.

Exhaust System H1

The house had a KOBE model RA9430SQB. The exhaust served a range/oven combination. The unit was 3 years old. The exhaust was sampled ~3m above the hood at the discharge on the roof. The background sample was not moved during the experiments. This was identified in original project notes as House J.

Figure A-29. Exhaust System H1, placement in kitchen.

Figure A-30. Exhaust System F5 with grease screens removed.

Table A-8. Summary of experiments and results for H1.

				Burner Fire		
Exp	Burners	Fan Setting	Fan (cfm)	Btu/hr	Fan/Plume	Eff
1	LF	Low	180	17,100	0.7	39%
2	RF	High	225	13,500	0.9	59%
3	LR	High	225	12,900	0.9	94%
4	Oven	High	225	27,500	0.7	89%
5	RR	High	225	17,600	0.8	91%
6	LF	High	225	17,100	0.8	49%
7	LR LF	High	225	34,200	0.7	56%
8	Oven	Med	200	27,500	0.6	87%
9	LR	Med	200	12,900	0.8	83%
10	RF	Med	200	13,500	0.8	57%
11	LR LF	Med	200	34,200	0.6	52%
12	Oven	Low	180	27,500	0.6	85%
13	LR	Low	180	12,900	0.7	79%
14	RF	Low	180	13,500	0.7	49%
15	LR LF	Low	180	34,200	0.5	45%
16	LR	Quiet	96	12,900	0.4	56%
17	RF	Quiet	96	13,500	0.4	38%
18	RR	Low	180	17,600	0.7	77%

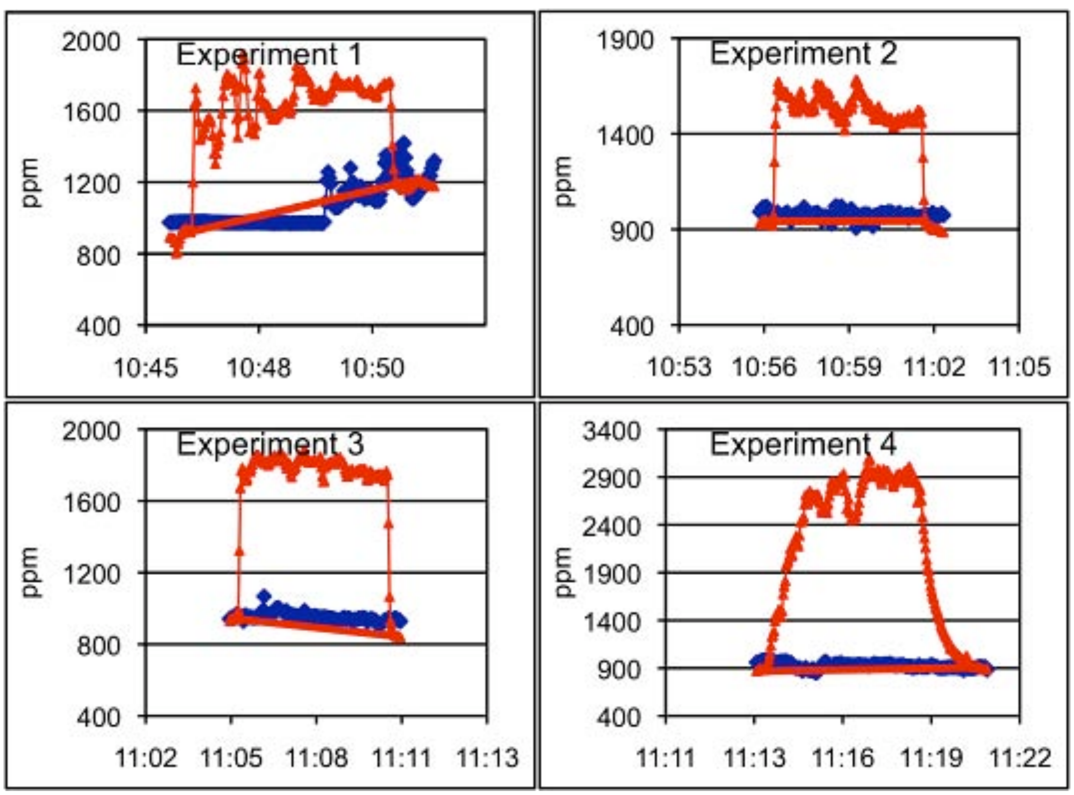

Figure A-31. Measured CO_2 in exhaust system H1, Exps. 1-4.

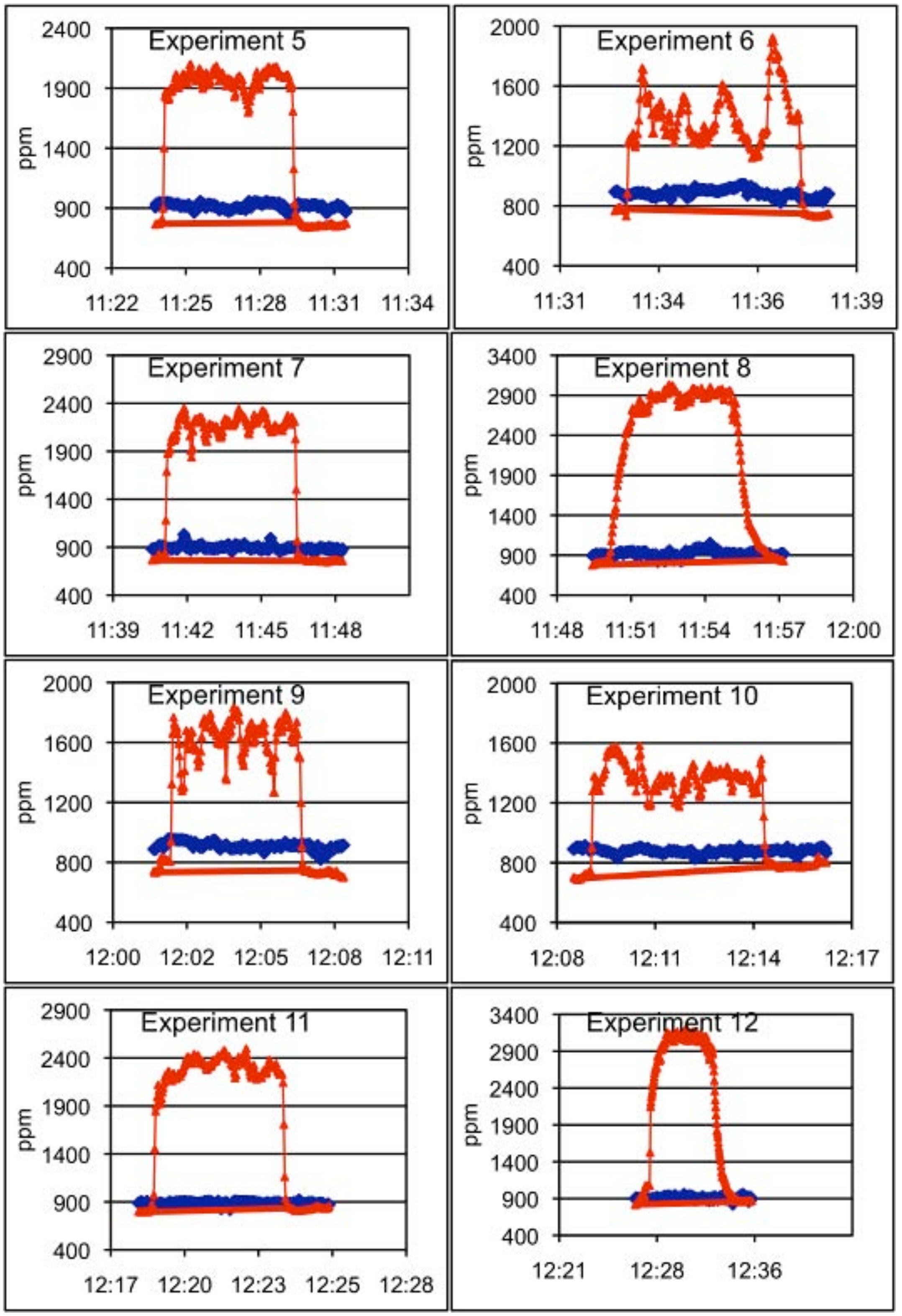

Figure A-32. Measured CO_2 in exhaust system H1, Exps. 5-12.

