Chapter 3: Energy-Efficient Ventilation and Source Control for Health Protection

3.1 Prioritizing Contaminants for Health-Based Ventilation Standards

People spend the majority of their time in residences, and the health burden of indoor air is significant. It is widely accepted that ventilation is critical for providing acceptable indoor air quality (IAQ) in homes. However, the definitions of "acceptable" and "good" IAQ, and the most effective, energy-efficient methods for achieving various levels of IAQ are still matters of research and debate. Considering the adequacy of ventilation standards to protect health requires identification of the pollutants that drive hazard and risk in the residential environment.

This subsection presents results of research conducted to identify and prioritize the pollutants that present a health risk in the indoor residential environment. This research includes a hazard assessment of pollutants in the indoor residential area (Logue, McKone, Sherman and Singer, 2011) and development and application of a health-impact assessment framework to quantify the costs of chronic air pollutant exposures in homes (Logue, Price, Sherman and Singer, 2011). Results of these related studies are already informing the consideration of changes to ventilation standards to improve health protection through communications with the ASHRAE 62.2 committee.

Prior to the start of this research, the focus of debate about and application of ASHRAE ventilation standards was primarily on the right amount of overall ventilation for a home. This focus was based on the idea that a key health-related objective of ventilation was to provide an adequate supply of outdoor air to dilute and remove pollutants emitted from indoor sources to maintain indoor concentrations at levels that are not hazardous. The lower bound for the overall ventilation rate that has been used was the airflow needed to control body odour, based on studies that have determined how much ventilation is needed to control body odour for hygiene typical of the western world. The general assumption has been that additional airflow is needed to control concentrations of pollutants that have diffuse emission sources in residences or that are caused by occupant activities.

One way of reducing the needed overall ventilation for a home, and the associated energy and cost penalty, is pollutant source control. Currently in the U.S. there is not sufficient information to estimate the benefits of source reduction by simulating the replacement of specific materials or applying specific existing standards or guidelines for material emissions (Willem and Singer 2010). Developing these databases could aid in the reduction of material loading or generation of contaminants of concern such as formaldehyde and acrolein. Implementing standards that reduced material loading in homes would reduce the required ventilation rate and save energy.

3.1.1 Hazard Assessment and Identification

The initial step in this analysis effort was to conduct a residential hazard assessment for non-biological air pollutants, including chemical gases and particles but not dampness and mold (Logue, et al. 2011). The analysis compiled data from 86 published studies reporting air pollutant measurements in residences. Contaminants considered in this study included some emitted purely from indoor sources, some that enter predominantly from outdoors, and some having both indoor and outdoor sources.

Summary results were compiled and used to calculate representative mid-range and upper-bound concentrations relevant to chronic exposures for over 300 pollutants and peak concentrations relevant to acute exposures for a few pollutants. For over 100 pollutants, measured concentrations were compared to available chronic and acute health-hazard standards and guidelines from the U.S. Environmental Protection Agency (U.S. EPA), California Office of Environmental Health Hazard Assessment (OEHHA), the U.S. Occupational Safety and Health Administration (OSHA), the Agency for Toxic Substances and Disease Registry (ATSDR), and the World Health Organization. Fifteen priority pollutants were identified as potential chronic or acute health hazards based on their prevalence in homes and the quality of available measurements in homes. Table 3.1.1 lists the identified priority hazards.

Table 3.1.1: Pollutants That Potentially Pose an Adverse Indoor Health Risks

Priority Pollutants for Chronic Exposure	Potential Acute Exposure Concerns
Acetaldehyde	Acrolein
Acrolein	Chloroform
Benzene	Carbon Monoxide
Butadiene, 1,3-	Formaldehyde
Dichlorobenzene, 1,4-	Nitrogen Dioxide (NO_2)
Formaldehyde	Fine Particulate ($PM_{2.5}$)
Naphthalene	
Nitrogen Dioxide (NO_2)	
Fine Particulate ($PM_{2.5}$)	

The hazard assessment narrowed the list of hundreds of chemicals to a much smaller group of pollutants of concern. But this approach considered only disease incidence for cancer standards and disease potential for non-cancer standards; it did not consider disease severity. Prioritizing mitigation efforts among residential indoor air pollutants and comparing their cumulative

health damage to other environmental hazards requires a consistent and comparative metric that accounts for both disease incidence and the severity or costs of the health endpoints. This need motivated development of an impact assessment methodology for indoor air pollutant inhalation.

3.1.2 Prioritizing Chronic Health Hazards

Disease incidence and health damage models were synthesized to develop a methodology for quantifying indoor air quality, and then the methodology was applied to calculate the population average health damage due to chronic inhalation of non-biological air pollutants in U.S. residences (Logue, et al. 2011). We first analyzed published data to calculate mean exposure concentrations, and then estimated age-dependent inhalation air intake over the course of a year. Disease incidence and health damage models were used to predict the pollutant-specific and total health damage in Disability Adjusted Life Years[1] (DALYs) and to identify the pollutants that dominate impacts on human health.

This analysis used the compilation of measured concentration data developed for the hazard assessment to calculate total DALYs lost due to inhalation of air pollutants in residences. Figure 3.1.1 shows the damage in DALYs per year per 100,000 people from exposure to the 15 pollutants with the highest central estimate of damage. The whiskers indicate the aggregate uncertainty (95th percentile confidence interval) in the disease incidence and disease damage factors.

