LBNL Report

Measured Performance of Over the Range Microwave Range Hoods

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Abstract

The California residential building code requires kitchen exhaust ventilation to protect indoor air quality. The requirement can be met with a kitchen exhaust fan or a range hood that conforms to airflow and sound specifications based on certified, standard test results. Appliances that integrate an exhaust fan with an over the range microwave (OTRs) are popular for their space saving utility; but for years there were none with the certified performance data required for building code compliance. This project, initiated during that period, aimed to evaluate OTR models found in new California homes and compare their performance to range hoods that minimally met code requirements. The study aimed to expand on limited information available about OTR performance with a particular focus on measuring the fraction of cooktop-generated air pollutants that are captured and removed by the exhaust devices, a parameter called "capture efficiency". Airflow and capture efficiency (CE) were measured in a simulated kitchen in Berkeley Lab's FLEXLAB facility. Airflows were measured using several variations of a balanced-pressure flow method (Walker et al. 2001) including a protocol that had been used in the California Healthy Efficient New Gas Homes (HENGH) field study. Measurements were made for six OTRs observed in the field study, including three with certified test results (published after the start of this project) for airflow and sound. Measurements were also made on two standard range hoods with comparable airflows and costs to the OTRs, when accounting for the microwave functionality. CE was measured using the CO_2 emitted from burners while heating pots of water (POW) as a tracer and calculating the ratio of added CO_2 in the exhaust flow over the total CO_2 generated from burning fuel. Results show that OTRs generally met the California code requirements for airflow, which are the same as those of the residential ventilation standard of ASHRAE. It was determined that the field protocol used in HENGH study homes was biased low by ~14% on average. The CE performance of OTRs tested in this study were consistent with those tested under controlled conditions in prior studies, showing CE increasing with airflow and being higher for emissions occurring at the back cooktop burner(s) compared with front burner emissions. The measured CE covered a range of 40% to 85% for the front burners and 60% to 100% for the back burners. The relationship of CE to airflow for OTRs was within the range of those found for standard range hoods in this study and prior studies, with the key caveat that OTRs appear to have more consistent CE performance for emissions on the front burner.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

Page

CHAPTER 1: Introduction

Venting range hoods and appliances mounted over the cooktop that combine a microwave oven and an exhaust fan (often called "over the range" microwaves or OTRs) can enable efficient removal of odors, moisture, and pollutants emitted during cooking activities. The term "venting" means that the hoods are connected by ductwork to the outdoors; they are designed to extract air from the kitchen, above the range, and expel or exhaust it outdoors. Several studies including both modeling and experimental tests have shown reductions in cooking related indoor air pollutants due to range hood use (Logue et al. 2013; Singer et al. 2012; Rim et al. 2012; Delp and Singer 2012; Lunden, Delp, and Singer 2015; Singer et al. 2017; Revzan 1986). While OTRs can be considered as a subset of the range hood product category, in this report the term "range hood" is sometimes used to distinguish devices that have only this functionality from devices that also include a microwave oven, which are described as OTRs.

Over-the-range microwave range hoods are popular for their space saving utility and are often installed in new homes. In 2015, LBNL conducted an online survey of residents of California single-family homes built in 2002 or later and found that roughly half of the respondents that provided information on their kitchen ventilation had OTRs, with the other half having traditional range hoods (Appendix A of Chan et al., 2019). The vast majority of homes for which data were reported were built before the California building code started to require kitchen exhaust ventilation; yet roughly 90% of the range hoods and 80% of the OTRs were reported to vent to the outdoors. In a follow-up field study of ventilation and indoor air quality in 70 single, detached homes constructed in California since 2011 (the "HENGH" study) 38 of the homes had venting OTRs and 32 had venting range hoods (Chan et al., 2019).

There are several relevant measures of range hood performance. The two most commonly used, and the measures for which data are most readily available, are airflow and sound level. These metrics are measured using standard test procedures published by the Home Ventilating Institute (HVI Publications 914 and 915). HVI certifies and publishes test results in a free online directory (HVI 2019), which includes both standard range hood and OTRs. HVI also provides guidance on minimum and recommended exhaust hood airflow rates in units of cubic feet per minute (cfm) per linear foot (lf) of cooking appliance width (HVI 2008). For a 30-inch (76.2 cm) wide range, these translate to minimum and recommended airflows of 100 cfm (47 L/s) and 250 cfm (118 L/s). The California Building Code requires every new or renovated home to have kitchen exhaust ventilation; when the requirement is met with a venting range hood or OTR, the device must move at least 100 cfm (50 L/s) at a sound level of 3 sone or less. These requirements match those of Standard 62.2 of the ASHRAE building performance society, which provides minimum ventilation requirements for acceptable indoor air quality in residences. The California Building Code requires that the kitchen exhaust fan performance either be verified on site or that installed products have HVI-certified airflow and sound ratings.

A third metric, for which very limited data are available, is capture efficiency (CE). Capture efficiency is defined as the fraction of contaminants emitted at the cooktop that are directly pulled into the range hood and exhausted to the outdoors before mixing throughout the house. A CE of 100% means all of the cooking pollutants are exhausted directly to the outside, and a CE of zero means that none of the cooking pollutants are directly exhausted, allowing all of them to mix with indoor air. Capture efficiency was first studied decades ago (e.g., Revzan, 1986; Li and Delsante, 1996) and the metric has received increasing attention since it was used in studies conducted by LBNL in the early 2010s (Singer et al., 2012; Delp and Singer, 2012). ASTM international recently published a standard test method for range hood capture efficiency, E-3087-2018. LBNL played a central technical role in developing the standard, as described in Kim et al. (2018).

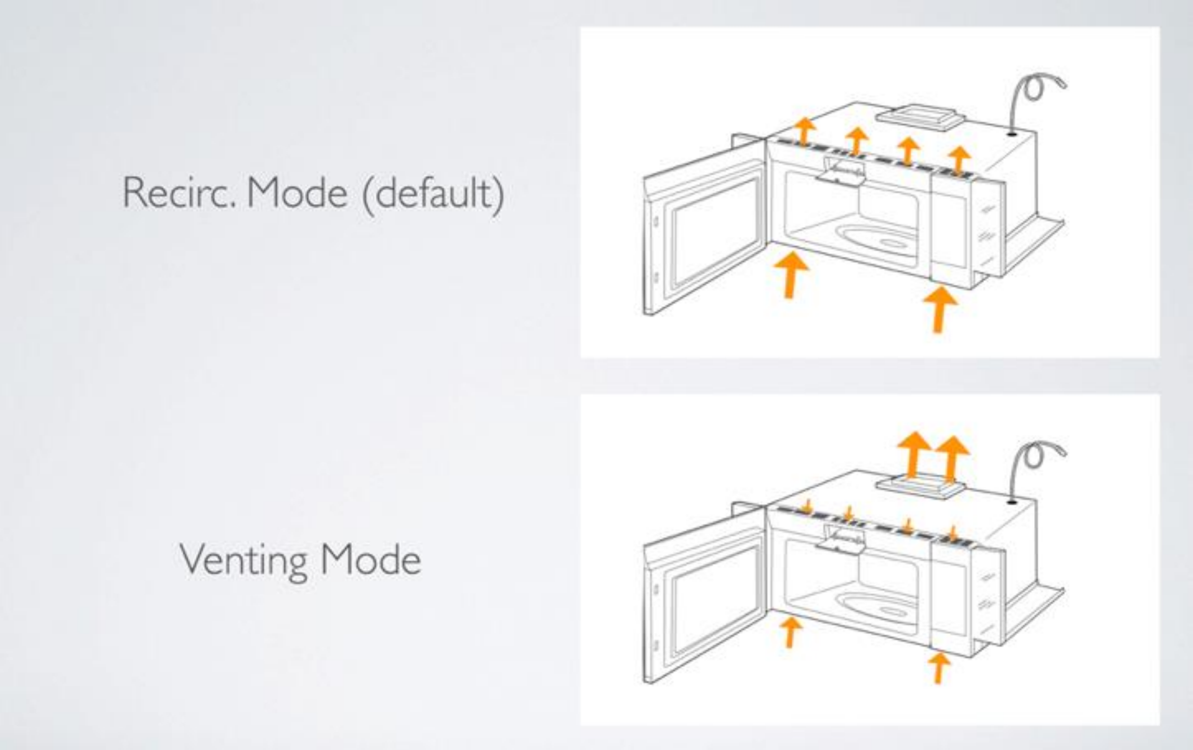
The airflow of a range hood installed in a home can differ from the value published by HVI because the static pressure in the duct system may be substantially higher than the duct static pressure in the HVI test. And the effect of higher downstream duct pressures varies based on the performance curve of the fan and the relationship of airflow to pressure in the duct system, both of which are non-linear. The HVI test procedure sets a downstream pressure for the range hood fan operating at its highest setting then measures airflow at other settings using the same system pressure curve. The ASHRAE 62.2 and California Title 24 standards require range hoods that move at least 100 cfm or 50 L/s of airflow with a downstream duct static pressure of 62.5 Pa. Yet the vast majority of range hoods listed in the HVI catalog have been tested at downstream static pressures of only 25 Pa when the fan is operating at high speed. And static pressure is often much lower at the "working speed" which is the setting designed to meet the standard flow requirement of 100 cfm or 50 L/s.

The installed sound level can also be higher than the value reported in a standard test, resulting from vibrations in the duct system or a loose mounting of the hood. However, the test that provides sound level results in sones cannot be replicated in a field setting.