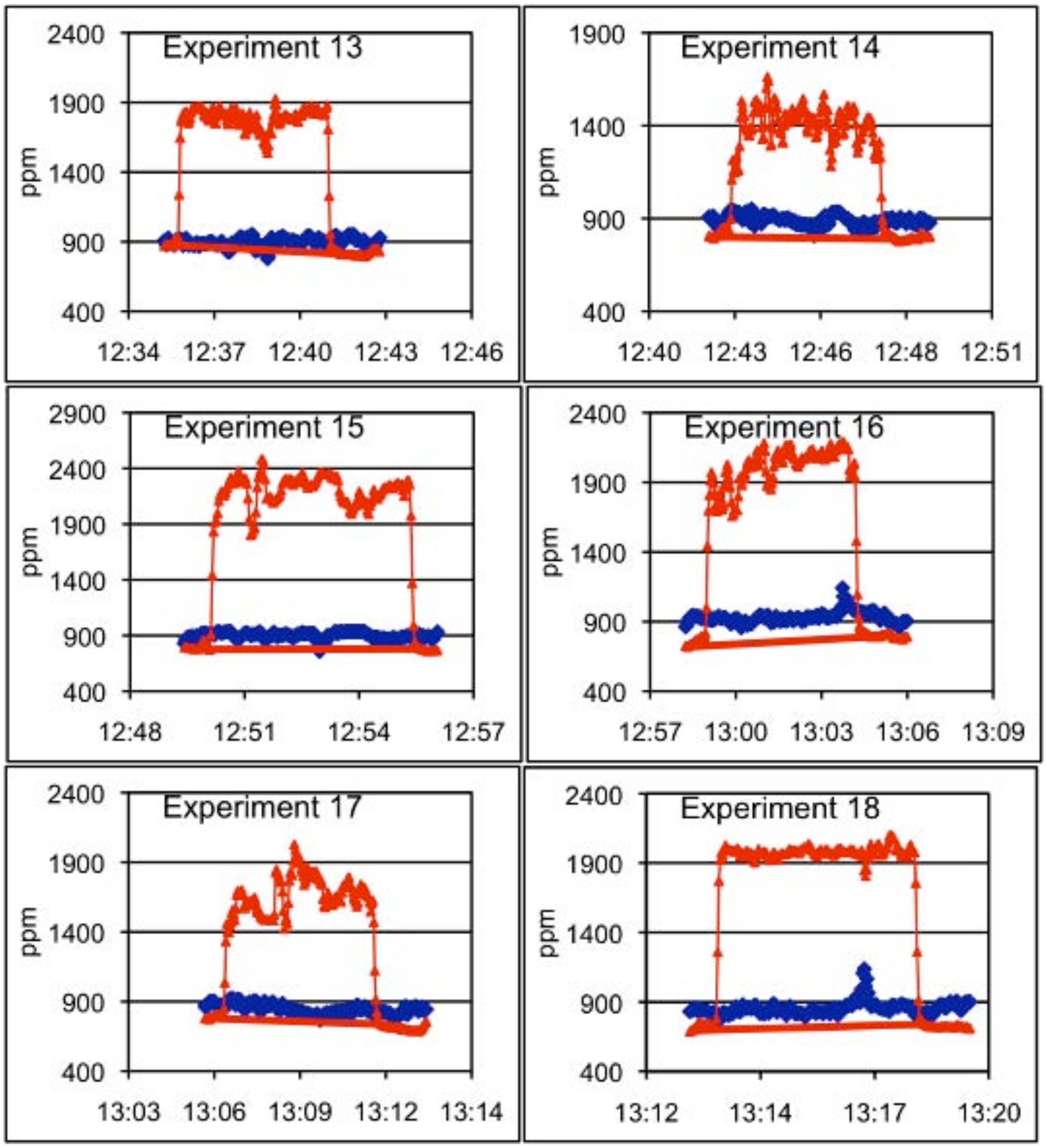

Figure A-33. Measured CO_2 in exhaust system H1, Exps. 13-18.

Exhaust System H2

The house had a BOSCH model DAH93 hood. The exhaust served a range/oven combination. The unit was 5 years old. The exhaust was sampled at the discharge directly behind the unit. Care was taken that we were adequately sampling the discharge stream (by changing the position and checking for repeatable numbers). The background sample was not moved during the experiments. Both the SF6 tracer method and the powered flow hood were used for flow measurement (the numbers agreed to within the measurement uncertainties). This was identified in original project notes as House C.

Figure A-34. Exhaust System H2, placement in kitchen.

Figure A-35. Exhaust System H2; top view showing coverage of cook top.

Table A-9. Summary of experiments and results for H2.

Exp	Burners	Fan Setting	Fan (cfm)	Burner Fire Btu/hr	Fan/Plume	Eff
1	O	Low	152	17,300	0.6	70%
2	LR RF	Low	152	27,800	0.5	66%
3	RF	Low	152	15,900	0.6	50%
4	LR	Low	152	12,900	0.7	75%
5	O	Med	234	17,300	0.9	85%
6	RF	Med	234	15,900	1.0	63%
7	LR	Med	234	12,900	1.0	76%
8	LR RF	Med	234	27,800	0.8	76%
9	LF	Med	234	9,200	1.2	63%
10	O	High	361	17,300	1.5	91%
11	LF	High	361	9,200	1.8	89%
12	LR	High	361	12,900	1.6	87%
13	RF	High	361	15,900	1.5	84%
14	LR RF	High	361	27,800	1.2	85%
15	RF	High	361	15,900	1.5	75%

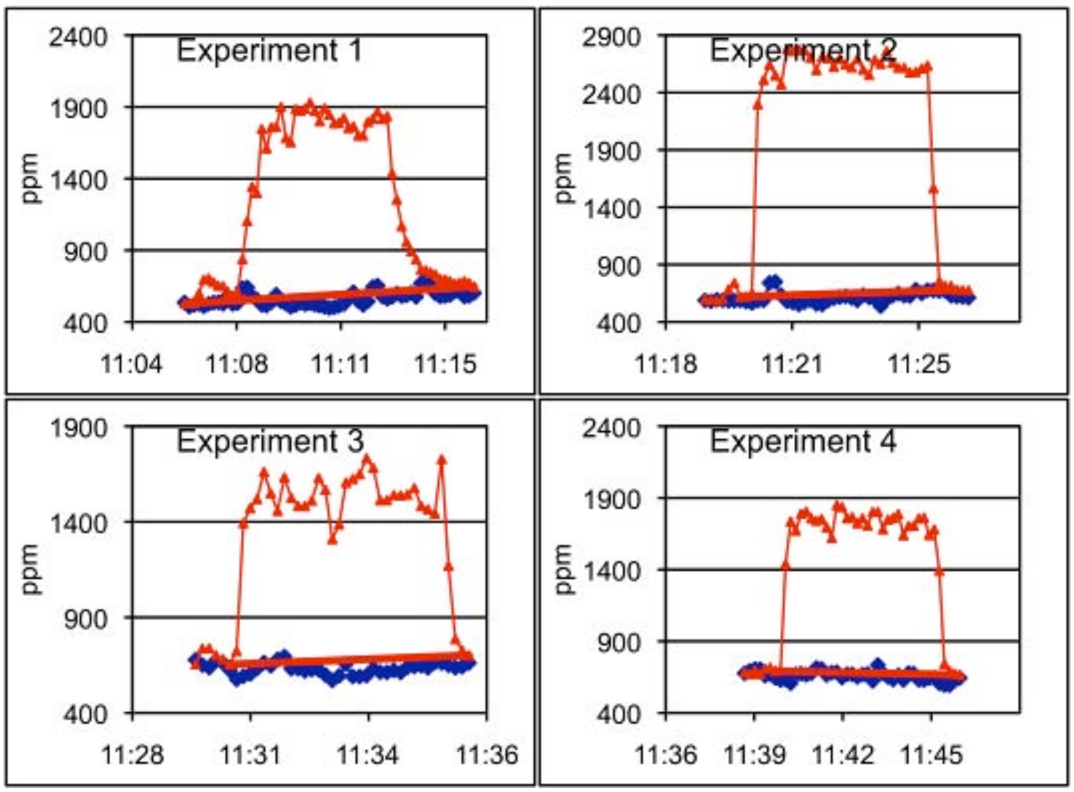

Figure A-36. Measured CO_2 in exhaust system H2, Exps. 1-4.

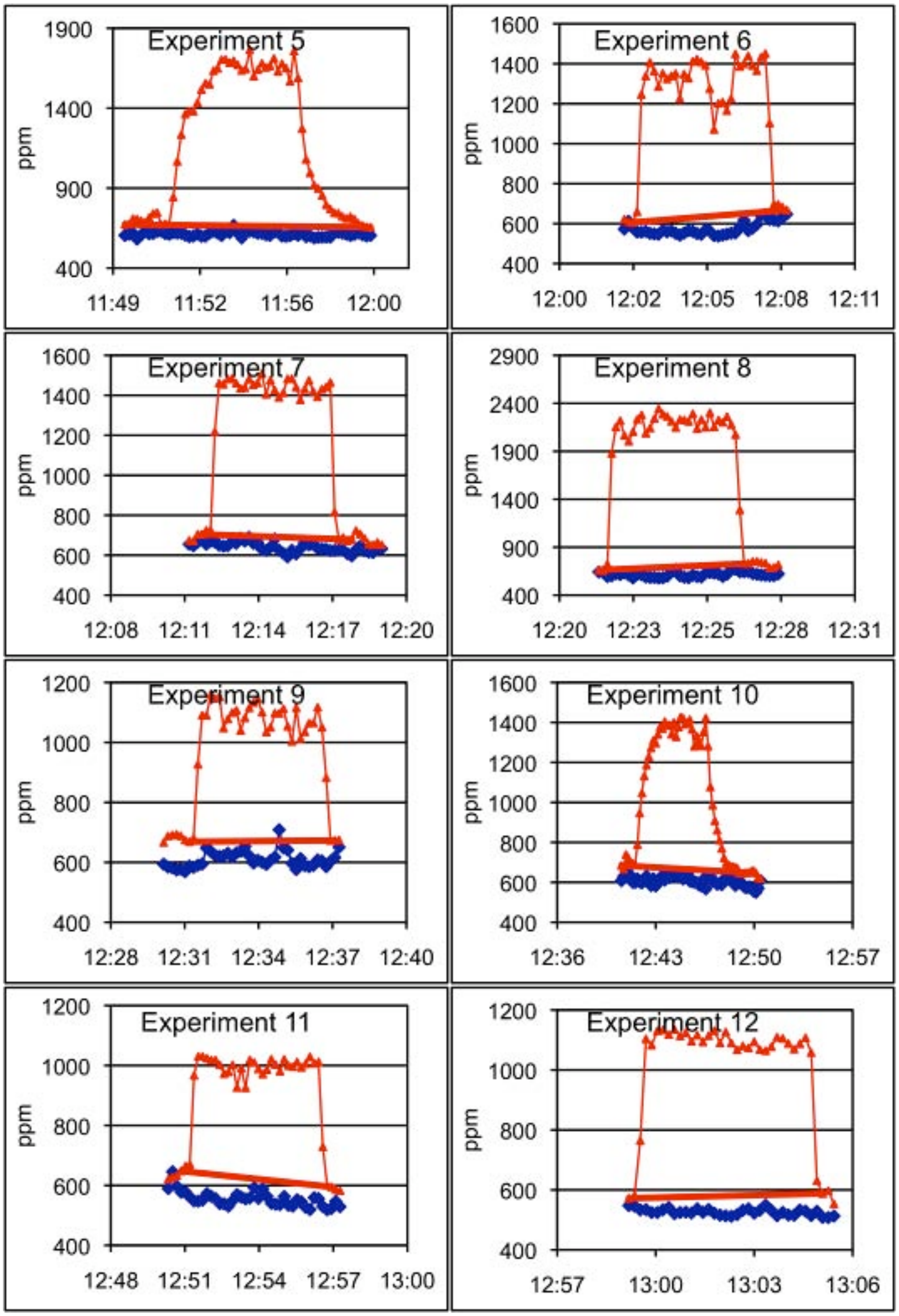

Figure A-37. Measured CO_2 in exhaust system H2, Exps. 5-12.