Figure 3.1.1 shows a clear result of this analysis: on a population average, the most harmful chronic pollutants in residential indoor air are $PM_{2.5}$, secondhand tobacco smoke (SHS), formaldehyde, acrolein, radon, and ozone. The hazards of SHS and radon are widely recognized, focused in a smaller fraction of homes, and already addressed through a wide range of controls. By contrast, $PM_{2.5}$, acrolein, and formaldehyde are present at substantial levels in most homes, yet there may be less widespread recognition of these hazards. Formaldehyde is primarily emitted from materials throughout the home. Acrolein is primarily emitted from materials and cooking. $PM_{2.5}$ concentrations indoors, unlike acrolein and formaldehyde, are due to both indoor and outdoor sources, and outdoor concentrations may exceed indoors in many locations.

To explore possible variations in the health impact rankings of pollutants across homes, a Monte Carlo approach was used to calculate the total chronic health damage from exposure to all pollutants included in the analysis, except radon and SHS. For each model run, we sampled with replacement from the distribution of estimated damage for each pollutant and calculated an estimate of total health damage for the occupants of the home. Sampling with replacement is a technique in which each time a parameter value is selected from the distribution of possible values, all possible values are available. In other words, it is theoretically possible for the same

[1] Disability Adjusted Life Years refers to the years of full life lost due to ill-health, disability, or premature death.

value to be selected more than once. An independent variability of all pollutants was assumed. This was repeated for a sufficient number of samples to yield a stable mean and standard deviation for the total health damage. It was assumed that individual pollutant damages vary independently. This approach did not account for any synergistic or antagonistic interactions of pollutant health effects. The resulting distribution of total health damage and the characteristics of each set of individual pollutant contributions to the total health damages were analyzed. For 80 percent of the sample sets (calculated damages for individual homes), $PM_{2.5}$ was the largest contributor. For 16 percent of the sample sets acrolein was the dominant contributor. For 4 percent of the sample sets, it was formaldehyde. The dominant contributor was a compound other than these three in less than 0.25 percent of the sample sets. For 90 percent of the sample sets, acrolein, formaldehyde, and $PM_{2.5}$ contributed more than 80 percent of the total health damage. This reinforces the finding that these three pollutants account for the majority of chronic health damage from intake of air pollutants in non-smoking homes. We estimate that the current indoor air quality-related heath damage to the U.S. population from all sources, excluding SHS and radon, is in the range of 4–11 mili-DALY/p/yr (mili-DALYs per person per year). This indicates that the damage attributable to indoor air is, comparatively, somewhere between the health effects of road traffic accidents (4 mili-DALY/p/yr) and all-cause heart disease (11 mili-DALY/p/yr) in the United States. The compounds that dominate that total are $PM_{2.5}$, acrolein, and formaldehyde.

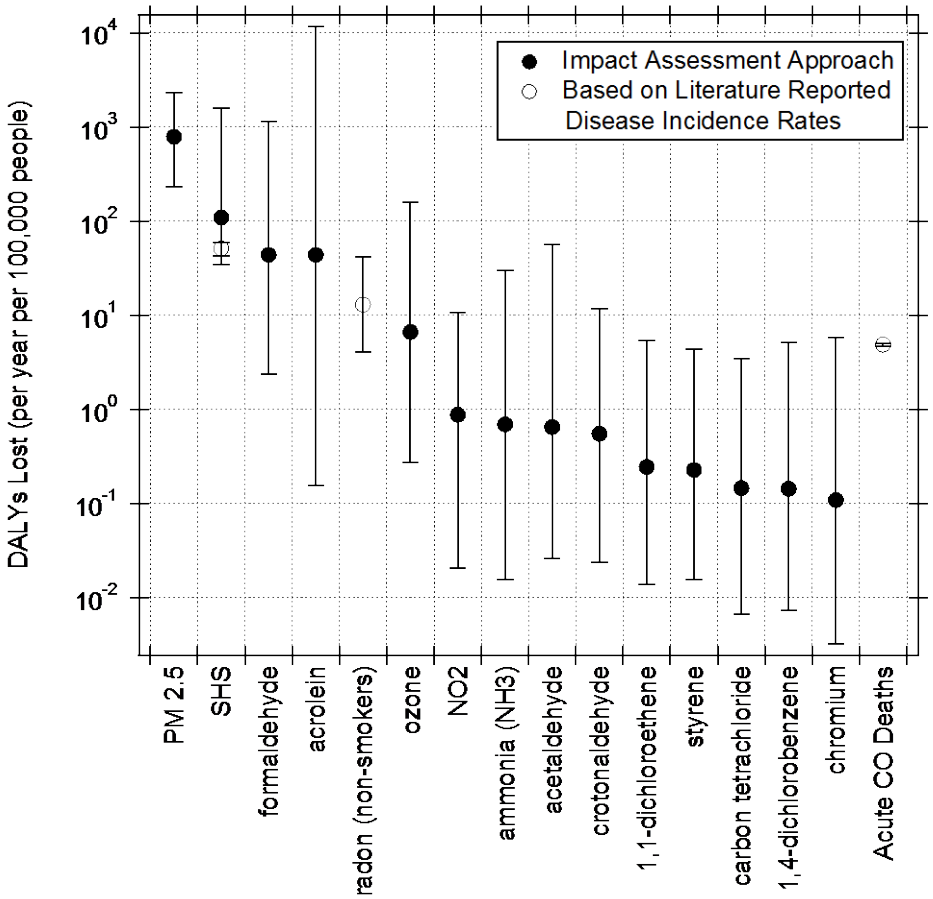

Figure 3.1.1: Estimated Population Averaged Annual Cost, in Disability Adjusted Life Years (DALYs), of Chronic Air Pollutant Inhalation in U.S. Residences. This figure presents only the results from the 15 pollutants with highest mean damage estimates.