In consideration of the potential differences between rated and installed airflows, it is important to collect data on airflows of hoods as installed in homes. A method to conduct airflow measurements of range hoods and other exhaust (or supply) fans was described by Walker et al. (2001). Briefly, the method involves affixing a calibrated fan to the exhaust (or supply) fan via a transition piece that allows for the differential pressure between the transition and the room to be measured. The calibrated fan is adjusted to the point that the pressure between the transition and the room is balanced. At that point, the airflow through the calibrated fan is matching the airflow through the exhaust (or supply) fan. For range hoods and OTRs, the challenge is to construct a transition that covers all air inlets from the room.

Compared to standard range hoods, OTRs present a greater challenge for determining airflow as installed. When configured to operate in recirculation mode, air is drawn into OTRs through inlets on the underside and expelled through vents at the top and front, above the door (top panel of Figure 1). When configured to exhaust air to the outdoors (venting mode), air is expelled through an opening at the top or back (which must be punched out during installation); and air enters through the openings at the bottom and through the vents above the door (bottom panel of Figure 1). Air can additionally enter through small holes and gaps in the outer shell; but due to their small cumulative area these pathways likely contribute very little as inlets. The OTR flow dynamics complicate the measurement of airflow when there is no access to the outlet. Applying the balanced-pressure flow method requires a customized transition box that covers both bottom and top air inlets.

Figure 1: OTRs Flow Pathway



When this research was initiated there were very few published data about OTR airflows. When the research project was first proposed, there were no OTRs listed in the HVI category (and thus none certified to meet ASHRAE/California standards). In August 2019, the HVI catalog had performance data for 219 unique model numbers, which included multiple color/finish variations of 57 OTR models. And the listed performance data suggest that these could represent as few as 9 distinct models of hardware, each marketed under several brand names. More information about this analysis is presented later in the report.

Research studies have used varied approaches for OTR airflow measurements under controlled lab conditions and as installed in the field. Lab studies have measured OTR airflows at the air outlets to take account of exhaust flows from both top and bottom inlets (Delp and Singer 2012; Walker et al. 2016; Lunden, Delp, and Singer 2015). In field studies, it is often not possible to access the exhaust outlet, so airflow has been measured by fitting a transition at the inlet. In a 2012 study, Singer et al. reported airflows for 2 OTRs based on measurements at the bottom inlet only. (The researchers did not at the time understand the OTR flow dynamics described above). The Healthy Efficient New Gas Homes (HENGH) study measured ventilation equipment performance in 70 detached houses built to meet the 2008 or later California Building Energy Efficiency Standards (Chan et al., 2019). That study estimated airflows for 38 OTRs with an approach that restricted air coming in through the top (by covering that inlet with tape) and measuring the air entering only at the bottom. As shown later in this report, that approach produces biased results; and the bias has not been evaluated previously. Prior studies reporting OTR airflow measurements are summarized in Table 1 below.

Table 1. Measured data on OTR airflows

Study	Lab/field	Number of OTR tested	OTR Airflow test method
Singer et al. (2012)	field	2	Balanced-pressure method at bottom inlet, top inlet open
Delp and Singer (2012)	lab	1	Balanced-pressure method at exhaust outlet
Lunden et al. (2015)	lab	1	Balanced-pressure method at exhaust outlet
Walker et al. (2016)	lab	1	Balanced-pressure method at exhaust outlet
Singer et al. (2017)	field	2	Balanced-pressure method at bottom inlet; top inlet taped
HENGH	field	38	Balanced-pressure method at bottom inlet; top inlet taped
HVI 2019	lab	9-57[a]	HVI standard flow test procedure

[a] While there are 57 unique model groups listed, matching of performance results for airflow and sound suggest that they may represent as few as 9 unique pieces of hardware

The performance metric that most directly addresses the effectiveness of a range hood (or OTR) at protecting indoor air quality is capture efficiency (CE). LBNL has conducted several studies of range hood and OTR CE in the laboratory and in the field, using varied test methods.

Singer et al. (2012) used a dynamic CO_2 mass balance method that involved heating of pots of water (POW) on a gas cooktop. CO_2 concentration was measured in the exhaust duct and combined with the measured airflow to calculate a mass flow. The CO_2 mass emission rate from natural gas combustion was calculated based on the firing rate of the burners and consideration of the fuel composition. Capture efficiency was measured and reported for 11 range hoods, 2 OTRs and 2 downdraft systems installed in occupied homes. Many tests were conducted for each kitchen exhaust device, evaluating the effect of varied burner selection and varied airflow setting. The source locations were one front burner, one back burner, front and back burners simultaneously, and the oven. Temporally resolved CE was calculated using time-series measurements of airflow (Q, m^3/min), the CO_2 concentration differences between the room background and the range hood exhaust (mL/m^3), and the CO_2 emission rate (E, mL/min), as shown in Equation 1 below:

$$CE = Q * (C_v - C_0) * 10^6 / E \tag{1}$$

The source of the CO_2 was the natural gas burners on the cooktop. The CO_2 emission rate was calculated from stoichiometry, assuming complete combustion and the measured gas fuel flow rate (based on information about the molar fraction of carbon in the fuel). Results indicate that CE varied by hood geometry, higher airflow generally led to higher CE, and the CE was much higher for the back burner.

Delp and Singer (2012) conducted laboratory tests for 6 range hoods and one OTR using the same approach, with CO_2 from gas burners as the tracer. That study showed very similar results to the field study, with CE values ranging from 17%–100% with a strong dependency on airflow and burner, pot, and range hood geometries.

Walker et al. (2016) and Kim et al. (2018) describe development of a steady-state CE test method in a controlled chamber. Instead of using gas burners with boiling pots of water as a source, a standardized tracer gas emitter was used to deliberately emit CO_2 over the heated surface. Steady-state CO_2 concentrations were measured in the chamber (C_c), in the hood exhaust stream (C_e), and at the air inlet to the chamber (C_i). The capture efficiency was calculated using Equation 2. The developed method was adopted as ASTM Standard E-3087-2018.

$$CE = (C_e - C_c) / (C_e - C_i) \tag{2}$$

In another field study, Singer et al. (2017) developed and applied a ratio test method that also used CO_2 emitted from burners with boiling pots of water as a tracer. The approach compared the flow of CO_2 through the hood under the normal operating condition to the flow of CO_2 when a foil curtain was used to extend the hood over the cooktop to ensure perfect or nearly perfect capture. This approach assumes no change in airflow between the conditions, meaning the CO_2 mass flow changes proportionally with the CO_2 concentration. CE is calculated using CO_2 concentrations measured under the normal operating condition (C_N) and with the hood extended to create nearly perfect capture conditions (C_{100}), and background concentrations with the cooking burners off (C_0), as shown in Equation 3.

$$CE = \frac{(C_N - C_0)}{(C_{100} - C_0)} \tag{3}$$

Using a dynamic room-based method, Lunden et al. (2015) determined the CE for particles produced during cooking. Two cooking procedures - pan-frying a burger and stir-frying string beans - were conducted in a ventilated test room. Particle concentrations were measured at the room exhaust with and without the range hood operating ($C_{\text{room-with hood}}$; $C_{\text{room-no hood}}$). Background concentrations (C_{bg}) were measured and CE was calculated using Equation 4. That study also reported CE calculated with the CO_2 mass balanced method, which was conducted at the same time. Results showed lower CE values for PM that for CO_2.

$$CE = 1 - \frac{\left(C_{room-with\,hood} - C_{bg}\right)}{\left(C_{room-no\,hood} - C_{bg}\right)} \tag{4}$$

There have been several studies reporting capture efficiency results for near-range exhaust devices, including range hoods, OTRs, and downdraft exhaust devices; but these included only 7 OTRs, as shown in Table 2.

Table 2. Studies Reporting Capture Efficiency Measurements

Study	Total Devices	OTRs	CE test method	Lab or field	Burner configurations
Singer et al. (2012)	15	2	POW, CO2 mass balance	Field	1 front, 1 back; 1 front + 1 back
Delp and Singer (2012)	7	1	POW, CO2 mass balance	Lab	2 front; 2 back
Lunden et al. (2015)	4	1	POW/real cooking; CO2 mass balance; PM mass balance	Lab	2 front; 2 back
Walker et al. (2016)	8	1	Chamber steady-state, ASTM development	Lab	1 front + 1 back
Singer et al. (2017)	6	2	POW, CO2 Ratio method	Field	2 front; 2 back
Kim et al. (2018)	2	0	Chamber steady-state similar to ASTM	Lab	2 front; 1 front; 1 back
This study	8	6	POW, CO_2 mass balance	Lab	2 front; 2 back; 1 front + 1 back
Total	50	13			

The study reported here was designed to substantially expand the state of knowledge about OTR capture efficiency and also to investigate the potential bias in testing of OTR airflows in the HENGH field study. We selected OTR models that were seen in homes in the recent HENGH study and from the HVI product directory. We conducted the following measurements:

a. Measure airflows of OTRs installed with a fixed duct configuration that is a reasonable surrogate for many homes;
b. Validate new method for measuring airflows at inlet of OTRs;
c. Measure CE and sound of OTRs installed as above;
d. Compare CE vs. airflow relationship of OTRs to standard range hoods within similar cost range;
e. Estimate bias of method used to measure airflow in HENGH field study.