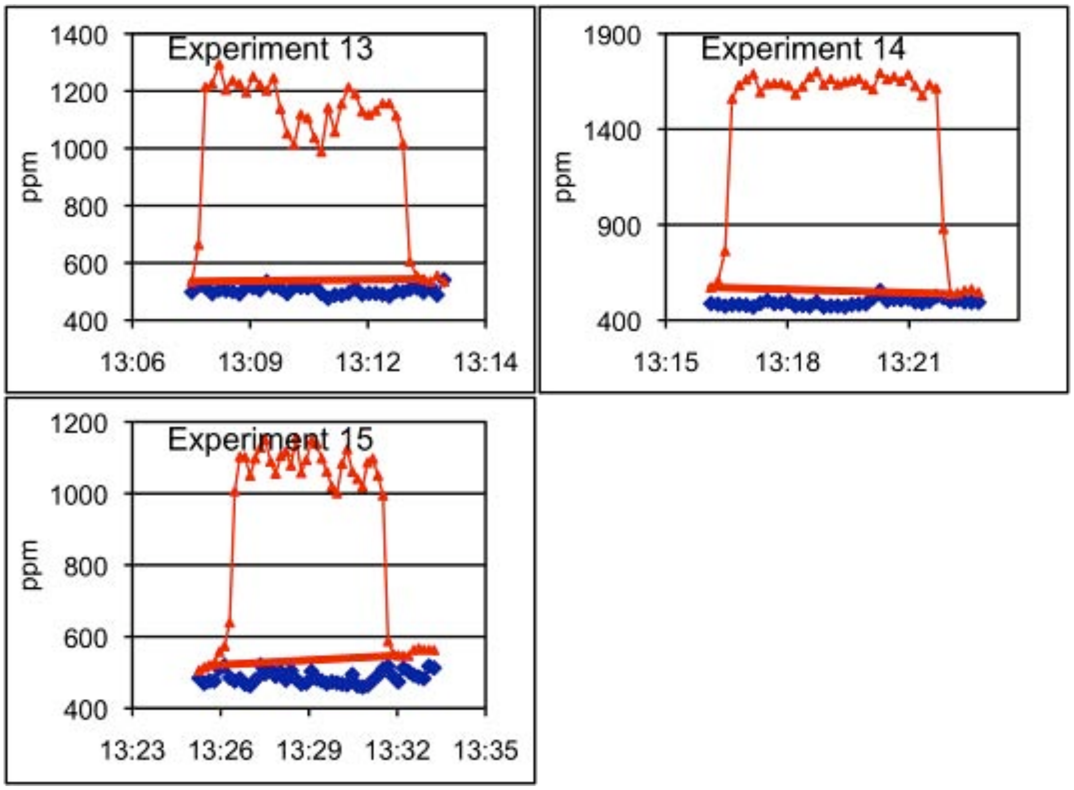

Figure A-38. Measured CO_2 in exhaust system H2, Exps. 13-15.

Exhaust System B1

The house had a BROAN model 42,000F hood. The exhaust served a range/oven combination. The unit was at least 15 years old. The exhaust was sampled ~1.5 m downstream by inserting a piece of copper tubing as far up into the duct above the unit as possible. The background sample was not moved during the experiments. This was identified in original project notes as House H.

Figure A-39. Exhaust System B1; note hallway at left.

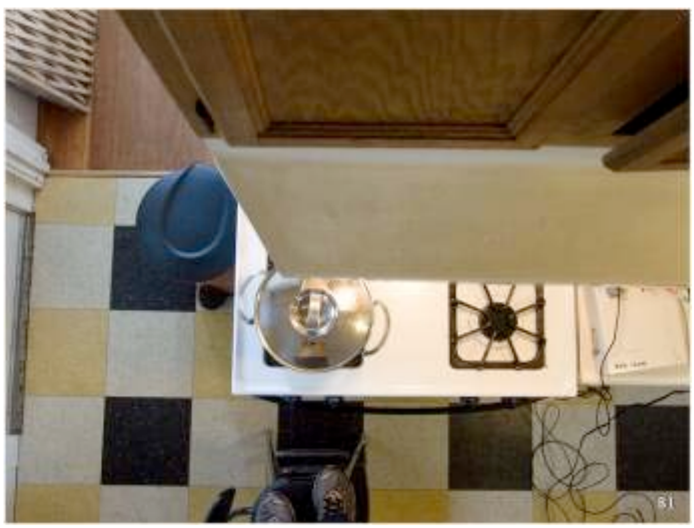

Figure A-40. Exhaust System B1; top view showing incomplete coverage of cooktop.

Table A-10. Summary of experiments and results for B1.

				Burner Fire		
		Fan	Fan			
Exp	Burners	Setting	(cfm)	Btu/hr	Fan/Plume	Eff
1	RR	High	74	7,500	0.5	56%
2	LF	High	74	11,300	0.5	17%
3	Oven	High	74	12,800	0.5	57%
4	LF RR	High	74	18,800	0.4	30%
5	RR	High	74	7,500	0.5	51%
6	LF	High	74	11,300	0.5	15%
7	RR	Low	45	7,500	0.3	37%
8	Oven	Low	45	12,800	0.3	41%
9	RR	Low	45	7,500	0.3	36%
10	LF	Low	45	11,300	0.3	7%
11	LF RR	Low	45	18,800	0.2	20%
12	LF	Low	45	11,300	0.3	11%

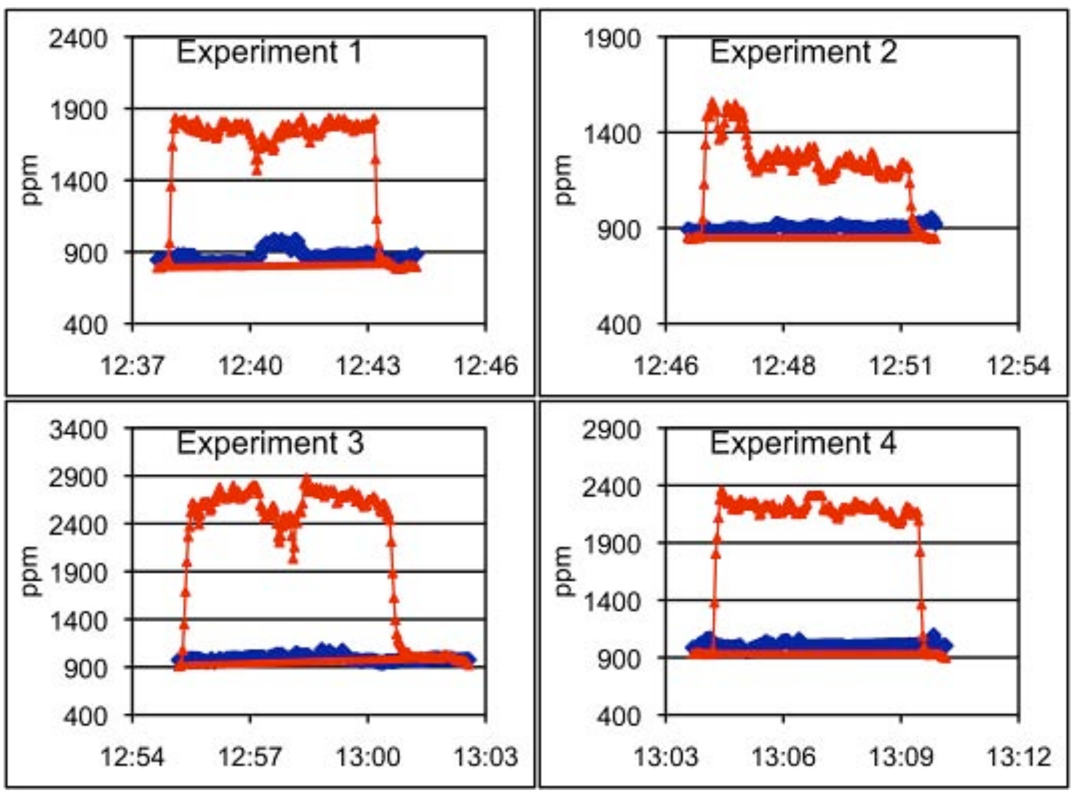

Figure A-41. Measured CO_2 in exhaust system B1, Exps. 1-4.