3.2 Ventilation Control of Formaldehyde and Other VOCs

Residential IAQ can be adversely affected by volatile organic compounds (VOCs) that are emitted by various sources in homes. The majority of existing homes do not currently meet health-based guidelines for formaldehyde chronic exposure levels, and guidelines for other VOCs are exceeded in a non-negligible minority of homes (Logue et al. 2011). New homes typically have elevated concentrations of formaldehyde and other VOCs that are emitted from new building materials or new furnishings brought into the home. Homes with lower outdoor air exchange rates, a condition that occurs when building envelopes are tightened to reduce uncontrolled infiltration, also typically have higher concentrations of VOCs from indoor sources.

Dilution and removal via ventilation is a straightforward and common approach to managing concentrations of pollutants from indoor sources. Historically, homes were leaky enough that the rate of infiltration of outdoor air (through cracks and other leakage pathways) was so large that there was no need to install mechanical systems to ensure minimum air exchange rates. Recent years have seen a substantial increase of more airtight, energy-efficient homes. If the air change rate is sufficiently low, then mechanical ventilation must be provided in order to provide adequate ventilation. As envelopes have been tightened and sealed to reduce uncontrolled infiltration, the minimum mechanical ventilation rate has become a design element.

Managing levels of VOCs from indoors sources is an implicit objective of ventilation, and it is commonly assumed that increasing the air exchange rate can be an effective measure to reduce in-home concentrations of VOCs that are emitted from materials built or installed in the home. The effect of ventilation on VOC concentrations in existing homes has been explored primarily through cross-sectional studies. The limitation to this approach is that large sample sizes are needed to identify an effect of ventilation within the context of variation in material and product-related emissions; variations in material emission rates related to temperature, relative humidity, and solar insolation; and other factors. To understand how formaldehyde emissions depend on environmental factors, emissions from single materials have been measured under varied conditions in controlled, laboratory environments. However, constructed homes contain a wide range of materials compared to chamber tests designed to evaluate one material or a small collection of materials. While lab experiments have been instrumental to understanding emission from a single material, it is very difficult to extrapolate from experimental studies what indoor VOC concentrations from building materials and furnishings are likely to be, due to the different varieties and quantities of VOC containing materials present in homes.

As a complement to existing datasets that allow cross-sectional analysis of ventilation impacts on VOC levels, we designed and implemented a field study in which ventilation rates were varied while environmental factors were either held constant or at least consistent between ventilation settings in new U.S. homes. This field study, termed the Ventilation and Indoor Air Quality study (VIAQ), sought to answer the following research questions:

- To what extent does increasing the air exchange rate in new homes reduce pollutant concentrations in the short term, and thus help to mitigate residents' exposure?
- For which chemicals does increasing the air exchange rate result in proportional reductions of indoor chemical concentrations, and for which chemicals is the relationship not proportional?

Answers to these questions are needed to inform the development of optimal strategies for controlling VOC exposures in relatively new or retrofit homes.

Provided below is a brief summary of the methods and results of the VIAQ study. Detailed results are available in Willem, Hult, Hotchi, Russel, Maddalena and Singer (2013).

3.2.1 Methods

The impact of air exchange rate on indoor concentrations of VOCs was investigated in nine residences, listed in Table 3.2.1. Using the installed ventilation systems as well as additional ventilation equipment where necessary, the experimental setup was designed to establish three distinct air exchange rates, with other environmental parameters consistent, then measure the resulting indoor VOC concentrations at each ventilation setting in each one of the study homes. This controlled approach provides information about how VOC concentrations in real residences respond to changes in ventilation.

The study design required that three ventilation settings in each home be achieved and maintained. Air samples were collected for each ventilation setting after a pseudo-steady-state condition had been achieved. The impact of air exchange rate on the indoor concentrations of 39 target VOCs was assessed by measuring air exchange rates and VOC concentrations at three ventilation settings in nine residences. Active sampling methods were used for VOC concentration measurements, and passive perfluorocarbon tracer gas emitters with active sampling were used to determine the overall air exchange rate corresponding to the VOC measurements at each ventilation setting.

3.2.2 Key Results

Summary results are presented in Figure 3.2.1 for formaldehyde and acetaldehyde and in Figure 3.2.2 for six other representative VOCs that have major indoor sources. These figures show several major features of the results obtained.

This study found, as many have in the past, that VOC concentrations varied widely across homes. The concentration levels and emission rates of the target VOCs varied widely among sites. For a given VOC, the measured concentration at the lowest ventilation setting varied by up to two orders of magnitude at the different sites. Aldehydes and terpenes were the classes of VOCs typically found in the highest concentrations, followed by alkanes, aromatics, and siloxanes.