CHAPTER 2:
Project Approach

OTR Microwaves Range Hood Selection

The original objective of this task was to assess whether microwave exhaust fans (OTRs) which were at the time not certified to meet the performance specifications in the code, could provide equivalent protection to range hoods that are minimally compliant with current code. After the project was approved and initiated, certified airflow and sound ratings were published for numerous OTRs via the HVI catalog. The objective was revised somewhat to evaluate the relative performance of OTRs and conventional range hoods of similar cost, with a focus on capture efficiency.

Six OTR microwave range hoods were selected and tested in this study. Models were selected from among OTRs seen in the HENGH field study and from products identified in the HVI Certified Home Ventilating Products Directory.

Our search of the microwave subcategory of the kitchen ventilation product category in the HVI catalog, conducted in August 2019, found 861 records of test results for 219 models. All were listed under the same brand owner, the Whirlpool corporation. The models were listed under 5 brand names: Whirlpool, Jenn-air, KitchenAid, Amana and Maytag. We sorted all 219 models by model number, blower capacity, speed settings, air flow and sound level. This sorting identified what appeared to be 57 unique models, each with variants representing different colors or finishes. The 57 models were grouped by their performance specifications. The grouping identified 9 sets of performance specifications, suggesting multiple models using the same hardware. From this list, we selected three OTR models that were observed in HENGH homes, as indicated in Table 3. For one of the models, the precise model that had been observed in HENGH homes (ending in "AS") was no longer available, so we procured one with the same base model number but a different ending code ("HB"), incorrectly thinking that the difference was aesthetic. In fact, the tested unit had a larger blower (rated at 300 cfm) compared with the model observed in HENGH homes (blower rated at 220 cfm).

We also selected 3 OTRs observed in many homes visited in the HENGH field study, as shown in Table 3. These included two GE models and one Frigidaire model. By the time of our lab study, the Frigidaire model had been discontinued by the manufacturer and was not generally available. We procured and tested the closest model that we could find, while acknowledging that the model we tested had a nominal 220 cfm blower whereas the model seen in the HENGH field study had a nominal 300 cfm blower.

Table 3. Comparison of OTR Models Tested with Models in HENGH Study

Brand	Product Series	Number in HENGH homes	Available from retailers in July 2019	Models tested in lab	HVI certificated in July 2019
Whirlpool	WMH31017AS	4	Yes [a]	WMH31017HB	Yes
Whirlpool	WMH53520 series	3	Yes	WMH53520CB	Yes
Whirlpool	WMH32519 series	1	Yes	WMH32519HV-4	Yes
GE	JVM3160 series	4	Yes	JVM3160RF5SS	No
GE	JVM7195 series	12	Yes	JVM7195SK3SS	No
Frigidaire	FFMVLS series	7	No [b]	FFMV1645TS	No
Sub-total [c]		31			

[a] The model tested in the lab had a different blower than the models observed in the HENGH study; see text for details. [b] This model was discontinued by the manufacturer before our laboratory study had begun. We purchased this unit from a retailer who had one remaining in stock. [c] These models represent 31 of the 38 OTRs found in HENGH homes.

Table 4 summarizes characteristics of the six OTRs that were selected and tested. Since OTR prices vary by exterior color and finish, for comparison purposes we provide pricing for the basic version with black exterior. The prices shown in the table were calculated as the average of regular prices (excluding special offers) listed online by four major retailers in August 2019: The Home Depot, BestBuy, Lowes and AJ Madison.

We also tested two standard under-cabinet range hoods with similar advertised airflow ranges as the OTRs tested in this study. The purpose was to confirm the consistency of our testing with prior published work by testing standard range hoods that are similar to models tested previously. The selected range hoods satisfied these criteria: 1) listed in the HVI catalog; 2) advertised airflow and sound level met the requirements in ASHRAE standard 62.2 for residential kitchen ventilation (airflow greater than 100 cfm and sound level less than 3 sone); 3) available for purchase in July 2019; and 4) priced similarly to OTRs when accounting for OTRs also providing the service of a microwave oven (with approximate value of $75-100). Specification of the two selected range hoods are also summarized in Table 4. The codes in Table 4 are used to identify range hoods throughout the remainder of the report.

Table 4. OTRs and Standard Range Hoods Tested

Brand	Model	Code	Type	Blower (CFM)	Price	HVI flow HS/WS [a] (CFM)	HVI sound HS/WS [a] (sone)
Whirlpool	WMH31017HB	WH1	OTR	300	$235	210/140	5/2
Whirlpool	WMH53520CB	WH2	OTR	400	$315	290/110	7/1.5
Whirlpool	WMH32519HV-4	WH3	OTR	300	$291	210/140	5/2
GE	JVM3160RF5SS	GE1	OTR	300	$204	N/A	N/A
GE	JVM7195SK3SS	GE2	OTR	400	$383	N/A	N/A
Frigidaire	FFMV1645TS	Frigidaire 1	OTR	220	$239	N/A	N/A
Air King	ESD1Q1303	RH1	RH	270	$227	270/150	4/1.5
Broan	BKSA130SS	RH2	RH	250	$156	230/140	5/1.5

[a] Airflows and sound levels for vertical discharge.

Experimental Setup

The experiment was set up in Cell 3A of the FLEXLAB facility at LBNL[1]. The experimental room within the cell measured 7.6 m long by 6 m wide with a drop ceiling at height of 2.7 m, providing a volume of 123 m^3. A simulated residential kitchen area was set up in front of set-back windows that occupied the top half of one of the 6 m wide walls. A plywood wall measuring 2.4 m by 2.4 m was installed in the horizontal middle of the FLEXLAB window-wall to provide a mounting surface for the simulated kitchen area. The simulated kitchen included a 76 cm wide gas cooking range, boxes to simulate floor and wall cabinets, and vertically adjustable brackets to allow mounting of OTRs or range hoods at varied heights above the cooktop. OTRs and range hoods were mounted between drywall boxes installed to simulate wall cabinets and a cooking range was installed between drywall boxes topped with steel sheeting to simulate side cabinets and countertops. During each test, a piece of 76-cm wide and 15-cm high cardboard was attached above the microwave range hoods between the two drywall boxes to mimic the cabinet typically installed above the microwaves.

A schematic of the experimental set up is shown in Figure 2 below. The range hoods were connected to a 30-cm long section of 15-cm diameter smooth galvanized ducting via a 22-cm long rectangular to round duct transition. Above this section was a 90-

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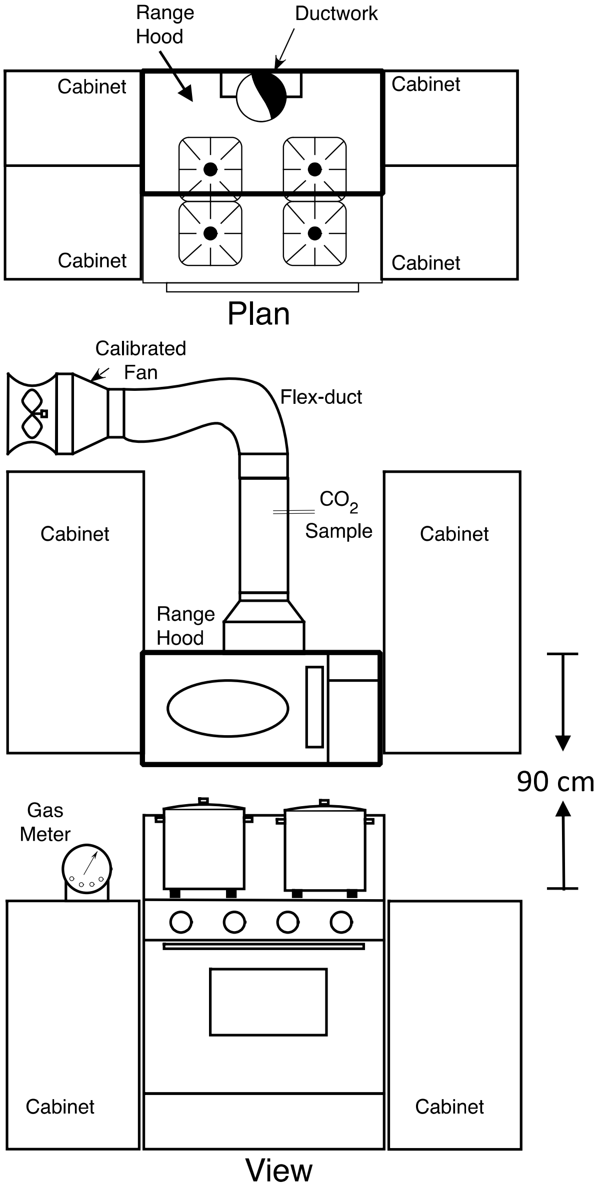
[1] www.flexlab.lbl.gov

degree duct elbow to vent outdoors through a wall vent cap outside. The estimated system curve provides a static pressure of about 60 Pa at 250 cfm and 20 Pa at 100 cfm. The OTRs were mounted with their tops 90 cm above the cooktop. The mounting heights of OTRs and range hoods in this study are consistent with the most common mounting heights found in HENGH study homes; but they are higher than manufacturer-recommended heights.

Figure 2. Experiment Setup



The cooktop had one nominal 12.7 MJ/h (12 000 BTU/h) burner at the front right position and three nominal 10.0 MJ/h (9500 BTU/h) burners. The range was supplied with 99.97% methane from certified cylinders (Airgas). Fuel flow was measured using a mass flow meter (Model MLD-20SLPM-D/5M, ALICAT), factory calibrated for methane with an accuracy of 1%. Flow was reported at a reference condition of 1 atm and 25°C. Fuel flow was controlled using the burner adjustment knobs on the appliance.