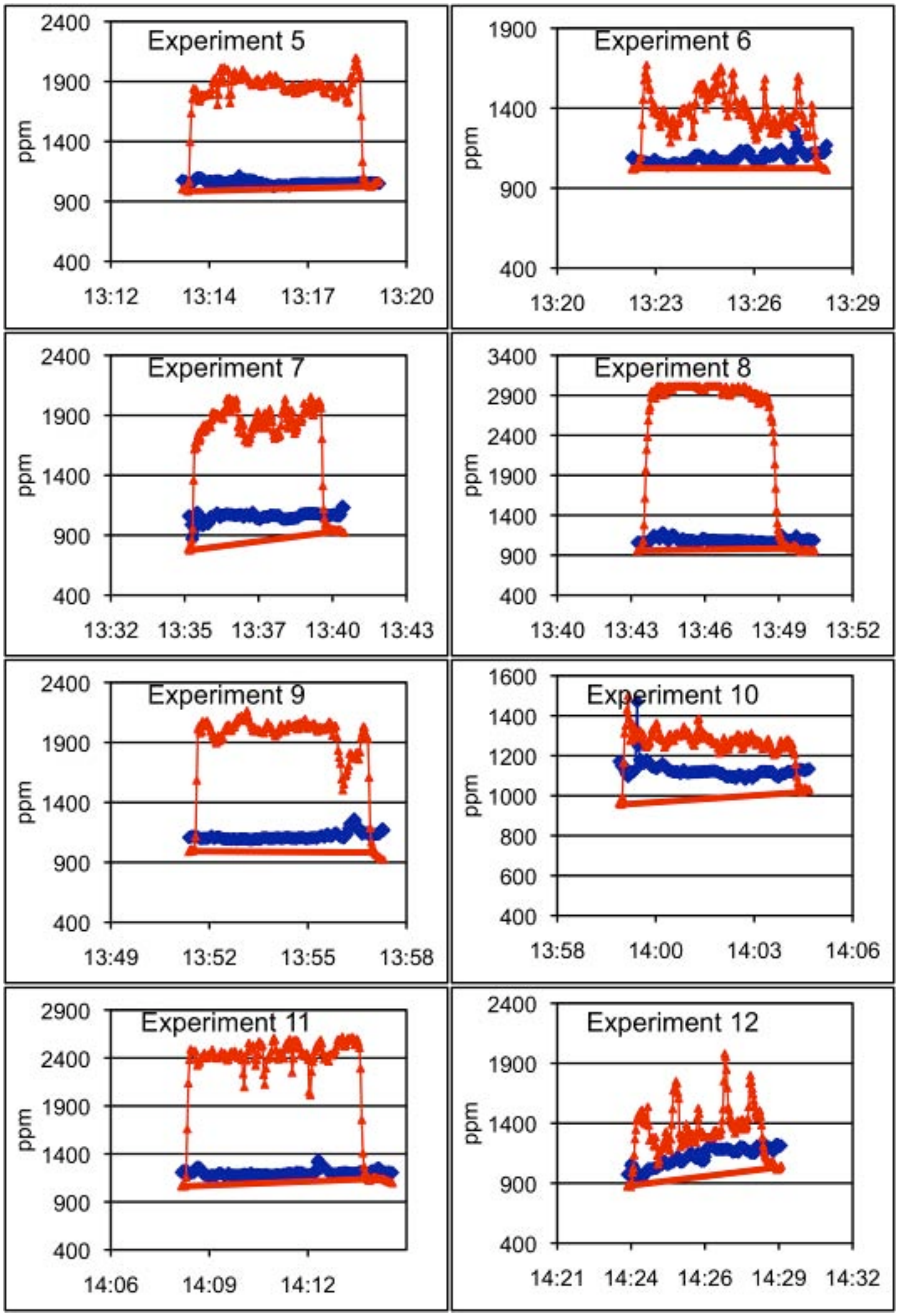

Figure A-42. Measured CO_2 in exhaust system B1, Exps. 5-12.

Exhaust System B2

The house had a DACOR model IVS1. The exhaust served a gas range top only. The exhaust served a range/oven combination. The unit was 15 years old. The exhaust was sampled ~5 m downstream at the outlet along the outside wall. Fan flow measurements were made with the SF6 tracer method only. In order to look at mixing/sampling issues, the background measurements were at a location dust downstream of the fan. This was identified in original project notes as House B.

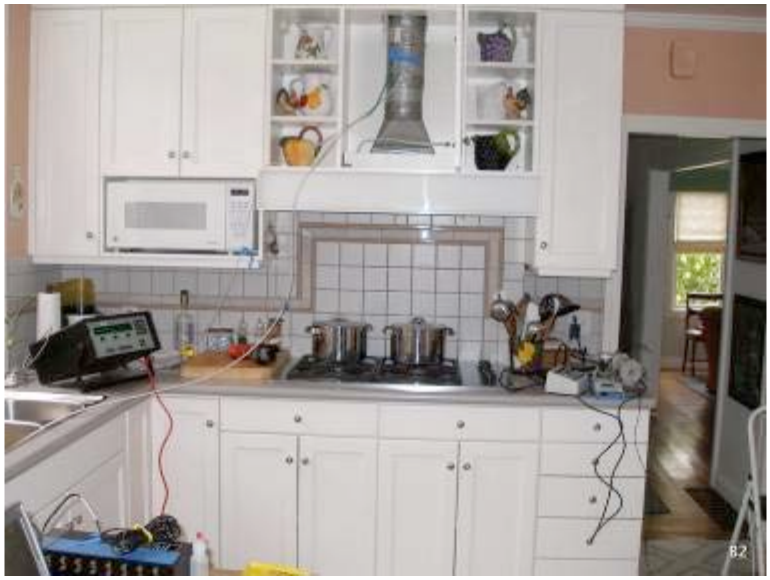

Figure A-43. Exhaust System B2; placement in kitchen.

Figure A-44. Exhaust System B2; side view showing coverage of cook top.

Table A-11. Summary of experiments and results for B2.

Exp	Burners	Fan Setting	Fan (cfm)	Burner Fire Btu/hr	Fan/Plume	Eff
1	RR	High	181	13,900	1.0	91%
2	LF	High	181	13,700	1.0	82%
3	LF RR	High	181	27,600	0.8	80%
4	RR	Low	159	13,900	0.9	89%
5	LF	Low	159	13,700	0.9	68%
6	LF RR	Low	159	27,600	0.7	81%
7	RR	Med	165	13,900	0.9	89%
8	LF	Med	165	13,700	0.9	67%
9	LF RR	Med	165	27,600	0.7	76%
10	LF RR	High	181	27,600	0.8	80%

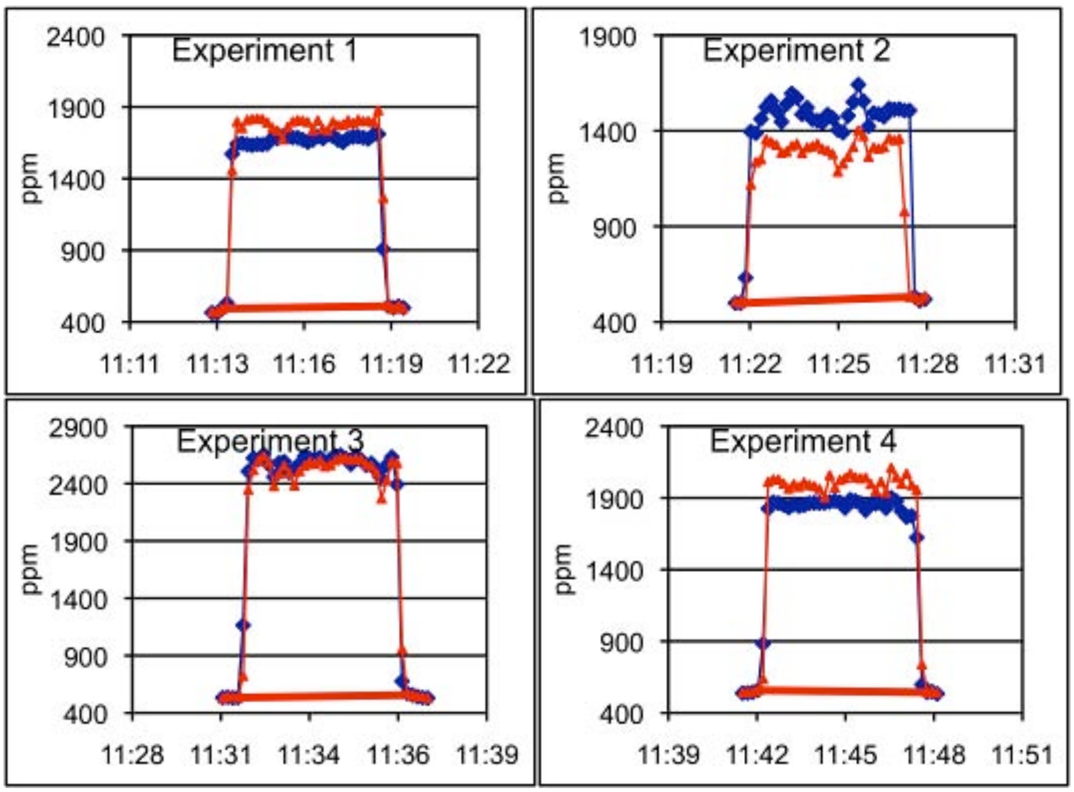

Figure A-45. Measured CO_2 in exhaust system B2, Exps. 1-4.