Table 3.2.1: Summary Characteristics of Homes for Which Ventilation Was Varied to Study the Impact of Air Exchange Rate on VOC Concentrations and Emission Rates

ID	Generally in-use for habitation	Occupied during sampling	Age^ (yrs)	Floor area (m^2)	# of story	# of bedrooms/ # of occupants	Air tight-ness (ACH_{50})	Low-emitting materials#	Ventilation system	Air distribution system	Study dates
H1	No	No	2.0	195	2	4/ 0	1.2	1,2	ERV with enthalpy wheel	Ducted exhaust	07-08/ 2011
R2	Yes	No	1.5	14[4]	1	1/ 0	4.0	1,2,3	Added balanced system	Single supply & exhaust	12/2010
R3	Yes	No	1.5	14[4]	1	1/ 0	4.0	1,2,3	Added balanced system	Single supply & exhaust	12/2010
H4	Yes	No	0.3	230	2	3/ 0	0.6	2,3	HRV	Ducted supply	08/2011
H5	Yes	No	7.5	141	1	3/ 0	4.3	NA	Added balanced system	Ducted supply	07-08/ 2011
H6	Yes	Yes	0.8	146	2	3/ 4	1.0	2,3	ERV	Single supply	05/2011
H7	Yes	Yes	1.0	210	2	3/ 4	0.7	2,3	ERV	Ducted supply	05/2011
H8	Yes	Yes	2.5	150	2	3/ 3	1.0	2	ERV	Ducted supply	07/2011
H9	Yes	Yes	2.5	320	2	4/ 2	4.0	2	Added balanced system	Single supply & exhaust	09/ 2011

^Age of home when study was conducted; #1= Wood products for the building structure, finishing, and cabinetry certified compliant with CA Title 17 or equivalent low- or no- formaldehyde standards, 2= Wet surface finishing product certified as low-emitting in accordance to CA Section 01350 requirements or equivalent low- or no-VOC standards, 3= Carpet materials and backing certified as low-emitting in accordance to CA Section 01350 requirements or Carpet and Rug Institute (CRI)-certified low-emitting carpet and backing system; ERV = Energy Recovery Ventilator; HRV = Heat Recovery Ventilator, 4= R2 and R2 are small rooms in the LBNL guesthouse (i.e. hotel rooms)

Concentrations of VOCs associated with indoor sources generally decreased as the air exchange rate was increased. Generally, concentrations were substantially lower when the air exchange rate was above about 0.4 air changes per hour (ACH). The dependence of indoor concentration on air exchange rate for each home was linear for most of these VOCs, meaning that concentrations decreased proportional to the increase in ventilation. For a subset of compounds, including formaldehyde, the indoor concentration exhibited a non-linear dependence on air exchange rate. This result is indicative of a chemical whose emission rate from materials is suppressed when there are substantial concentrations in the air, relative to those that would exist in an equilibrium condition. In other words, there is enough of the compound already in the air to affect the rate at which it is emitted from materials. At low air exchange rates, emissions are reduced because of this. When ventilation is increased, the concentration of the

compound in air is lowered and the emissions then increase. The result is that the concentration in the air is not reduced proportional to the increase in ventilation rate.

Despite efforts to control environmental factors, it was difficult to maintain constant ventilation conditions in the residences (particularly in occupied homes). For example, intermittent sources of VOCs from cleaning, as well as opening of windows, affected the results. The uncertainty in some of the measured and calculated quantities, principally the air exchange rate, was considerable; this affected the degree to which the impacts of interest (which are the changes in concentration and especially calculated emission rate as a function of air exchange rate) could be resolved. Nevertheless, the experiments still provided a clear indication that increasing ventilation can be used to mitigate high concentrations of VOCs in new homes.

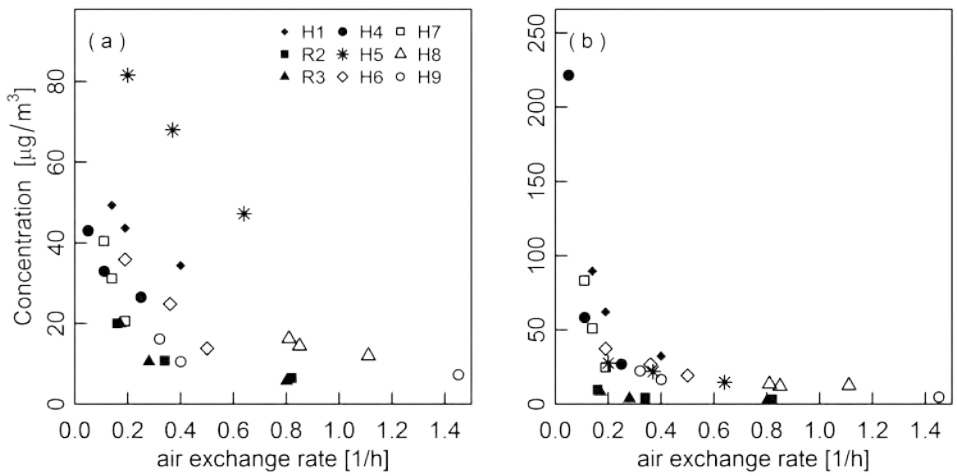

Figure 3.2.1: Concentration of (a) Formaldehyde and (b) Acetaldehyde for Three Air Exchange Rates at Each Study Home