The test room was connected to an adjunct space which is directly connected to outdoor air though an exterior door. The door was slightly open during each test to maintain the pressure in the adjunct space equal to outside. Air continuously entered the test room through an entrance covered by transparent film curtains to maintain the pressure balance in the test room while operating the exhaust hoods. Other than the OTR or range hood, there were no drivers of airflow in the vicinity of the range that would have influenced the plume from the cooktop.

OTR Performance Test Procedures

Airflow Performance

Exhaust air flow from the hoods and OTRs was measured using the balanced-pressure flow hood method described by Walker et al (2001). The method uses a calibrated and pressure-controlled variable-speed fan (Minneapolis Duct Blaster, Energy Conservatory) connected to either the airflow inlet or outlet. A pressure sensor (DG-700 Pressure Gauge, Energy Conservatory) was used to control the Duct Blaster fan to match the flow of the exhaust fan while maintaining the pressure at the exhaust inlet or outlet at a neutral value with the surroundings. The airflow rates were calculated by using the relationship of pre-calibrated speed versus flow of the Duct Blaster.

The balanced-pressure flow hood method can measure airflow at the inlet or outlet of any ventilation fan, provided that a proper transition piece is in place; examples of measurements at the outlet and the inlet for a standard range hood are shown in Figure 3a (outlet) and Figure 3b (inlet).

Figure 3. Configurations to Measure Airflow at (a) Outlet and (b) Inlet

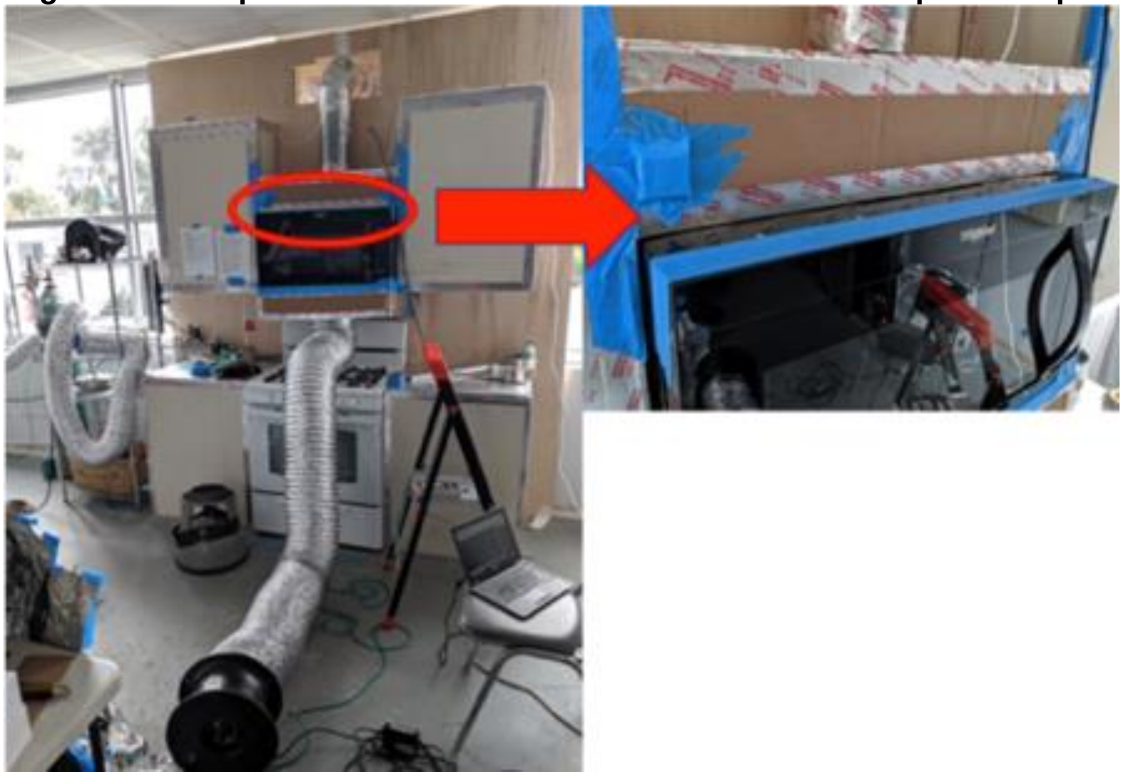
With the objectives of ensuring accurate test results and verifying the more complicated measurements at the inlet, we conducted airflow testing for each device at both the inlet and outlet. The key challenge of applying the balanced pressure method at the inlet is to construct a customized transition box to create the neutral pressure volume. It is particularly challenging to construct a suitable transition to measure OTR inlet airflows because the OTRs have multiple inlets as noted earlier in this report. We thus designed and fabricated a customized transition that combines separate pieces to cover the bottom and top inlets, as shown in Figure 4a. Airflow was measured by connecting the Duct Blaster fan to the bottom of the transition, as shown in Figure 4b, and adjusting the fan to achieve neutral pressure inside the transition, as described above.

Figure 4. Configuration to measure total airflow into OTR at Inlets

Another objective of the airflow testing was to determine the bias that results when using the test method employed for OTRs in the recent HENGH field study in new California homes. In the HENGH study, the field teams blocked the top inlets to OTRs using tape and mounted a transition to cover only the bottom air inlets, as shown in Figure 5. (This approach was used because it enabled the use of similar transitions for common range hoods and OTRs.) The bias investigation was done out of concern that the tape over the top inlets in the OTR field method can cause flow restriction that reduces overall airflow through the blower.

Each of the OTRs and range hoods was tested for airflow at each available setting.

Figure 5. Example of Airflow Measurement at Inside with Top Inlet Taped



Sound Level

OTR and range hood sound levels were measured on an iPhone6 using the Real Time Analyzer tool of the Audio Tools app (version 8.9.X from Studio Six Digital) 2. The Real Time Analyzer records sound pressure (in decibels, dB) as a function of frequency. The sound pressure distribution was measured for background conditions (range hood off) and for each available range hood speed when the test room was in an otherwise quiescent condition. A-weighted total sound pressure (dBA) reported by the app was recorded and we applied the *sound pressure weighting procedure* described in HVI Publication 915 to calculate a sone value. One objective was to assess how this widely accessible technique compared with certified data from the HVI test procedure, which requires testing of devices in an anechoic chamber and using laboratory-grade acoustic equipment. Measurements of dB(A) were also made using a digital sound meter (Extech 407736, Waltham, MA, USA) placed 0.5 m in front of the hood, level with the hood bottom opening and horizontally on center.

Capture Efficiency

Capture efficiency (CE) refers to the fraction of pollutants emitted from the cooking burner that are removed by the venting range hood before mixing into the air of the kitchen. We measured the CE of the OTRs and range hoods using the mass balance method used in Singer et al. (2012) and presented earlier, as Equation 1. For this calculation, Q is volumetric airflow rate through the hood (lpm), which is measured from the outside; C_V is the CO_2 concentration measured in exhaust duct above the range hood (ppm); C_0 is the CO_2 background concentration in the room, interpolated from CO_2 in duct before and after burner use. E is the CO_2 emission rate from the burner (L CO_2/min), described in Equation 5 below:

$$E = Q_{fuel} * N \tag{5}$$

In Equation 5, Q_{fuel} is fuel flow rate in liters per minute (lpm) and N is the molar fraction of carbon in the fuel (mol C per mol fuel, equal to 1 for pure methane). Carbon dioxide concentrations were measured in the exhaust duct at a point that was approximately 3 duct diameters downstream of the hood. Measurements were made with an EGM-4 infrared analyzer (ppsystems.com) The logging interval was 1.6 s. The analyzer has a rated accuracy of better than 1% of the span concentration over the calibrated range. The span calibration was checked with a verified standard mixture of CO_2 gas.

Three burner configurations were used: 1) both front burners, 2) both back burners and 3) one front burner and one back burner (using the nominal 9500 BTU/h front burner). Covered 5L stainless steel pots filled with approximately 3 L of water were placed on the cooktop burners to simulate cooking. After the pots were placed on the stovetop, the burners were ignited and operated for ~3 min and then turned off. The researcher moved slowly away from the range after placing the POW to minimize activity-based air currents that can affect CE. This approach will be referred to as the POW CE test. Fuel flow rates were 9.5±0.2 lpm, 8.5±0.1 lpm and 8.6±0.3 lpm for the two front burners, two back burners and one front and one back burners, respectively.