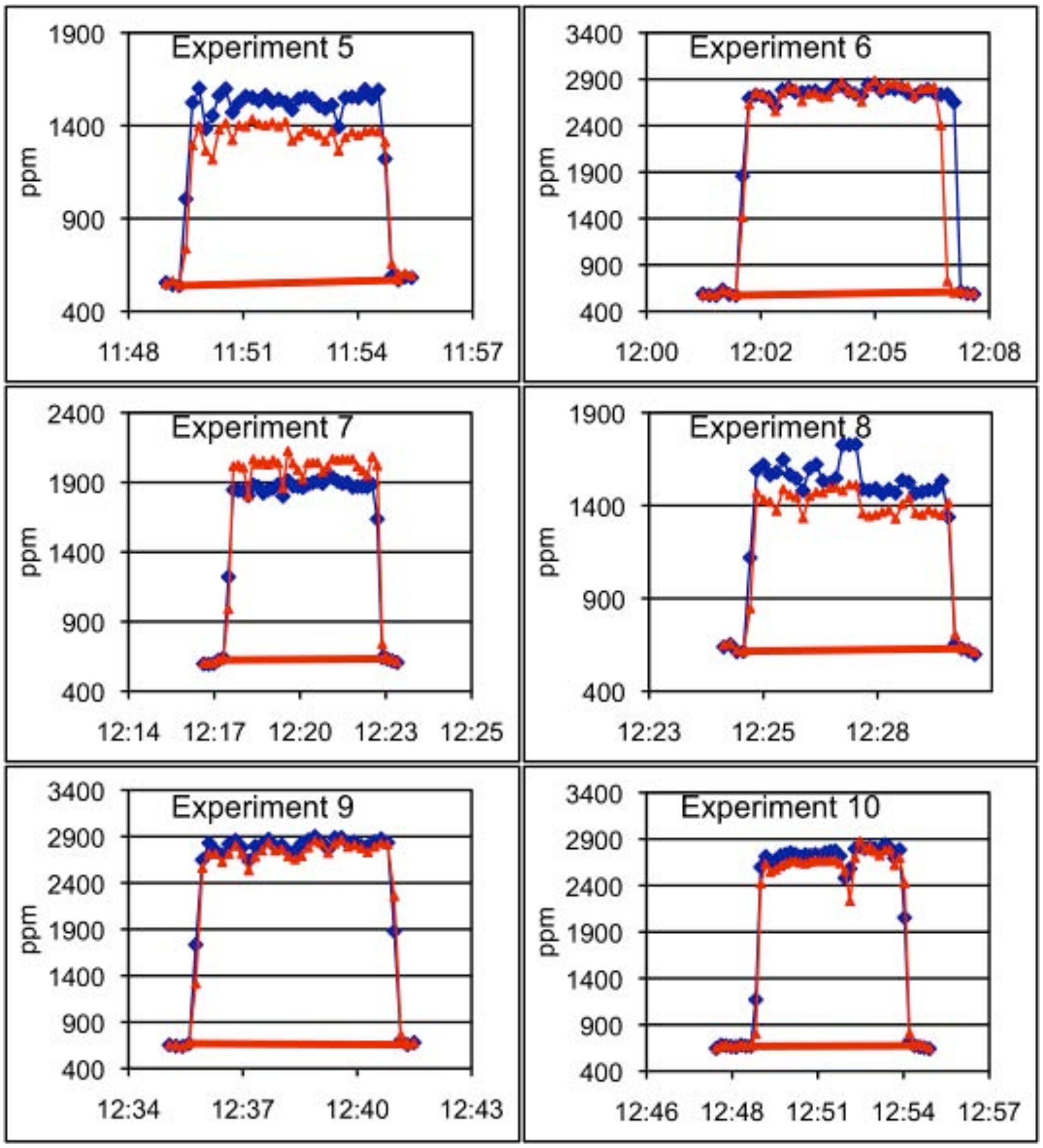

Figure A-46. Measured CO_2 in exhaust system B2, Exps. 5-10.

Exhaust System B3

The house had a VENT-A-HOOD model PYD-18 island style hood. The exhaust served a gas range top only. The unit was 6 years old. The exhaust was sampled ~2.5 m downstream at the outlet along the outside wall. The background sample was not moved during the experiments. This was identified in original project notes as House M.

Figure A-47. Exhaust System B3 showing location in kitchen.

Figure A-48. Exhaust System B3; side view showing coverage of cook top.

Table A-12. Summary of experiments and results for B3.

Exp	Burners	Fan Setting	Fan (cfm)	Burner Fire Btu/hr	Fan/Plume	Eff
1	LR	High	223	15,900	1.0	99%
2	RF	High	223	18,400	1.0	52%
3	RR	High	223	17,700	1.0	67%
4	LF	High	223	16,600	1.0	78%
5	RR LR	High	223	33,600	0.8	71%
6	LR	High	223	15,900	1.0	97%
7	RF LF	High	223	34,900	0.8	49%
8	LF	High	223	16,600	1.0	50%
9	RR LF	High	223	34,300	0.8	58%
10	LR	High	223	15,900	1.0	87%
11	LF	High	223	16,600	1.0	50%

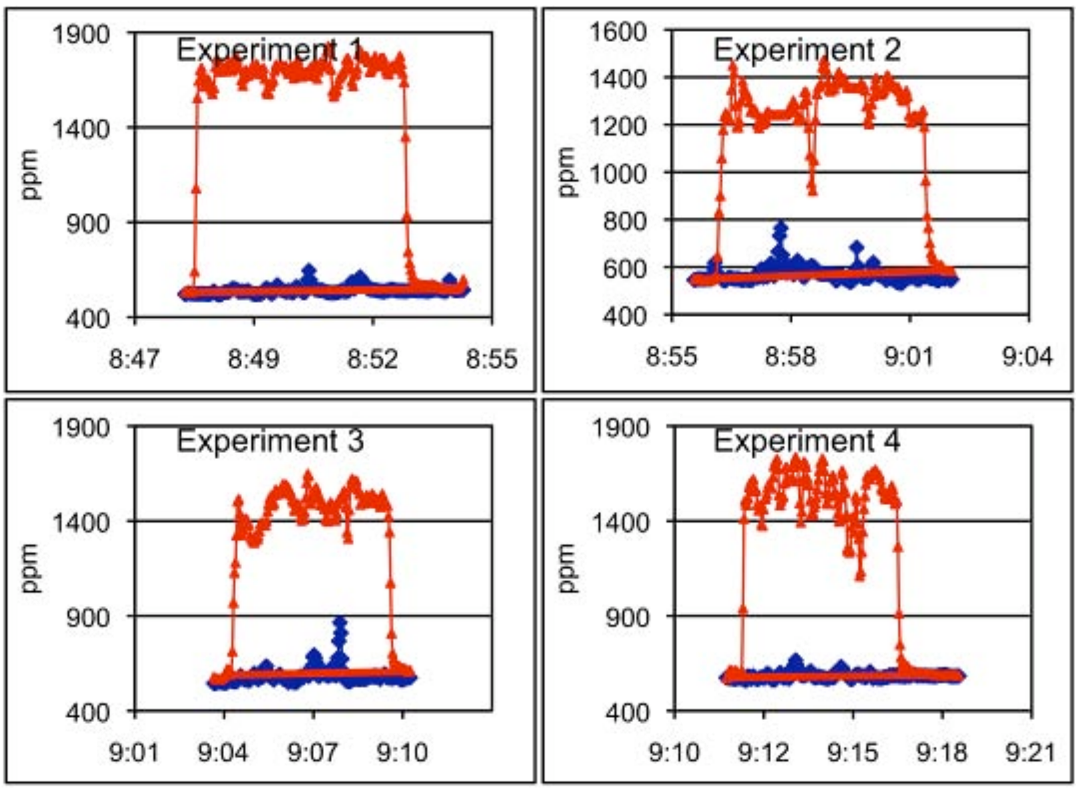

Figure A-49. Measured CO_2 in exhaust system B3, Exps. 1-4.