The results of this study indicate that increasing the ventilation rate tends to lower indoor concentrations of VOCs with indoor sources. For most compounds for which indoor sources are much larger contributors than entry from outdoors, the indoor concentration is proportional to the inverse of the air exchange rate in the space. For a minority of the target compounds studied here, it appears that the concentration does decrease with increasing air exchange rate, but that the reduction is less than proportional (i.e., for chemicals with a large amount of material in storage in building materials and furnishings, doubling the air exchange rate will reduce the indoor concentration, but not to as low as one-half of the original concentration). This improved understanding of the chemical specific dependence of indoor concentration on air exchange rate is helpful. However, increasing the air exchange rate remains an effective mitigation strategy to reduce the indoor concentration of VOCs with indoor sources. Reductions in indoor VOC concentrations are most dramatic when increasing the ventilation rate up to roughly 0.4 ACH or greater. To understand how VOCs may be depleted from building materials and furnishings over time, further research is needed. Of particular value would be data collected from the same buildings over months and years, rather than just days. The ventilation rate can alter not only the immediate indoor concentration but also the rate at which compounds are depleted from

building materials and furnishings. When short-term concentrations are reduced in a manner that is not proportional to the inverse of the air exchange rate, it is because the emission rate increases. A higher emission rate means faster depletion of the source. The impact of this increase in depletion rate varies, but in general it leads to lower concentrations over time.

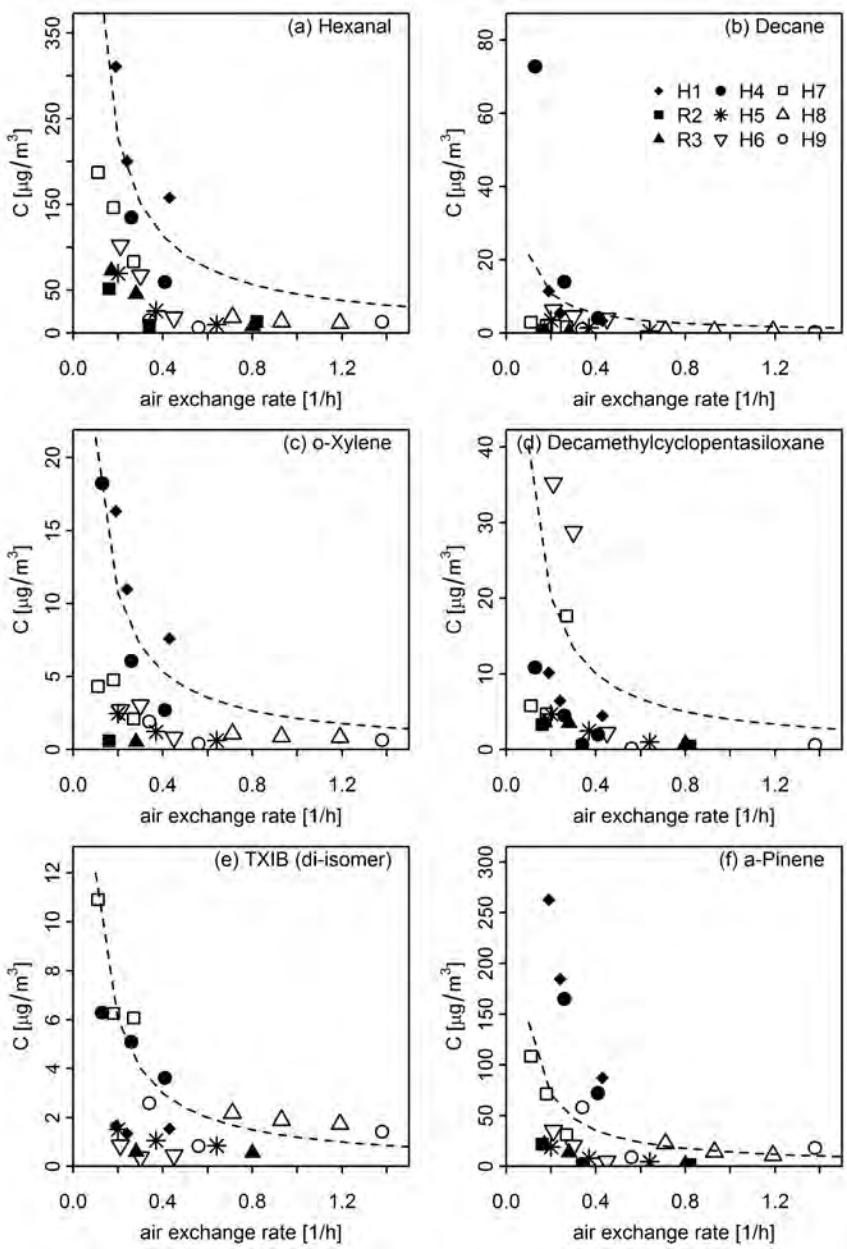

Figure 3.2.2. Concentrations of Selected VOCs for Three Air Exchange Rates at Each Site. The dashed line represents results for a reference case in which concentrations are proportional to the inverse of the air exchange rate (i.e. doubling ventilation would half concentrations).

3.2.3. Model-Based Estimates of Ventilation Benefits and Costs

The hazard assessment identified chronic VOCs that exceed standards in some or many homes. Those with indoor sources potentially could be controlled with ventilation. The DALY-based impact assessment later identified acrolein and formaldehyde as the most important of these VOCs with indoor sources that need to be controlled in homes. A theoretical analysis was conducted to determine if ventilation using clean outdoor air could be cost-effectively

employed to mitigate exposures to VOCs generated in the home. We developed and applied a mass-balance indoor pollutant simulation modeling approach that works with the incremental ventilation energy (IVE) model and REGCAP model results to calculate pollutant concentrations for California homes based on air leakage inputs and mechanical ventilation and indoor emission data (Logue, et al. 2011). The analysis assumed a whole-house continuous emission rate of acrolein, though more work is needed to determine the intermittent versus continuous emission rate of acrolein in homes. This analysis found that the cost of increasing ventilation to reduce exposures to VOCs emitted in the home was balanced by the health benefits as assessed with the DALY-based approach. The caveat is that the analysis did not consider the costs of bringing in more outdoor particles, nor the benefits of diluting and removing particles generated indoors. More detail is presented in the Willem 2013 report.