CHAPTER 3:
Project Results

OTR airflow performance

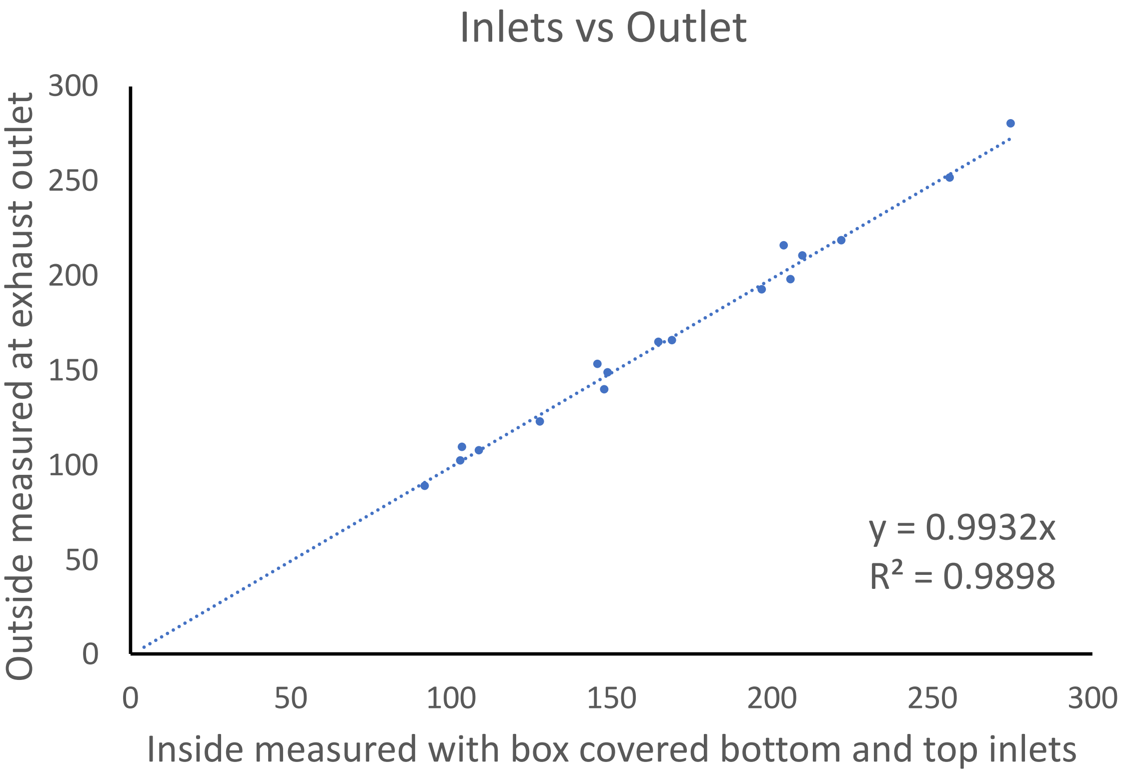
Comparison of OTR airflow measured at outlet and inlets

The results of OTR airflows measured using the balanced-pressure flow method with transition boxes on the outlet or covering both the top and bottom inlets are shown in Table 5. The ratios of the flows measured at the inlets to flows measured at the outlets are also presented. The result shows that the inlet and outlet airflow measurements match within 5% for all of the tested devices and speed settings. A plot of inlet versus outlet airflow measurements is shown in Figure 6; it shows that the two approaches provided highly correlated results with a linear slope of 0.99 and a root-mean-square error of 5.6. The average (±SD) difference between airflows measured at outlets and those measured at inlets is 2.8%±1.9%. The approach of measuring from the inside with a transition that covers both the top and bottom inlets is equivalent to measuring the flow at the outlet.

Table 5. Airflows of OTRs Measured at Inlets and Outlet

Airflow (CFM)	Speed Setting	Outlet	Boxes covered both inlets	Inlet/ outlet
WH1	Highest	210	210	1.00
	Lowest	149	148	0.99
WH2	Highest	256	251	0.98
	Med-high	206	197	0.96
	Med-low	148	139	0.94
	Lowest	92	88	0.96
WH3	Highest	197	192	0.97
	Med	169	165	0.98
	Lowest	128	122	0.95
GE1	Highest	222	218	0.98
	Lowest	109	107	0.98
GE2	Highest	275	280	1.02
	Med-high	204	215	1.05
	Med-low	146	153	1.05
	Lowest	104	109	1.05
Frigidaire 1	Highest	165	164	0.99
Frigidaire 1	Lowest	103	102	0.99

Figure 6. Airflow Measured at OTR Inlets versus Outlet [a]



[a] Each data point is a flow setting on one of the 6 OTRs tested.

Airflows of OTRs and Range Hoods

Table 6 summarizes the airflows measured at each speed setting of the 6 OTRs and 2 range hoods, using the measurement at the outlet. The minimum airflow requirement of ASHRAE 62.2 for kitchen ventilation (100 cfm) was met at the lowest settings of most of the OTRs and both of the range hoods; for WH2, the 100 cfm requirement was met at the second lowest setting. The highest airflows of two OTRs (WH2 and GE2) and one regular range hood (RH1) met the HVI recommended exhaust airflow level for standard 30-inch wide range (250 cfm). The highest airflows were 165 to 268 cfm.

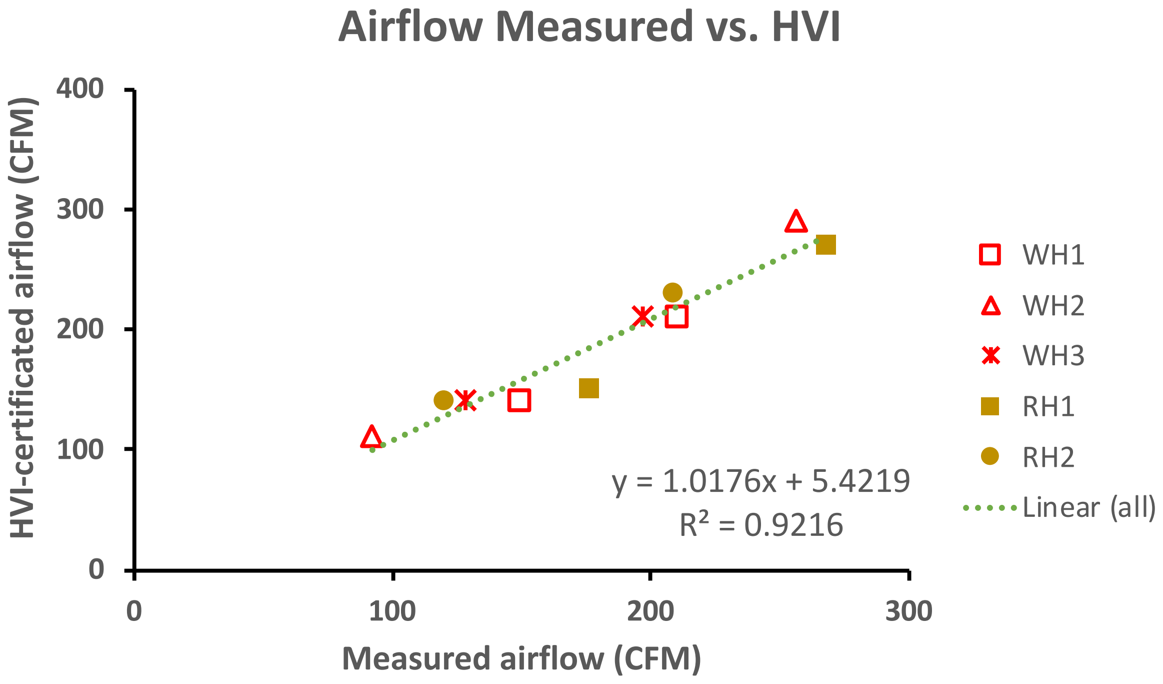
The HVI-certified airflows for three of the OTRs and the two range hoods are shown in Table 6. The airflows measured in our study were all within 17% of the values reported by HVI. Of the 10 data points (2 settings each for 5 devices) available for comparison, in 3 cases the values measured in our lab were <90% of those reported by HVI and in one case our measurement was >110% of the HVI value. A plot of measured airflows versus HVI-certificated airflows is shown in Figure 7, which shows that measured flows were correlated with HVI-certificated values with r-square of 0.92. The generally good agreement is expected since the measurement configuration in FLEXLAB had modest airflow resistance.

Table 6. Measured Airflows (cfm) of 6 OTRs and 2 Range Hoods

Device ID	Highest	Med-high	Med-low	Lowest	HVI HS [a]	HVI WS [a]
WH1	210			149	210	140
WH2	256	206	148	92	290	110
WH3	197	169		128	210	140
GE1	222			109		
GE2	275	204	146	104		
Frigidaire 1	165			103		
RH1	268	253		176	270	150
RH2	208			120	230	140

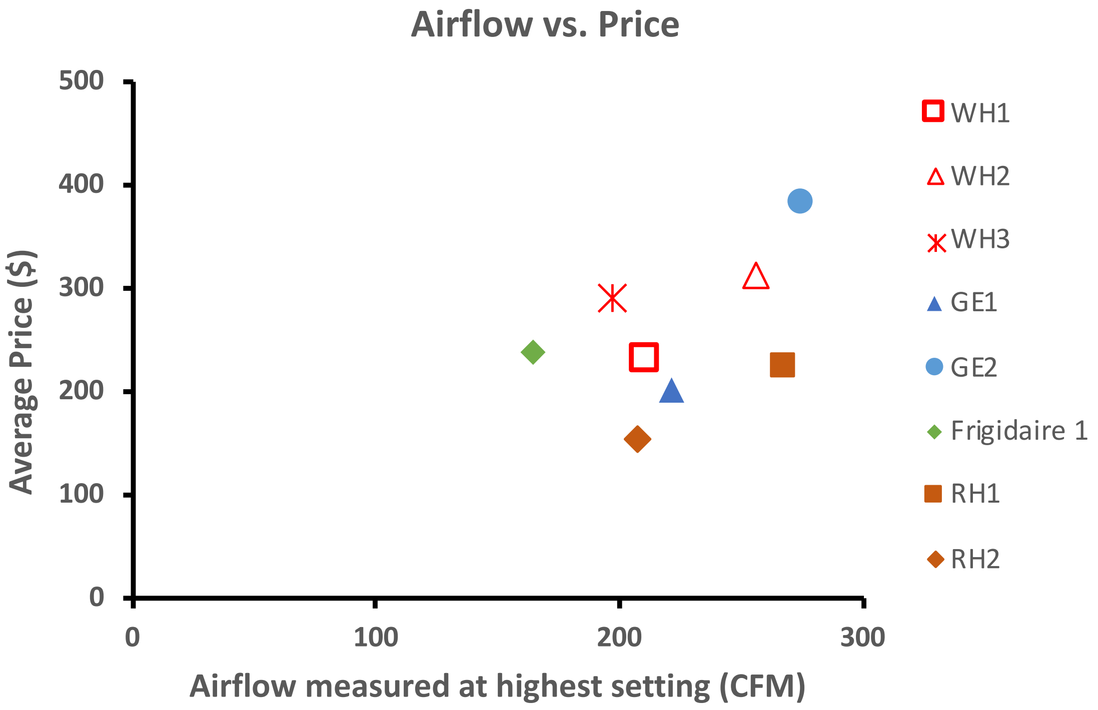
[a] Listed HVI airflows at high speed (HS) and working speed (WS) values are for vertical discharge.