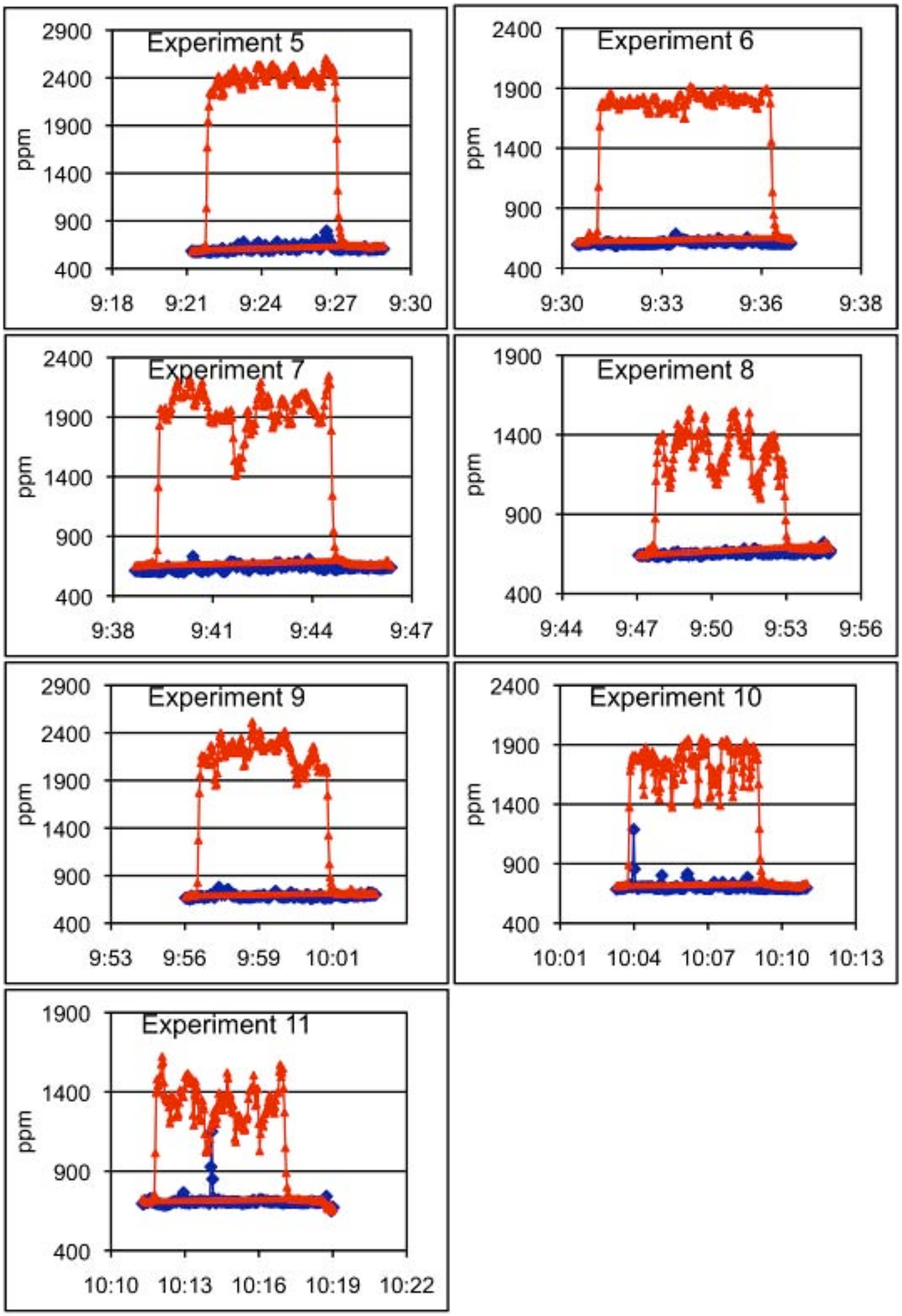

Figure A-50. Measured CO_2 in exhaust system B5, Exps. 5-11.

Exhaust System B4

This hood was a KENMORE model 233.52340590. The exhaust served a 'dual-fuel' unit with a gas range and an electric oven. The unit was 8 years old. The exhaust was sampled ~1.5 m downstream by inserting a piece of copper tubing as far up into the duct above the unit as possible. The background sample was not moved during the experiments. Experiments 6, 11, and 15, simulated cooking activity by stirring a pot for 30 seconds every minute. This was identified in original project notes as House G.

Figure A-51. Exhaust System B4; note pass-through behind range.

Figure A-52. Exhaust System B4; side view showing coverage of cook top.

Table A-13. Summary of experiments and results for B4.

Exp	Burners	Fan Setting	Fan (cfm)	Burner Fire Btu/hr	Fan/Plume	Eff
1	RF	High	254	14,400	1.2	90%
2	LR	High	254	12,600	1.3	95%
3	LF	High	254	9,000	1.4	96%
4	RF LR	High	254	27,000	1.0	83%
5	RF	High	254	14,400	1.2	83%
6	RF	High	254	14,400	1.2	67%
7	LR	Med	205	12,600	1.0	85%
8	LF	Med	205	9,000	1.2	90%
9	RF	Med	205	14,400	1.0	75%
10	RF LR	Med	205	27,000	0.8	73%
11	RF	Med	205	14,400	1.0	64%
12	LR	Low	88	12,600	0.4	68%
13	RF	Low	88	14,400	0.4	49%
14	LF	Low	88	9,000	0.5	62%
15	RF	Low	88	14,400	0.4	41%
16	RF LR	Low	88	27,000	0.3	44%

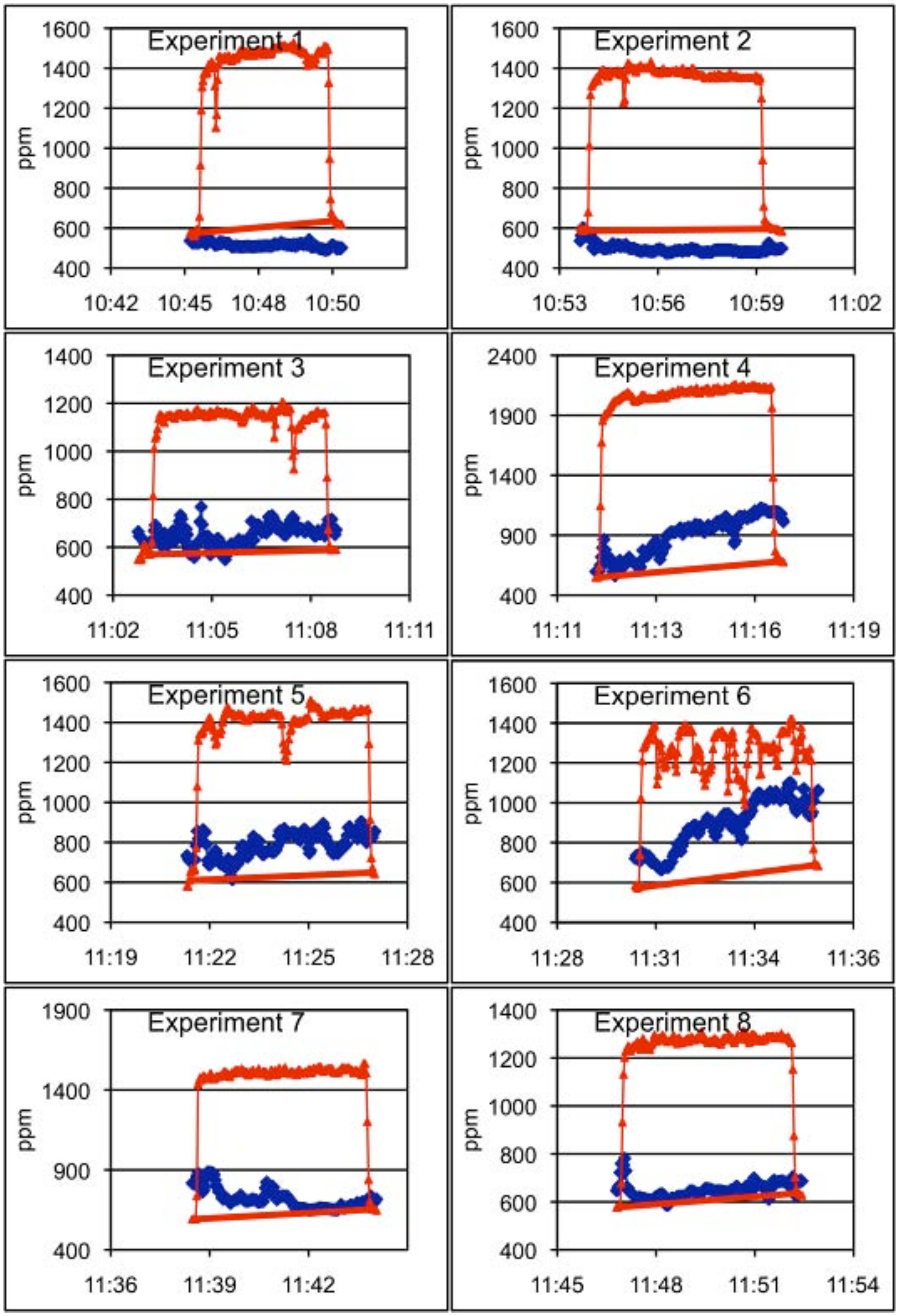

Figure A-53. Measured CO_2 in exhaust system B4, Exps. 1-8.

