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Indoor Air Quality in 24 California Residences Designed as High Performance Green Homes

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By

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Professor Gail Brager, Chair

Professor Stefano Schiavon

Professor Duncan Callaway

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Abstract

Indoor Air Quality in 24 California Residences Designed as High Performance Green Homes

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Today's high performance green homes are reaching previously unheard of levels of airtightness and are using new materials, technologies and strategies, whose impacts on IAQ cannot be fully determined by past efforts. This research assessed IAQ in 24 new or deeply retrofitted homes designed to be high performance green buildings in California using pollutant measurements, home inspections, diagnostic testing and occupant surveys. Measurements included six-day passive samples of nitrogen oxides (NO_2 and NO_x), formaldehyde (HCHO), acetaldehyde (CH_3 CHO) and air exchange rate (AER); time-resolved data loggers were used to measure carbon monoxide (CO), particle counts (PN), temperature (T) and relative humidity (RH), as well as ultrafine particle count (UFP) during stovetop testing.

Only 13 of 24 homes provided continuous mechanical ventilation, and no relationship was found between mechanical venting and either AER or pollutant levels, with the exception of particulate, which was actively filtered by 12 of 13 ventilation systems. Naturally vented homes were much less airtight, on average (6.7 vs. 2.3 ACH_{50}). Numerous faults were observed in complex mechanical ventilation systems, suggesting need for more rigorous commissioning. AER did not significantly determine either formaldehyde or particulate levels, but they did for NO_2. Median formaldehyde concentrations in bedrooms and kitchens (17.5 and 20.1 $\mu g/m^3$) were approximately half those found in conventional new CA homes by previous research (36 $\mu g/m^3$) (Offermann, 2009). Source control (engaged in by 22 of 24 households) was most likely responsible for this result. NO_2 concentrations were generally low, with concentrations in gas cooking kitchens 2.4 times higher than electric (13.1 vs. 5.4 ppb). Three gas cooking homes exceeded the CalEPA annual ambient air standard for NO_2. Those homes that provided active particle filtration had lower indoor particle count levels than unfiltered homes. UFP emissions were dramatically lower on induction electric cooktops, compared with either gas or resistance electric models. Kitchen exhaust fan usage rates were low, with occupants believing that everyday cooking was harmless, suggesting a lack of education on IAQ impacts of cooking. Finally, shortcomings affecting high performance green homes were identified in current U.S. codes and standards. The results of this research suggest that with better occupant education, careful system design and commissioning, particle filtration and source control, high performance green homes can provide acceptable or enhanced IAQ.

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List of Acronyms

Term	**Acronym**
Air Changes per Hour	ACH
Air Exchange Rate	AER
Air Infiltration and Ventilation Centre	AIVC
American National Standards Institute	ANSI
Air Quality and Meteorological Information System	AQMIS
American Society of Heating Refrigeration and Air Conditioning Engineers	ASHRAE
American Standard Test Method	ASTM
Building Performance Institute, Inc.	BPI
Building Science Corporation	BSC
California	CA
California Environmental Protection Agency	CalEPA
California Air Resources Board	CARB
Combustion Appliance Zone	CAZ
California Energy Commission	CEC
Central Fan Integrated Supply	CFIS
Cubic Feet per Minute	CFM
Carbon Monoxide	CO
Chronic Reference Exposure Level	CREL
Disability Adjusted Life Year	DALY
Deep Energy Retrofit	DER
2,4-Dinitrophenylhydrazine	DNPH
Energy Efficient Building	EEB
Energy Performance of Buildings Directive	EPBD
Energy Recovery Ventilator	ERV
Hazardous Air Pollutant	HAP
Hexafluorobenzene	HB
Formaldehyde	HCHO
High-Efficiency Particle Air	HEPA
House to Garage	HG
High Performance Liquid Chromatograph	HPLC
Heat Recovery Ventilator	HRV
Indoor-Outdoor	I/O
Indoor Air Quality	IAQ
International Agency for Research on Cancer	IARC
International Code Council	ICC
Indoor Environmental Quality	IEQ
Lawrence Berkeley National Lab	LBNL
Leadership in Energy and Environmental Design	LEED
Limit of Quantitation	LOQ