Figure 7. Airflow Measured versus HVI Reported



Airflows measured at the highest speed settings of the 6 OTRs and 2 range hoods are plotted against their retail price in Figure 8 below. Result shows that the OTRs can provide similar exhaust airflows as range hoods within similar cost range (marked as brown). The price of OTRs are approximately $75-150 higher than range hoods providing similar exhaust airflows. To get a rough sense of whether this price difference can be entirely attributed to the cost of the microwave oven functionality of the OTRs, we checked the costs of countertop microwave ovens within the same brand and having similar size, power, features, and exterior color as the OTR models that we tested. OTR costs ranged from $30 to $170 (average of approximately $80) more than the countertop units with seemingly similar microwave ovens. As this is very roughly consistent with the observed price difference, it appears that the exhaust functionality of OTRs are providing roughly similar airflow vs. cost value as range hoods.

Figure 8. Airflow Measured at Highest Speed Setting versus Price



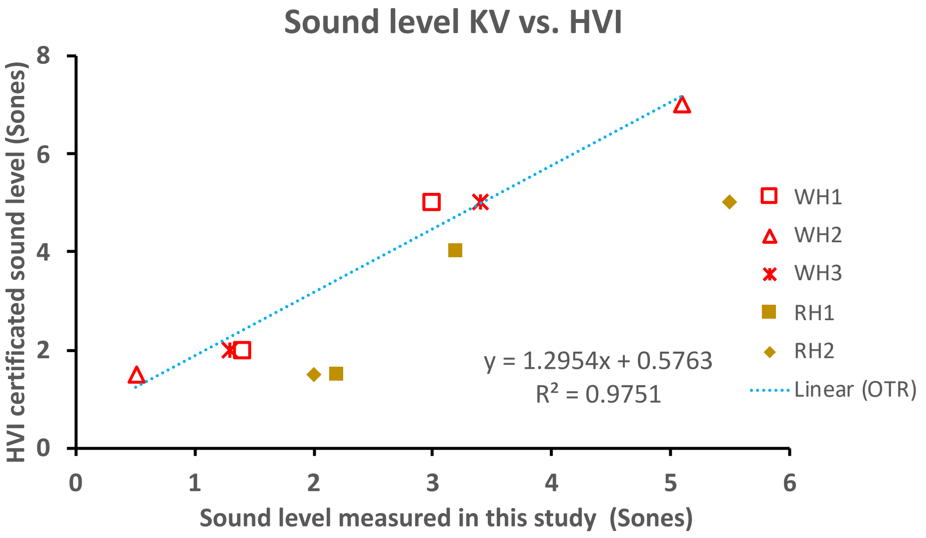
Sound Level of OTRs and Range Hoods

Table 7 and Figure 9 present the certified sound levels reported for the devices listed in the HVI catalog and the sound levels measured for all devices using the AudioTools app. Figure 9 shows that the sone levels estimated with AudioTools measurements are correlated to the HVI certified values for OTRs but there is a substantial non-zero intercept and the slope is far from 1:1. And the relationship is substantially different for the two range hoods than for the OTRs. Unsurprisingly, these results show that the AudioTools measurements on the iPhone cannot be relied upon as translatable surrogates for certified sound testing by the HVI 915 method.

Table 7. Measured Sound Level (Sones) of 6 OTRs and 2 Range Hoods

Device ID	Sound measured by Audio Tools app High speed	Med-high speed	Med-low speed	Low speed	HVI Certified Sound High speed	Working speed
WH1	3			1.4	5	2
WH2	5.1	3.8	1.7	0.5	7	1.5
WH3	3.4	2.7		1.3	5	2
GE1	4.3			0.6		
GE2	6	4.6	2.4	1.7		
Frigidaire 1	2.8			0.7		
RH1	3.2	3.8		2.2	4	1.5
RH2	5.5			2	5	1.5

Figure 9. Measured sound versus HVI-certificated sound



Evaluation of Airflow Measurements in HENGH Study

Table 8 compares airflows measured for OTRs at the exhaust outlet, which is taken as the most accurate, and also using the modified balanced-pressure flow method employed in the HENGH field study, which restricted the airflow through the top inlets. Airflows measured using the modified field method were substantially lower than those measured at the exhaust outlet, with the ratio varying by OTR model over the range of 0.72 to 0.96 (means by model, across multiple speeds). Results are also provided in

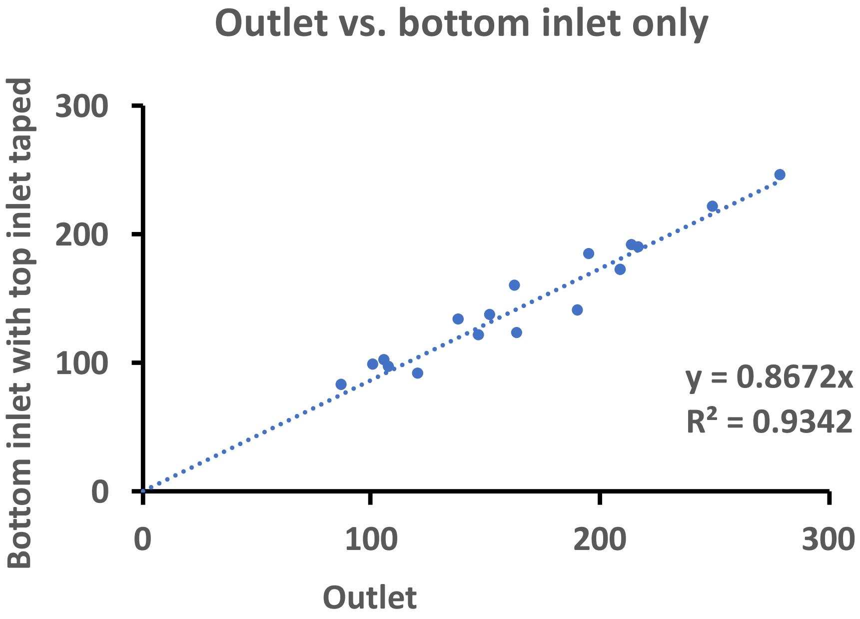
Figure 10. The mean ± standard deviation of the error of the modified method was 13%±8%. This reveals that we underestimated airflows by approximately 13% overall for OTRs tested in the HENGH study.

Table 8. OTR Airflows Measured at Bottom Inlet Only

OTR	Speed Setting	Airflow at outlet (CFM)	Airflow at bottom inlet with top taped (CFM)	Ratio: airflow at bottom inlet with top taped to outside airflow
WH1	Highest	210	171	0.81
	Lowest	149	121	0.81
WH2	Highest	256	221	0.86
	Med-high	206	184	0.89
	Med-low	148	133	0.90
	Lowest	92	82	0.89
WH3	Highest	197	140	0.71
	Med	169	122	0.72
	Lowest	128	92	0.72
GE1	Highest	222	190	0.86
	Lowest	109	102	0.94
GE2	Highest	275	246	0.89
	Med-high	204	192	0.94
	Med-low	146	137	0.94
	Lowest	104	97	0.93
Frigidaire 1	Highest	165	159	0.96
	Lowest	103	99	0.96

If the unit has 4 speed settings, they are shown Highest, Med-high, Med-low and Lowest; If only 3 settings: Highest, Med and Lowest; If 2 settings: Lowest and Highest.

Figure 10. Comparison of OTR airflows measured at outlet and bottom inlet only



The results in Table 8 were used to correct the field measurements from the HENGH study. The 38 OTRs tested in HENGH homes included 17 GE units, 11 Whirlpool units, 7 Frigidaire units and 3 other brands. We sorted all these units by model number, blower capacity, speed settings and motor parts number, and compared the devices tested in HENGH homes to models we tested in this study. From this evaluation, we determined that the devices tested in our lab are representative of 20 OTRs from the HENGH study, as indicated in Table 9. For each of these OTRs we adjusted the field measurements of airflow using the lab-measured relationship between field method and actual airflow for the specific OTR model.