3.3. Source Control for Cooking Burners

3.3.1 Importance of Cooking Burners to Pollutant Exposures

Cooking activities and natural gas burners can emit significant quantities of pollutants into the indoor space. We conducted an analysis to assess the impact of natural gas cooking burners on indoor pollutant concentrations and the potential benefits of widespread range hood use. This work was initiated as part of the Natural Gas Variability in California: Environmental Impacts and Device Performance activities, and advanced as part of the current project.

A mass balance model was applied to calculate time-dependent concentrations of nitrogen dioxide, carbon monoxide, and formaldehyde for one week each in summer and winter for a representative sample of homes in Southern California. The model simulated pollutant emissions from cooking, nitrogen dioxide, and carbon monoxide entry from outdoors, dilution throughout the home, and removal by ventilation and deposition. Residence characteristics were obtained from the Residential Appliance Saturation Survey and other sources. Ventilation rates, occupancy patterns, and burner use were inferred from household characteristics. Pollutant emission factors were measured for the Natural Gas Variability in California project mentioned above. The current project advanced this analysis by improving several of the model parameterizations, by incorporating an analysis of range hood use, and by producing a scientific paper to report this work through the peer-reviewed archival literature.

Our analysis indicates that unvented cooking is a substantial health hazard in California and potentially nationwide. Measured indoor concentrations were compared to outdoor standards (the National Ambient Air Quality Standards) for carbon monoxide and nitrogen dioxide and published guidelines for formaldehyde. Unvented natural gas cooking significantly affects occupant exposures on acute and chronic exposure time frames. For winter conditions the model estimates that 59 percent, 8 percent, and 53 percent of residents in homes that cook with natural gas without regular use of vented range hoods are exposed to nitrogen dioxide, carbon monoxide, and formaldehyde respectively at levels that exceed federal guidelines for acute exposure. Table 3.3.1 presents the statistics on the frequency of homes that exceed relevant air quality metrics. This means that indoor environmental concentrations in many California

homes are at levels that, if they existed outdoors, would make those areas "nonattainment" with respect to ambient air quality standards.

The analysis was repeated for the hypothetical situation that all homes in the virtual sample used a venting range hood for the duration of each cooking event. We used a pollutant capture efficiency of 55 percent for the range hood based on measurements from (Delp and Singer 2012). With regular use of even such moderately effective range hoods, the number of homes and individuals experiencing concentrations in excess of standards was reduced dramatically. The percentage of homes exceeding an acute standard decreased by over 70 percent. As shown in Table 3.3.1, when a range hood was used, the percentage of homes with an exceedance for nitrogen dioxide was reduced from 52 percent to 15 percent; for carbon monoxide, from 7 percent to 2 percent; and for formaldehyde, from 51 percent to 27 percent.

Table 3.3.1: Households with Concentrations Exceeding an Acute Health-Based Pollutant Standard from Use of Natural Gas Cooking Burners

Homes in SoCal (n=6,634)	Winter no hood	Summer no hood	Winter with hood
NITROGEN DIOXIDE			
1-hour Standard Exceedances (NAAQS)			
Percent of homes with exceedance	52%	37%	15%
Percent of homes with exceedance due to indoor emissions only	48%	34%	14%
Mean exceedances per home exceeding standards	3.5	3.2	3.0
CARBON MONOXIDE			
1-hour Standard Exceedances (CAAQS)			
Percent of homes with exceedance	6%	3%	1%
Percent of homes with exceedance due to indoor emissions only	6%	3%	1%
Mean exceedances per home exceeding	2.5	2.4	2.4
8-hour Standard Exceedances (NAAQS)			
Percent of homes with exceedance	7%	2%	2%
Mean exceedances per home exceeding standards	2.4	2.1	1.8
FORMALDEHYDE			
1-hour Standard Exceedances (CAAQS)			
Percent of homes with exceedance	25%	17%	11%
Mean exceedances per home exceeding	3.5	3.3	2.8
8-hour Standard Exceedances (NAAQS)			
Percent of homes with exceedance	51%	26%	27%
Mean exceedances per home exceeding standards	3.3	3.1	3.0

3.3.2 Performance of Currently Available Range Hoods

Controlled laboratory experiments were conducted to characterize the performance of a sample of range hoods that span the range of designs and nominal capabilities of hoods costing up to about $650 in 2011 (Delp and Singer 2012). These experiments were designed to build on performance measurements conducted on installed units in residences for the Natural Gas Variability in California project. The installed, in-use devices were in many cases found to have flow rates below those advertised in product literature and to have capture efficiencies that allowed a large percentage of cooktop or oven exhaust to enter the living space of the home. It could not be determined from the in-home measurements how much the specifics of the installation or equipment aging contributed to the measured performance. The experiments for the current project used new range hoods installed and operated under standard conditions; this enabled a more clear and objective assessment of currently available cooking exhaust devices.