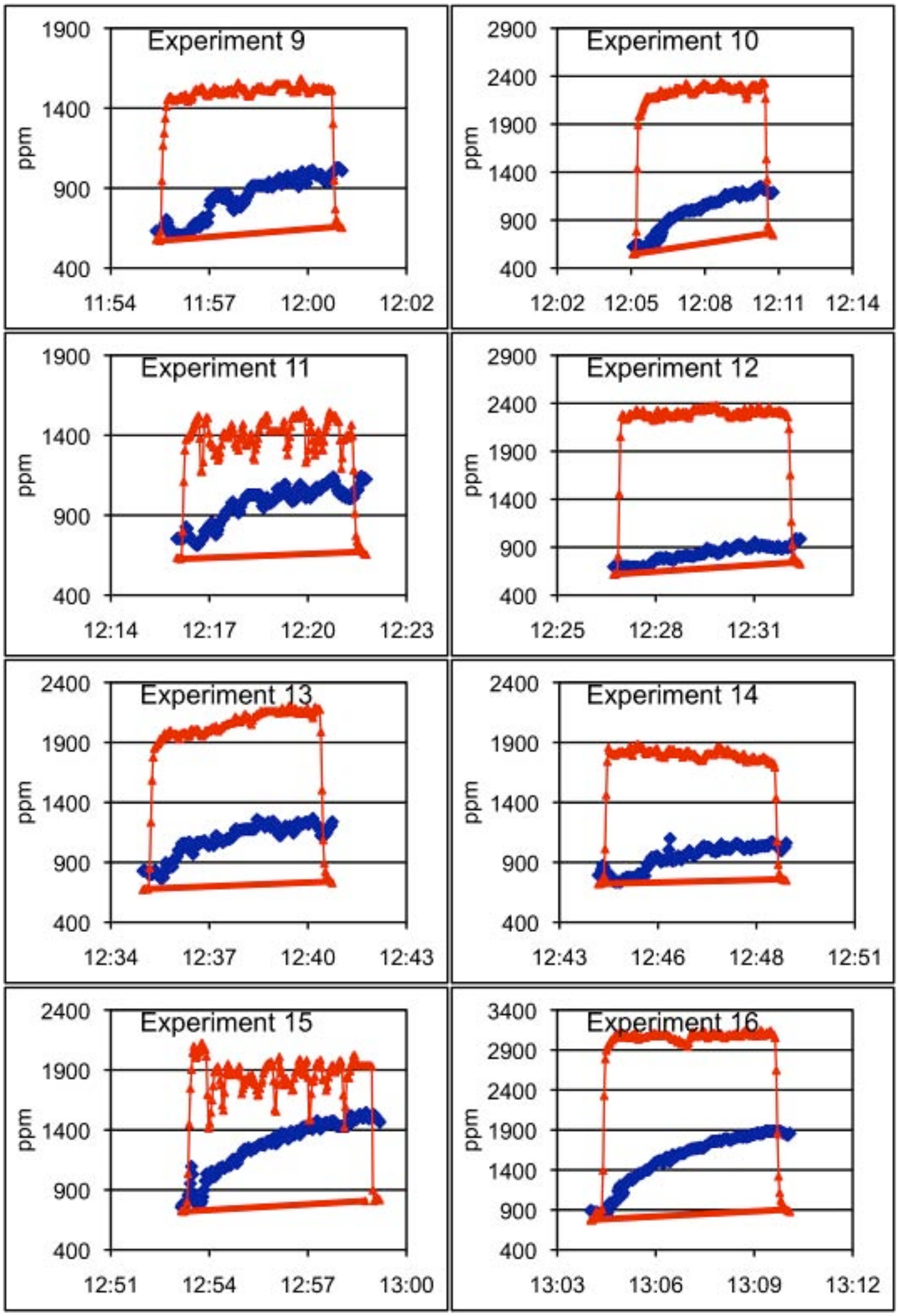

Figure A-54. Measured CO_2 in exhaust system B4, Exps. 9-16.

Exhaust System B5

This house had a VENT-A-HOOD model NP9-236 hood. The exhaust served a range/oven combination. The unit was 3 years old. The exhaust was sampled ~1.5 m downstream by inserting a piece of copper tubing as far up into the duct above the unit as possible. The background sample was not moved during the experiments. This was identified in original project notes as House N.

Figure A-55. Exhaust System B5; placement in kitchen.

Figure A-56. Exhaust System B5; top view showing coverage of cook top.

Table A-14. Summary of experiments and results for B5.

Exp	Burners	Fan Setting	Fan (cfm)	Burner Fire Btu/hr	Fan/Plume	Eff
1	RF	High	314	15,500	1.5	95%
2	Oven	High	314	29,500	1.2	94%
3	LR	High	314	15,900	1.5	89%
4	CF	High	314	15,700	1.5	99%
5	CR	High	314	15,600	1.5	86%
6	RF CR	High	314	31,200	1.2	91%
7	Oven	Low	255	29,500	1.0	93%
8	LR	Low	255	15,900	1.2	90%
9	RF	Low	255	15,500	1.2	81%
10	CR	Low	255	15,600	1.2	89%
11	CF	Low	255	15,700	1.2	88%
12	RF CR	Low	255	31,200	1.0	82%

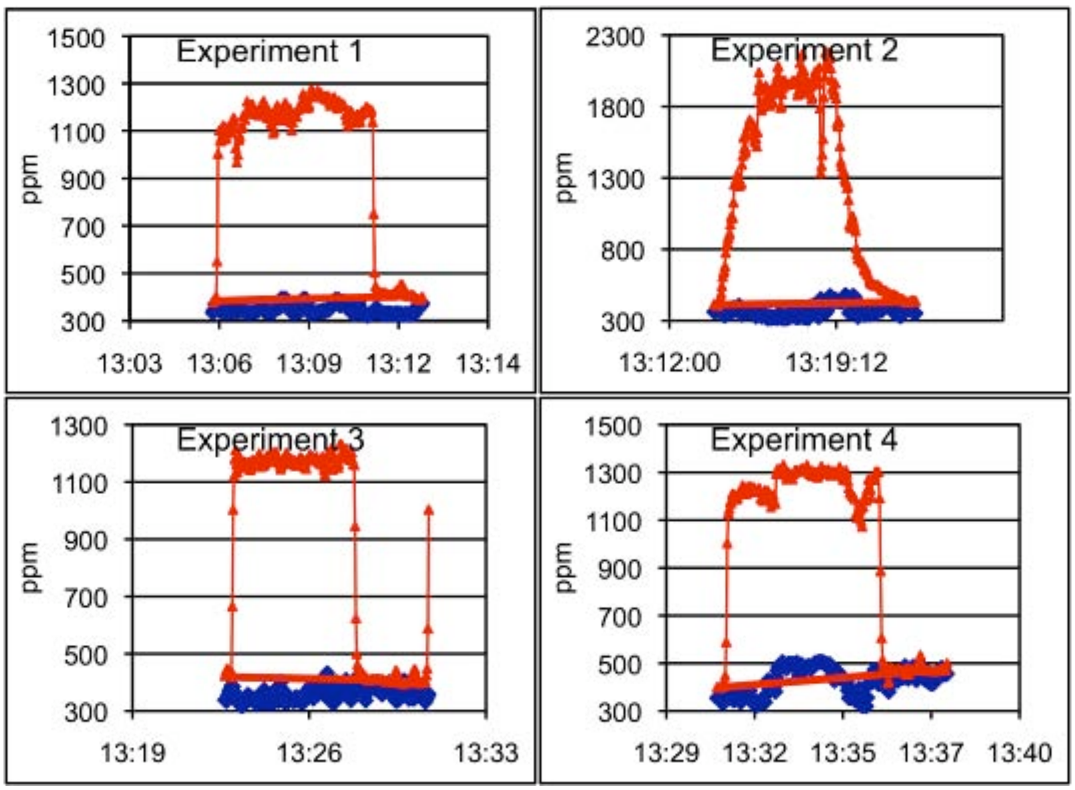

Figure A-57. Measured CO_2 in exhaust system B5, Exps. 1-4.

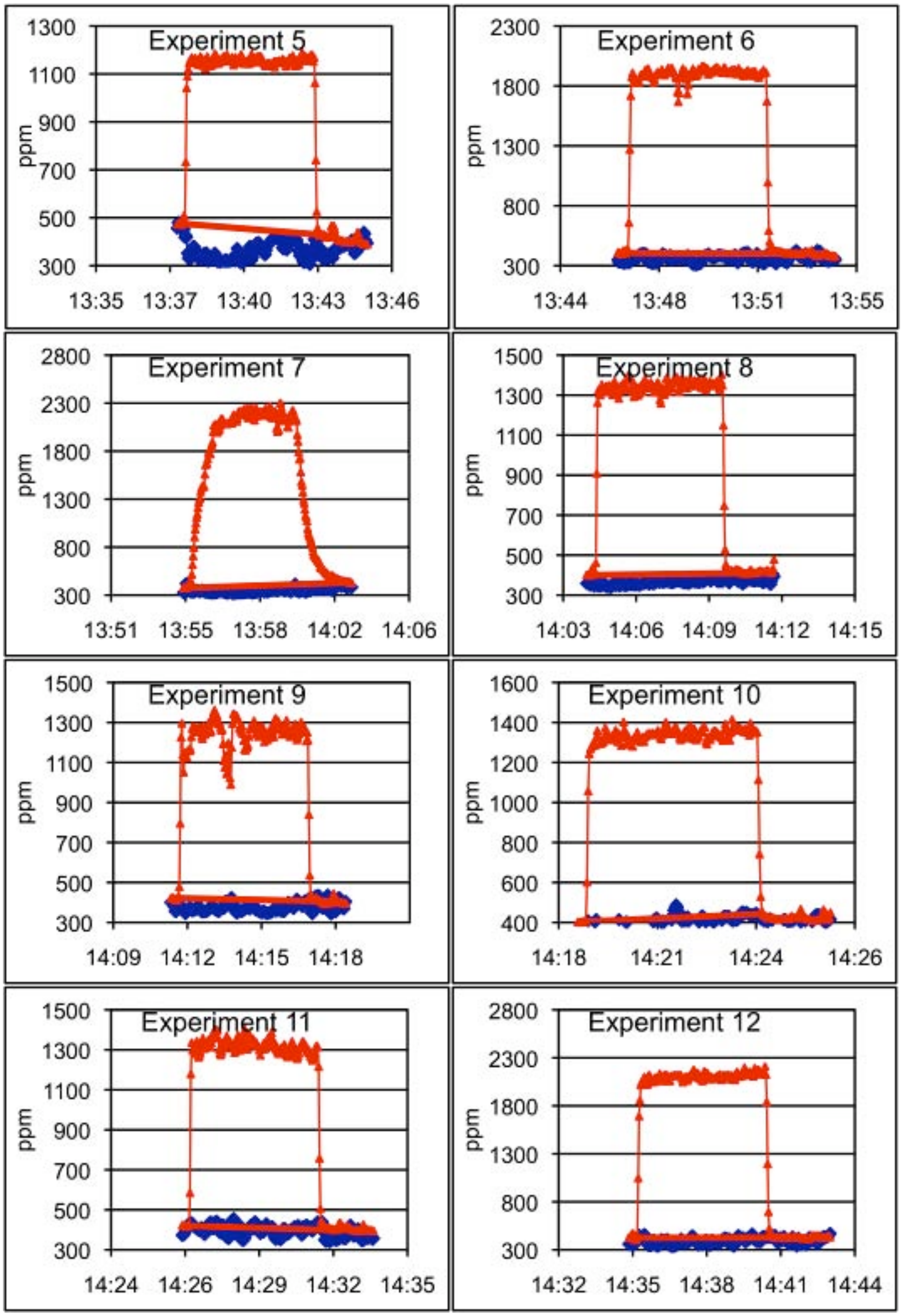

Figure A-58. Measured CO_2 in exhaust system B5, Exps. 5-12.