Model Conservation Standards	MCS
Medium Density Fiberboard	MDF
Method Detection Limit	MDL
Minimum Efficiency Reporting Standard	MERV
Material Safety Data Sheet	MSDS
Mechanical Ventilation with Heat Recovery	MVHR
National Association of Homebuilders	NAHB
Nation Center for Healthy Housing	NCHH
Non-Energy Benefits	NEB
Nitrogen Oxide	NO
Nitrogen Dioxide	NO_2
Nitrogen Oxides	NO_x
Office of Environmental Health and Hazard Assessment	OEHHA
Oriented Strand Board	OSB
Occupational Safety and Health Administration	OSHA
Pascal	Pa
Polycyclic Aromatic Hydrocarbons	PAH
Particulate Matter	PM
Particle Number	PN
Parts Per Billion	ppb
Parts per Million	PPM
Quality Control/Quality Assurance	QA/QC
Relative Average Deviation	RAD
Reference Exposure Level	REL
Relative Humidity	RH
Respirable Suspended Particulate	RSP
Specific Leakage Area	SLA
Temperature	T
Total Volatile Organic Compound	TVOC
United State Environmental Protection Agency	U.S. EPA
Ultrafine Particles	UFP
United Kingdom	UK
U.S. Green Building Council	USGBC
Weatherization Assistance Program	WAP
World Health Organization	WHO

Introduction

The reduction of energy use in homes has become an issue of national and international importance. Numerous building codes, optional building performance rating systems and service industries have been created in an effort to deliver energy reductions in new and existing homes. The desires to cut energy costs, reduce green house gas emissions and mitigate global climate change have led to an all-out, global sprint to design and build high performance green homes.

Many energy reduction efforts have included other goals in addition to energy savings, such as increased affordability, energy cost stability, improved indoor environmental quality (IEQ) (including thermal comfort, lighting, acoustics, and indoor air quality (IAQ)), and occupant health. In fact, most marketing efforts to sell high performance green homes to the public explicitly include claims of improved indoor environmental quality. Research suggests that these non-energy benefits (NEB), such as increased comfort, better indoor air quality and the like, may in fact be the primary drivers of a homeowner's decision to purchase a low energy or high performance home, or to incorporate these elements into their existing residence (Mills & Rosenfeld, 1996). In fact, a review of NEB valuation in whole-house retrofits suggests that these improvements have values ranging from 50% to 300% of the annual utility bill savings (Amann, 2006). But what if the indoor air quality in high performance green homes is not in fact better than their run-of-the-mill counterparts; what if energy reductions inadvertently lead to air quality problems and costly human health impacts?

Many have begun to consider and question the ambient and indoor air quality impacts of global climate change and energy efficiency. In particular, some possible outcomes of energy savings measures in buildings—reduced air infiltration and higher indoor humidity or moisture intrusion—have been identified as potentially leading to increased human health risks (Committee on the Effect of Climate Change on Indoor Air Quality, Public Health, & Institute of Medicine, 2011). Outside the context of climate change, public health professionals are being warned of the potential "health pitfalls" of efficient home retrofits, due to poor workmanship, reduced ventilation rates and potentially hazardous materials, such as spray polyurethane foam (Manuel, 2011). Concurrently, others, such as the National Center for Healthy Housing, are arguing that home energy reduction programs, such as the Weatherization Assistance Program (WAP) are especially well suited to reducing health risks, particularly in low-income, stressed housing[1]. This is because of their ability to mediate hazards such as lead paint, moisture and mold, insufficient ventilation, carbon monoxide and others alongside efficiency improvements (Kuholski et

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[1] Kuholski et al. (2008) suggest that stressed housing refers to conditions such as leaky roofs, peeling paint, structural problems, chronic dampness, improperly vented combustion appliances, and poor ventilation. These conditions can cause injury, illness, and increased energy consumption.

al., 2008). Similar arguments can be made for the home performance industry, which has IAQ requirements built into its standard practices for carbon monoxide, natural gas leaks, moisture management and minimum ventilation requirements. Finally, high performance and green home certification systems—such as Energy Star (U.S. EPA, 2011a), LEED for Homes (USGBC, 2008) and EPA Indoor airPLUS (U.S. EPA, 2009a)—have incorporated measures to address IAQ alongside energy and other environmental concerns.