Table 3.3.2 presents summary characteristics of the range hoods evaluated in the laboratory study. All hoods were purchased new from retailers. The experimental protocol included measurement of airflow across a range of duct static pressures and measurement of capture efficiency across a range of airflows. The latter set of measurements enables assessment of the capture efficiency (CE) performance of the basic hood geometry independent of the fan performance. First pass capture efficiency is the fraction of pollutants emitted at the burner that are drawn up into the hood before they can mix throughout the kitchen and potentially other parts of the house, i.e. they are captured on their first pass up from the stove and past the range hood. Also quantified was fan efficacy, an efficiency measure defined as the volumetric airflow per unit of power input. The current ENERGY STAR qualification for range hoods is that they produce at least 2.8 cubic feet per minute of airflow per watt of power input (cfm W^{-1}) at a setting that also produces less than 2 sones of sounds. The rightmost column of Table 3.3.2 shows that only one of the seven hoods achieved the rated or advertised airflow at the high speed setting with duct pressure at the standard rating point of 25 Pa. Three more of the hoods achieved airflows above 90 percent of rated and two more had airflows above 80 percent of rated flow. It is noteworthy that one of the ENERGY STAR-qualified hoods only achieved 52 percent of the rated flow. This result was confirmed by purchasing a second unit of the same model.

Table 3.3.2: Characteristics of the U.S. Cooking Exhaust Devices Evaluated in this Study.

Hood[a]	Description	Price	Fan Type	Rated sound (sone) and flow ($L \cdot s^{-1}$) at 25 Pa				Measured flow at 25 Pa
				Low		High		High
				Sound	Flow	Sound	Flow	(% of Rated Flow)
L1	Basic, Low cost	$40	Axial	n/a [b]	n/a [b]	6	90	86
B1	Basic, Quieter	$150	Axial	n/a [b]	n/a [b]	4.5	104	93
A1	ASHRAE 62.2 [c]	$250	Centrifugal	0.3	52	5.5	132	80
E1	ENERGY STAR	$300	Centrifugal	1.5	71	4	127	52
E2	ENERGY STAR	$350	Centrifugal	1.1	57	6	118	94
M1	Microwave	$350	Centrifugal	n/a [b]	61 [d]	n/a	198 [d]	95
P1[c]	Premium	$650	Centrifugal	- [e]	- [e]	5.4	129	100

[a] All devices were 30" (76 centimeter, cm) nominal width, designed to mount against a wall. Depth is the length from back to front of the device; air inlets spanned only part of this distance for most devices (see Supplemental Information in Delp and Singer 2012 for details).

[b] Rating information not available.

[c] Compliant with requirements of the ASRHAE 62.2 residential ventilation standard. Hood A1 was the least expensive hood that was found to be a commonly available hood and compliant with the standard.

[d] Airflow and sound provided in product literature without a specified backpressure condition.

[e] Single-speed unit.

Figure 3.3.3 shows the summary results of the CE experiments for these hoods. Complete results, including calculated fan efficacy and the method for measuring CE, are presented in Delp and Singer (2012).

This study demonstrates the importance of considering multiple criteria to evaluate cooking exhaust hood performance. The low- to moderately-priced devices evaluated in this study achieved high CE, high fan efficacy, and quiet operation, but not all at the same time. A microwave hood (M1) and an ultra-quiet hood (A1) demonstrated capacity for quiet operation at low speed and first-pass CE exceeding 70 percent for oven and front burners and exceeding 90 percent for back burners when operated at high speed. These devices use very high flow rates to overcome physical designs that are less conducive to capturing cooktop burner exhaust. The best and most robust device for CE (P1) has a large volume, open hood that extends farther

over the cooktop and exhausts air at Home Ventilating Institute (HVI)-recommended flows. This hood achieved CEs exceeding 90 percent for back burners and more than 80 percent for oven or front burners, even when added airflow resistance reduced air flow rates below HVI recommended levels. Fan efficacy for this device was just below the ENERGY STAR criterion, but sound levels were significantly above the 2-sone ENERGY STAR limit. Current ENERGY STAR standards do not consider the pollutant removal purpose of cooking exhaust fans and therefore do not adequately address performance efficiency.

Currently there is no standard test or rating system for CE of residential cooking exhaust hoods. Development of a test and rating system would allow incorporation of capture efficiency into ENERGY STAR, ASHRAE 62.2, and other standards.

To avoid increasing the backdrafting risk for natural draft appliances and to reduce energy penalties, it is necessary to improve pollutant removal performance without resorting to increased air flows. Our results indicate that products can be improved by (1) improving geometry of hood construction by being deeper front to back, and having recessed grease traps and blower entries up inside the hood; and (2) incorporating better fans and motors.

Routine use of even moderately effective venting range hoods can substantially reduce in-home exposures to cooking and burner-generated air pollutants. Effectiveness can be substantially enhanced by preferential use of back versus front cooktop burners and by using higher fan settings.