Exhaust System B6

The house had a VENT-A-HOOD model PYD-18 island style hood. The exhaust served a gas range top only. The unit was 6 years old. The exhaust was sampled ~2.5 m downstream at the outlet along the outside wall. Some experiments simulated cooking activity by stirring a pot for 30s every minute (see report). This was identified in original project notes as House I.

Figure A-59. Exhaust System B6; location in kitchen.

Figure A-60. Exhaust System B6; side view showing coverage of cook top.

Table A-15. Summary of experiments and results for B6.

Exp	Burners	Fan Setting	Fan (cfm)	Burner Fire Btu/hr	Fan/Plume	Eff
1	RR	High	382	9,900	2.2	89%
2	LF	High	382	19,100	1.8	95%
3	LR	High	382	11,000	2.1	80%
4	RR LF	High	382	29,000	1.6	93%
5	RR RF	High	382	24,100	1.7	84%
6	RF	High	382	14,200	2.0	85%
7	RR LR	High	382	20,900	1.7	80%
8	RF LF	High	382	33,400	1.5	89%
9	LR LF	High	382	30,100	1.5	86%
10	LR	High	382	11,000	2.1	74%
11	RF	High	382	14,200	2.0	85%
12	LR	High	382	11,000	2.1	73%
13	RF	High	382	14,200	2.0	88%

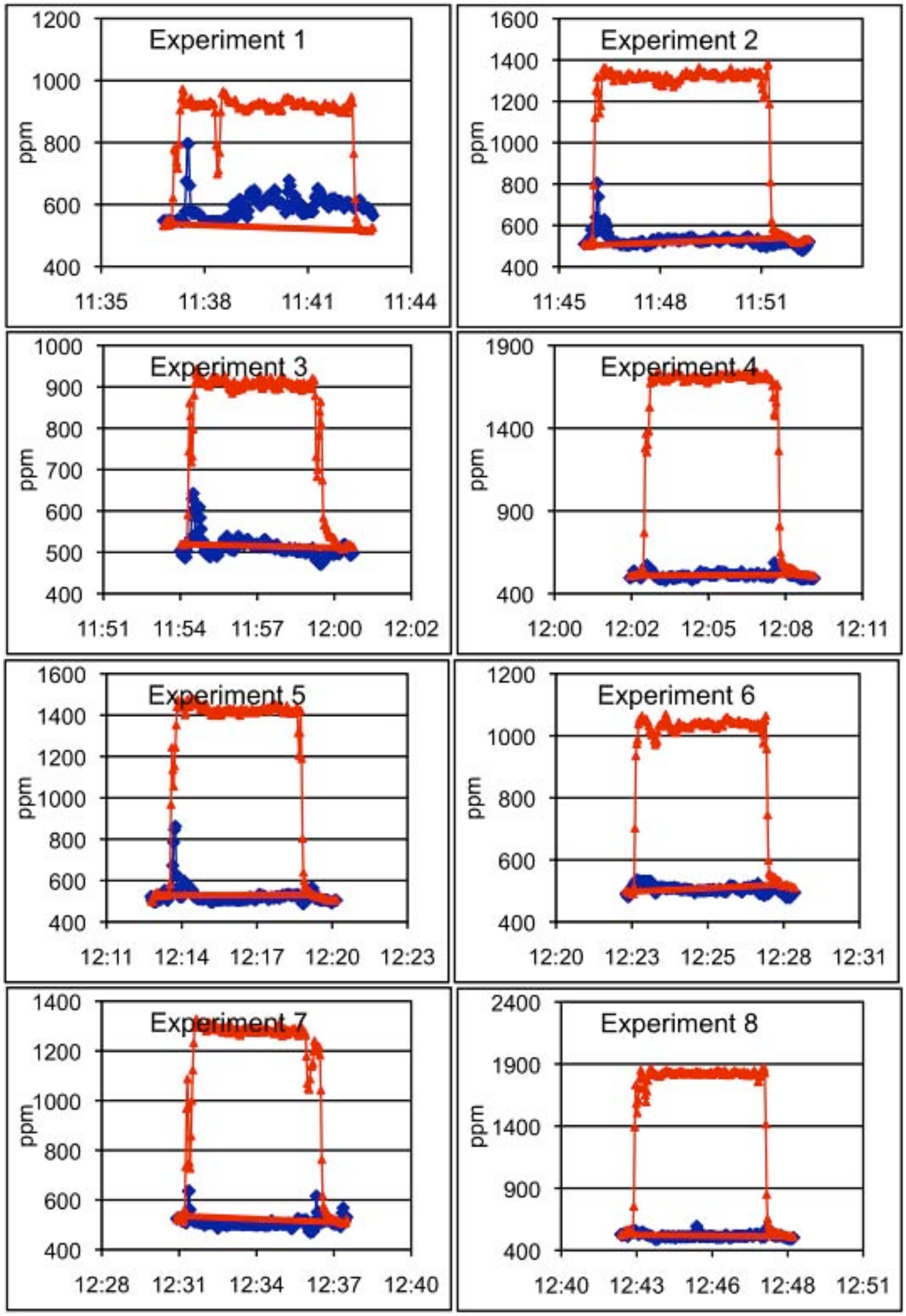

Figure A-61. Measured CO_2 in exhaust system B6, Exps. 1-8.

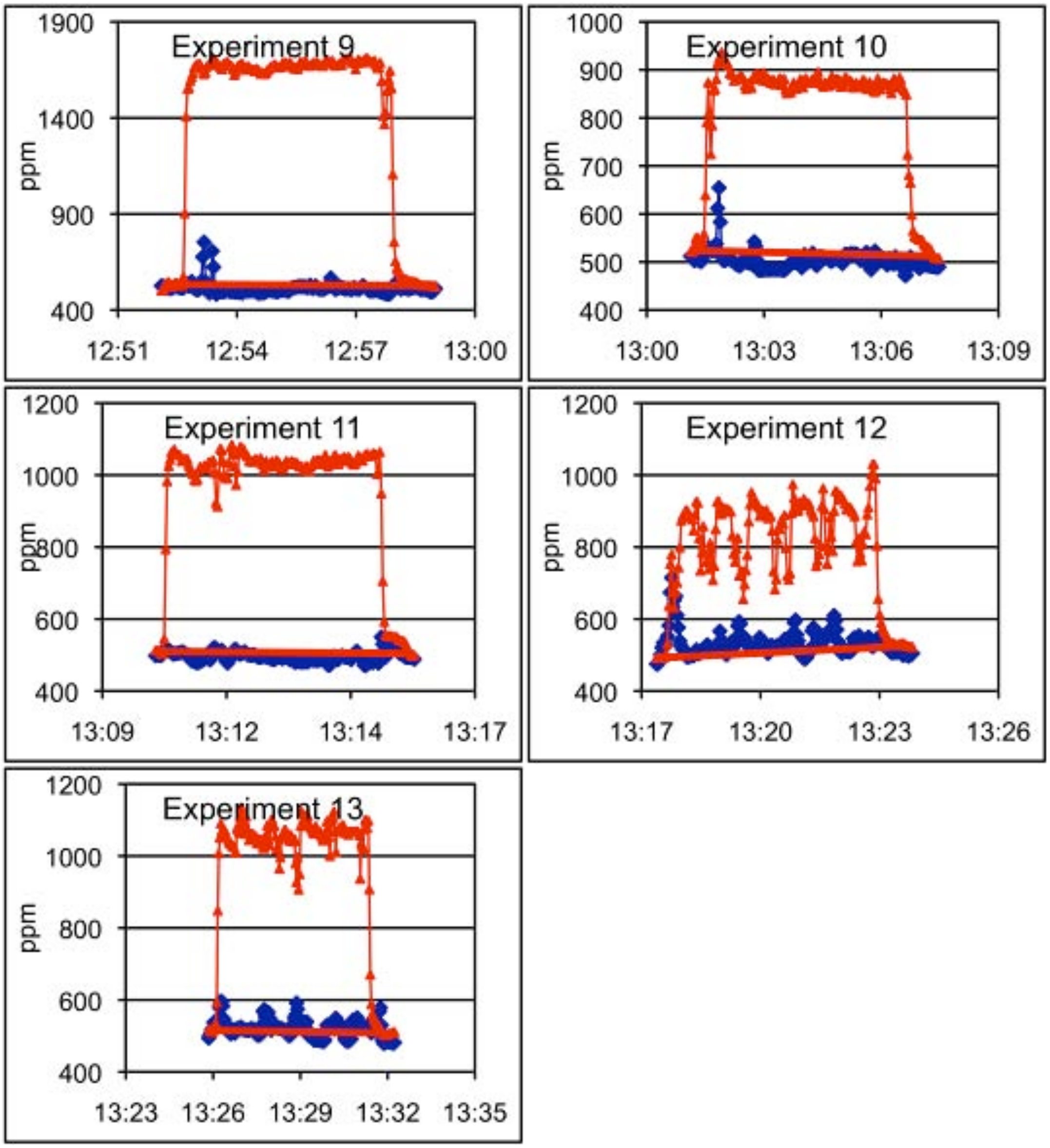

Figure A-62. Measured CO_2 in exhaust system B6, Exps. 9-13.