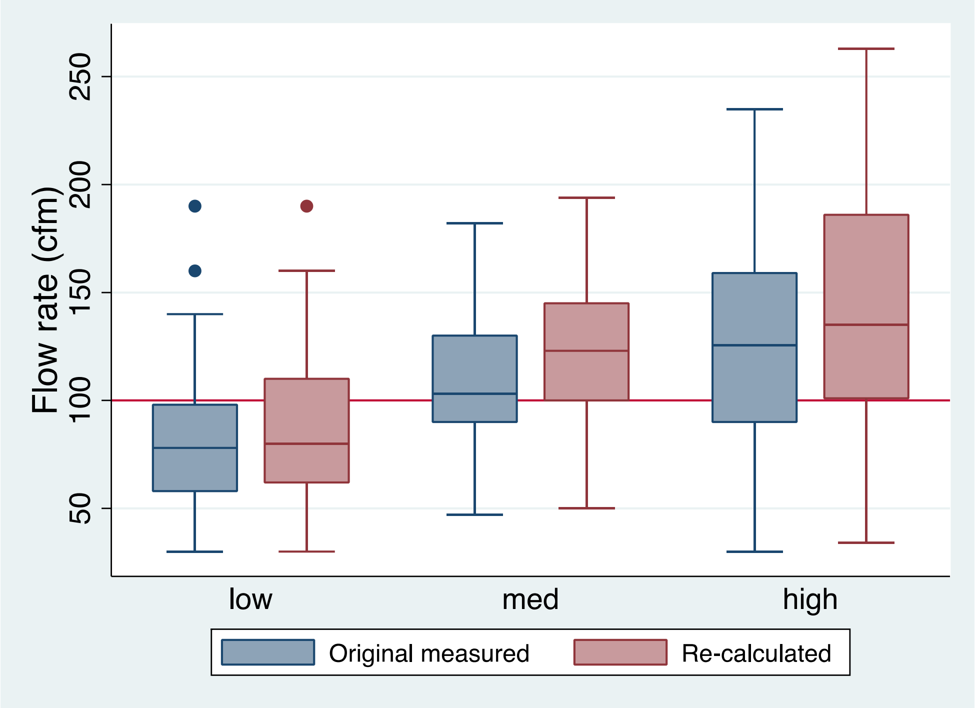
Table 9. Comparison of OTR Models Tested with Models in HENGH Study

Model tested in this study	Same model tested in HENGH homes
WH2	3
WH3	1
GE1	4
GE2	12
Total	20

Figure 11 shows how the corrections impacted distributions of estimated airflows for OTRs encountered in the HENGH field study. The correction slightly changed the statistics of how many HENGH homes had kitchen ventilation that met the ASHRAE 62.2

and Title 24 requirements of 100 cfm. Before adjustment, there were 9, 13 and 29 homes with OTRs meeting the 100 cfm target at low, medium, and high-speed settings, respectively. After adjusting the test results for the 20 OTRs that were well represented by the devices tested in the lab, there were 11, 16 and 30 homes with OTRs meeting the 100 cfm target at low, medium, and high-speed settings, respectively.

Figure 11. OTR airflows in HENGH study before and after correction

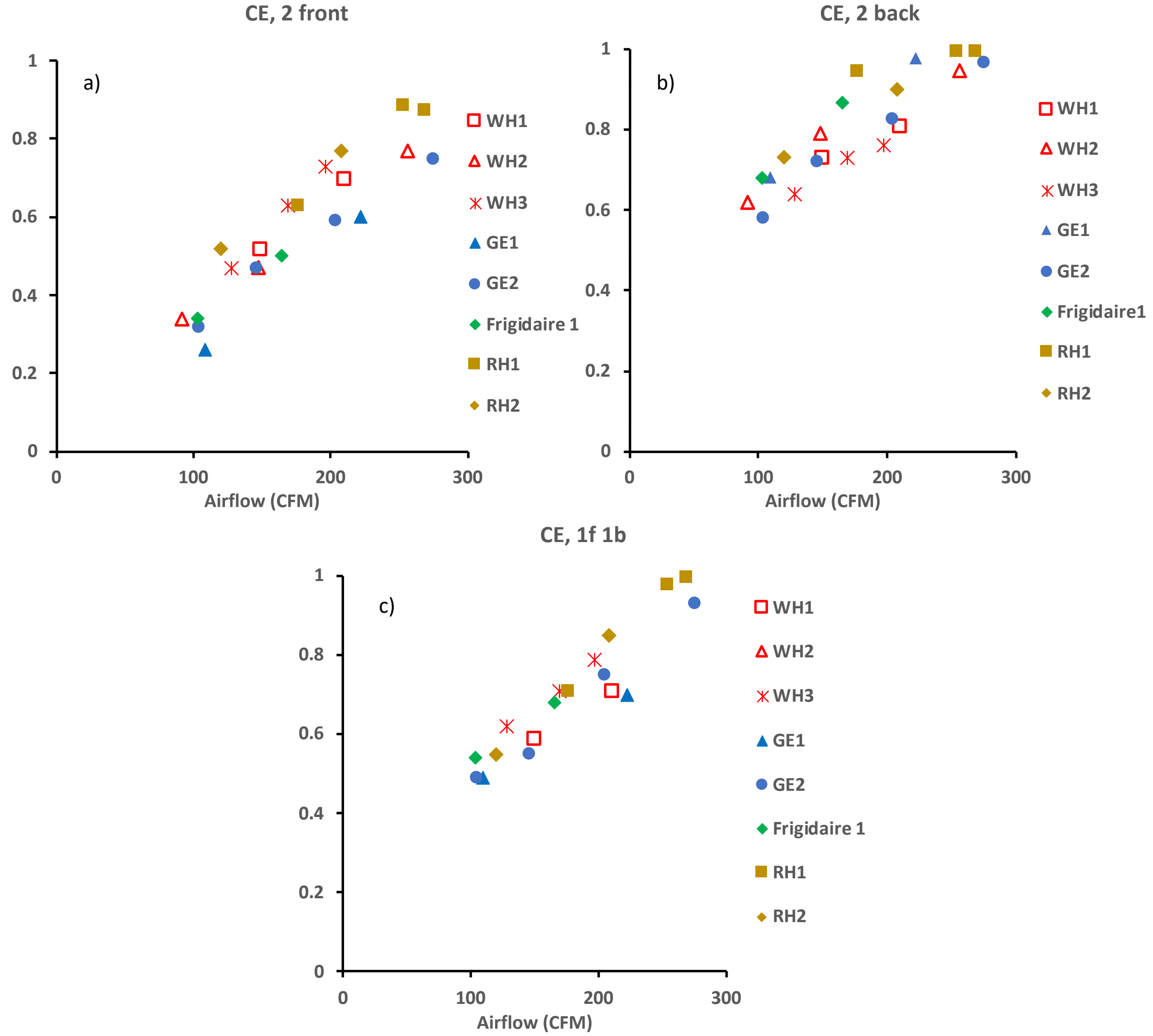


OTR Capture Efficiency Performance

Measured CE of OTRs and regular range hoods

The results of capture efficiency testing in this study for OTRs and range hoods as a function of their measured airflows are shown in Figure 12. Panels a, b, and c of Figure 12 show CE measured with 2 front burners, 2 back burners, and 1 front + 1 back burner, respectively. The measured CEs generally increased with airflow. CE was much higher when using the back burners, above 90% when airflow was roughly 250 cfm, 75-90% when airflow was around 200 cfm, and roughly 60% at 100 cfm airflow. Capture efficiency was much lower when cooking on front burners, approximately 75-85% with airflow of roughly 250 cfm, 60-75% at 200 cfm airflow and, very importantly, <35% at 100 cfm airflow. Results for CE testing with one front and one back burner generally appear to be in the middle of the results obtained with use of two front or two back burners. The relationship between airflow and CE for OTR models listed in the HVI directory (red markers) do not appear to be very different with those not certified by HVI (blue and green markers). Additionally, the measured CEs of the two range hoods (brown markers) are not significantly different than those of OTRs at similar airflow and burner configuration.

Figure 12. CE related to airflow for OTRs and range hoods in this study

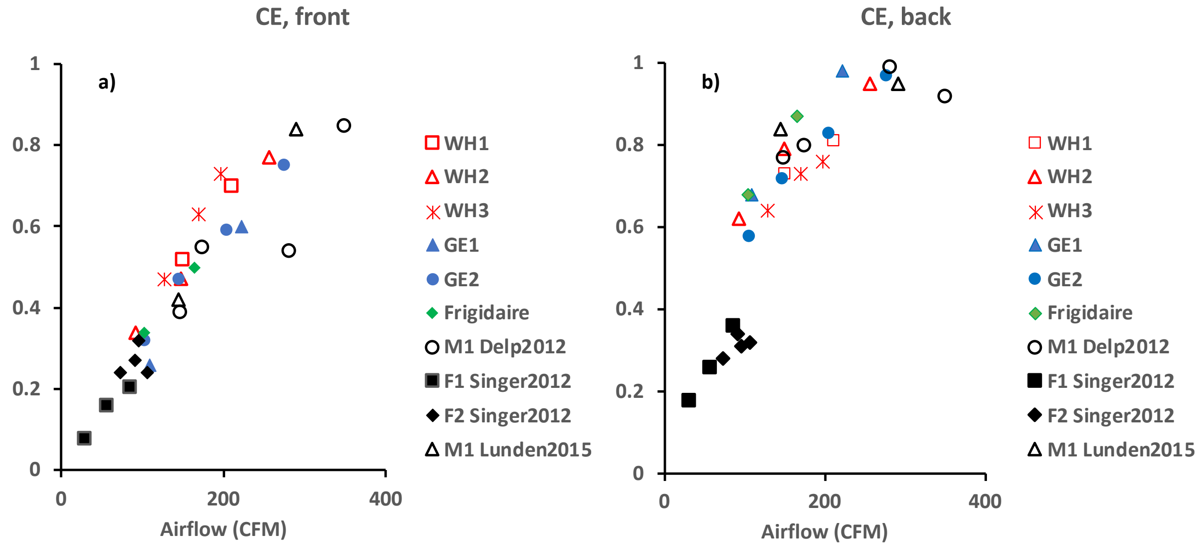


Capture efficiency as a function of airflow measured for OTRs and range hoods with a) two front burners b) two back burners and c) one front and one back burners. HVI listed OTR models are marked red and regular range hoods are marked brown.