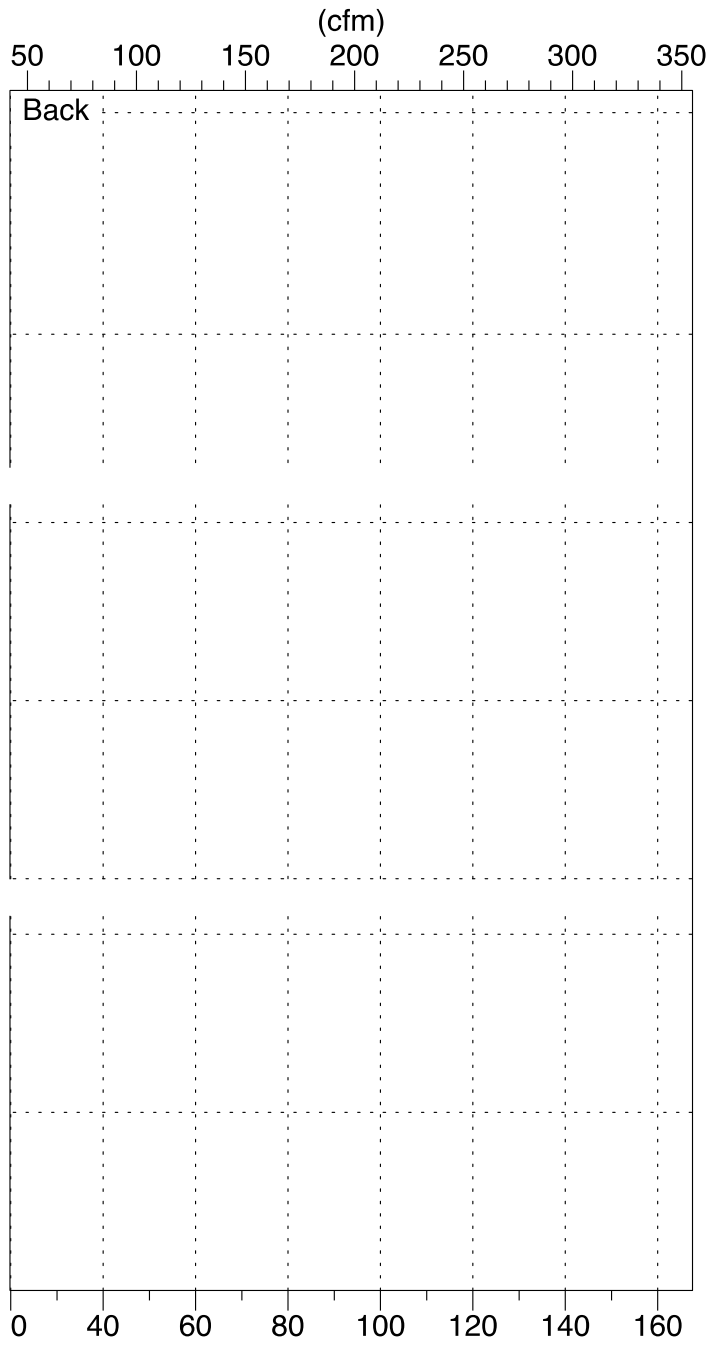

Figure 3.3.3: Measured Capture Efficiency of Common U.S. Cooking Exhaust Hoods. Stacked panels present results for back, oven, and front burners from top to bottom. The heavy vertical gray lines indicate minimum flow specified by HVI and ASHRAE 62.2, and the HVI-recommended flow HVI. Error bars reflect variations in exhaust CO_2 measurements (refer to text for details). Dashed lines present a logistic function fit to the data to aid identification of hoods that perform better or worse than the trend.

3.4. Summary of Findings

Formaldehyde and acrolein and $PM_{2.5}$were found to be the pollutants of highest concern in homes. Increasing ventilation in the home reduces exposure to formaldehyde and acrolein. However, increasing airflow through the home can increase the rate at which outdoor pollutants are brought indoors, particularly $PM_{2.5}$. This study identified $PM_{2.5}$ as the most important pollutant for chronic health impacts in residential environments. While indoor sources such as combustion and chemistry significantly impact indoor $PM_{2.5}$ concentrations, a significant fraction of homes may have higher concentrations outdoors than indoors, indicating that more ventilation may actually increase health risks. Providing ventilation air via filtered supply or filtered balanced ventilation using heat/enthalpy recovery ventilators is one potential solution. Another option is to filter the indoor air independent of the ventilation system to reduce indoor $PM_{2.5}$ concentrations. Including measures to reduce indoor particle concentrations in ventilation standards could greatly improve IAQ from a health perspective.

Our analysis indicates that removing pollutants near their point of release using effective localized exhaust ventilation is key to maintaining good IAQ. The two main types of localized exhaust in ventilation standards are kitchen and bath ventilation. Effective kitchen ventilation is needed to mitigate acute pollutant events resulting from combustion-based cooking appliances and food preparation activities. Task ventilation (e.g., range hoods) can also significantly mitigate chronic exposures by removing pollutants at their source. ASHRAE 62.2 requires a kitchen exhaust fan that is above the cooktop and provides at least 100 cubic feet per minute (roughly 50 $m^3\ h^{-1}$) of airflow while producing 3 sones or less of noise. The standard does not specify a minimum pollutant capture efficiency or sound limits at higher flow rates. Our experiments found that for common hood designs, meeting the current ASHRAE standard of 100 cfm does not ensure high capture efficiencies. When front burners are used, common hood designs can require 200 cfm or greater to achieve capture efficiencies exceeding 80 percent. Requiring a high pollutant capture efficiency and potentially requiring automatic fan use when the range is operated could significantly improve indoor air quality. Four out of five of the identified acute contaminants of concern (except chloroform) are emitted by combustion or cooking. It is critically important to make sure that there is effective ventilation for all indoor combustion. Research is needed to determine if the health benefit of adding a commissioning requirement to ventilation standards is worth the cost.

The identification of formaldehyde, acrolein, and $PM_{2.5}$ as the highest priority pollutants for chronic exposure opens opportunities to improve energy efficiency through consideration of control measures complementary to ventilation.