Comparison with OTR CE Measured in Previous Study

Figure 13 presents CE test results for OTRs in this study along with those reported in prior lab and field studies that used the dynamic mass balance method. The results are again presented with CE shown in relation to airflow. Results from prior studies are marked in solid black for field studies and unfilled black for lab studies and the OTRs are identified with the codes used in the prior studies. For front burners, the current lab and prior lab and field test results show a consistent trend of CE linearly decreasing with decreasing airflow from 200 cfm down to very low airflows. For back burners, prior results appear to present a slightly different relationship than the recent lab tests, with much lower CE around 100 cfm.

Figure 13. OTR CE as function of airflow, including prior published data.

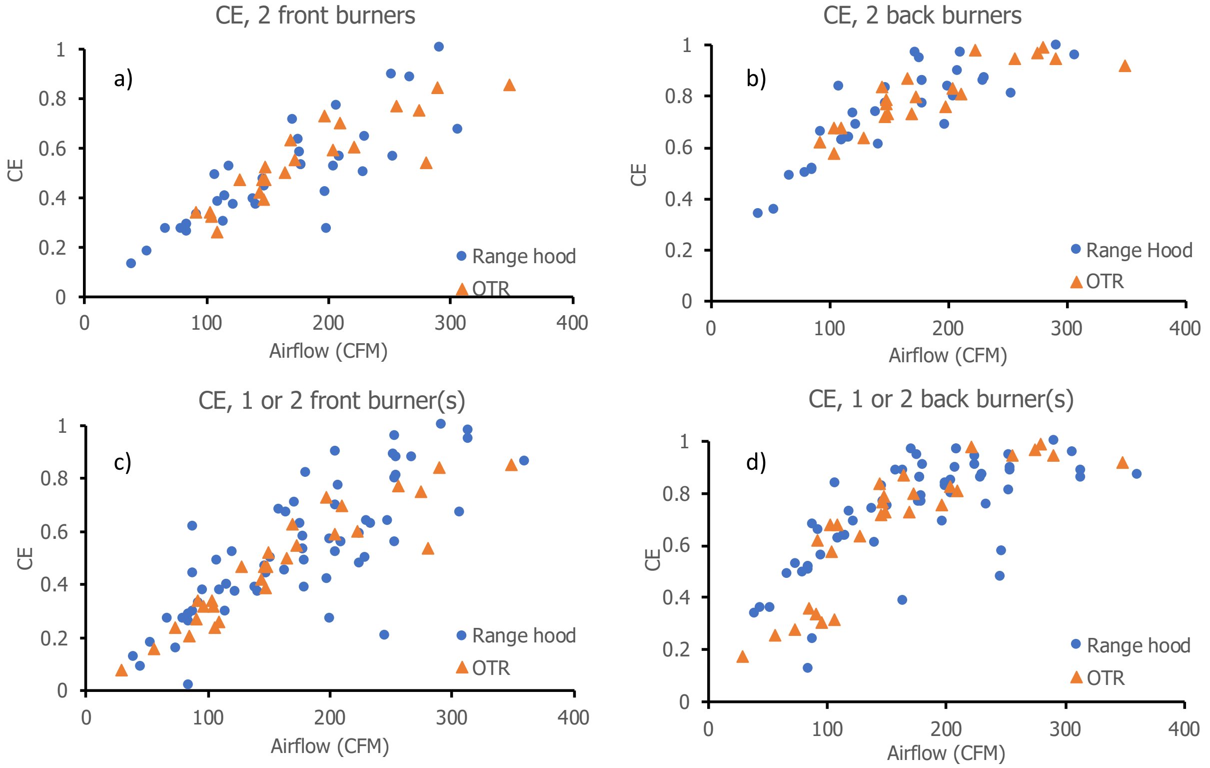


OTR Capture efficiency measured in this study and previous studies for a) front burner(s) and b) back burner(s). Results from previous field study are marked in solid black and results from previous lab study are marked as unfilled black.

Comparison of CE Results for OTRs and Range Hoods

Figure 14 presents a comparison of CEs for OTRs and range hoods when tested with the CO_2 mass balance method including the heating of pots of water on gas cooktops. The presented data include results from the measurements conducted in the current study along with results reported in prior studies (Singer et al., 2012; Delp and Singer, 2012; Lunden et al., 2015). Results are first presented (in panels a-b) only for studies that used two burners at a time (current work; Delp and Singer, 2012; Lunden et al., 2015) then also including studies that used either two burners or one burner (adding Singer et al., 2012). The presentation excludes range hood E1 from Delp and Singer (2012) which appears to be an outlier with very low front burner CE even with airflow exceeding 200 cfm. The reported CE values are again plotted against the reported airflow measurements, which were sometimes made at the outlet and sometimes at the inlet. The data show generally similar performance for OTRs and range hoods; CEs of both OTRs and range hoods generally increase with airflow and follow similar trends for front and for back burners. At the same airflows, CEs are higher and more consistent across devices for back burners than for front burners. For front burners, roughly 250-300 cfm is needed to reliably get to above 60% CE, whereas 60% CE appears to be achieved on back burners at less than 150 cfm for most devices (excluding a few outliers). One apparent difference between OTRs and range hoods is that range hoods appear to have more variable performance for front burners. The more consistent CEs of OTRs on front burners may result from greater consistency in their geometry including the inlets above the door, which is more important for front burners. Range hoods vary a lot more in the degree to which they capture emissions from front burners, based substantially on varied geometries of the hood relative to the cooktop burners. The overall finding here is that OTRs appear to provide similar capture efficiency as range hoods at the same airflow.

Figure 14. OTR and Range Hood CE as function of airflow in lab/field studies using CO_2 mass balance method with different burner configurations



OTR and regular range hood capture efficiency measured in this study and previous studies with POW CO_2 mass balance method for a) two front burners, b) two back burners, c) one or two front burner(s) and d) one and two back burner(s).

CHAPTER 5:
Conclusions

OTR Airflows

In this study, we selected six over-the-range microwave range hood combinations (OTRs) and two standard under-cabinet range hoods based on listings in the HVI catalog and devices observed in the HENGH study. We tested their airflows and capture efficiency in an installation with downstream ducting that provided similar flow resistance to HVI standard testing, up to about 250 cfm. Three different approaches were utilized to measure airflows, including measurements at the outlet of the exhaust duct, measurements that capture airflow into both of the main inlets, and a protocol that was used in the recent HENGH field study that involved taping over the top vents of the OTRs and measuring only the airflow entering at the bottom. Airflows measured using these approaches were compared to evaluate consistency and bias. Comparisons also were made between OTRs and range hoods and between models with and without HVI cortication. These assessments provide the following results:

1. Airflows measured with a transition that covered both the top and bottom inlets of an OTR match those measured at the outlet.
2. The method used in the HENGH field study – in which the top inlet was taped and airflow was measured going into the bottom inlet - underestimated OTR airflows, presumably by changing flow dynamics inside the hood. Correction factors were determined for the 6 hoods and used to correct data for 20 OTRs in the HENGH dataset.
3. Airflows of OTRs were similar to range hoods of similar cost, when an adjustment is made for the functionality of the microwave (which adds cost).
4. Airflows of OTRs not listed in the HVI catalog were similar to those that were listed and met the airflow requirements of ASHRAE 62.2.

OTR Capture Efficiency

The capture efficiency of six OTR microwave range hoods and two standard under-cabinet range hoods were also tested using a CO_2 mass balance method with boiling pots of water. Three different burner configurations were tested including 2 front burners, 2 back burners and 1 front and 1 back burner. The results were compared to previous studies on OTR and range hood CE. These tests support the following findings:

1. OTR capture efficiency generally increases with airflow, and the trend was consistent with CEs reported for OTRs in previous lab and field studies using the same method.

2. OTRs and standard range hoods both have much lower CEs when emissions occur on front vs. back burners and CE is a function of airflow for both types of exhaust devices, and for both front and back burners.
3. The central relationship of CE to airflow is similar for OTRs and range hoods for both front and back burners, but CEs for range hoods as a group were much more variable than CEs of OTRs when emission occur on the front burners.
4. Capture efficiency depends greatly on the specific conditions of the test method. Capture efficiency was much lower for particles from cooking. Looking Ahead

As this report is being finalized, HVI appears very close to completing all necessary preparations to certify capture efficiency test results based on a steady-state chamber method developed from ASTM-E3087-18. Data from certified CE test results may soon provide a much more expansive record of OTR and range hood capture efficiency performance than the limited data reported in this document.

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