This is not a new debate. Whether or not energy efficiency is compatible with good indoor air quality has been questioned since the late 1970s, when a mobile test laboratory was created at Lawrence Berkeley National Laboratory to measure IAQ in energy efficient buildings (Hollowell et al., 1978). The question has not been extensively answered yet. In the context of a changing climate and continually adapting building industry, the high performance green homes built today may pose different threats than those of the past. Building materials and consumer products have changed, as have ventilation practices, air tightness levels, and a host of other factors that could affect IAQ in high performance green homes. As they currently stand, most building codes and energy codes are not suited to maintain acceptable IAQ, because of strong institutional processes for energy conservation, which are nearly non-existent for IAQ (Mudarri, 2010). Furthermore, most codes and standards focus on single issues and do not address integrated performance. Debate and concern surrounding this topic is as vibrant as ever.

There are equally valid sets of arguments that support two contradictory statements: (1) high performance green homes will have improved air quality over otherwise comparable conventional homes, and (2) high performance green homes will experience poorer air quality than otherwise comparable conventional homes. It is possible that both statements are true, one or the other is true, or neither is true. This will depend upon how indoor air quality is defined, what exactly is measured or assessed, and what construction and design techniques and building materials are employed to achieve high performance green. In addition, how the occupants use the home can be of critical importance. This is true in terms of the pollutants they generate from their activities (e.g., cooking, cleaning, and consumer product use) as well as their interaction with ventilation systems and other equipment.

Differences in indoor air quality could exist between conventional and high performance green homes due to a variety of factors, including ventilation system type, air exchange rate, building air tightness, use and effectiveness of task ventilation equipment, materials used in construction, ventilation of combustion pollutants, equipment maintenance and others. Major differences may also exist between different types of high performance green homes that use different technologies and energy reduction strategies. Arguments in favor of statements 1 and 2 are summarized below. Any of these statements could also apply between groups of high performance green homes.

(1) Reasons that high performance, low energy homes may provide enhanced IAQ include:

- Homes will provide continuous mechanical ventilation and local exhaust from bathrooms and kitchens, often in accordance with ASHRAE Standard 62.2-2010 (ANSI/ASHRAE, 2010a).
- Homes will tend to be airtight and more consistent ventilation rates will be achieved with mechanical ventilation, lessening the likelihood of periods of under or over-ventilation.
- To the extent that high performance green homes actually have lower air exchange rates, they should have lower levels of outdoor pollutants that have indoor deposition or loss rates, or that are removed during infiltration.
- Building science design methods are employed, which are intended to avoid moisture issues and limit transport of pollutants from polluted zones, such as attics, crawlspaces and garages. Examples include the sealing of crawlspaces, the proper venting of attics and building enclosure design to avoid condensation.
- Homes will often have been inspected during construction and commissioned after completion by a building performance professional as part of a certification program, such as Energy Star, LEED or Passive House. These quality control measures are used to identify typical problems experienced in homes. Ventilation flows and envelope air tightness are measured and verified[2], insulation and water management details are inspected, etc.
- Sources of combustion pollutants will be minimized, because space conditioning and water heating equipment will either be electric or will use energy-efficient sealed combustion appliances. Atmospherically vented gas appliances will be rare[3], because of their lower combustion efficiencies, and issues of back drafting and combustion gas spillage should disappear as a result.
- Homes certified by a green building or energy efficiency program will have been forced to implement mandatory indoor air quality measures and to consider optional ones, such as use of low-emitting materials.
- The use of balanced mechanical ventilation systems is more common in very airtight homes, and the source of fresh air can be controlled and filtered. In homes with exhaust ventilation systems or no ventilation systems, fresh air comes through adventitious openings in the building envelope[4], and may be sourced from polluted zones, such as the attic, crawlspace, garage, etc.

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[2] LEED for Homes Guide, in Five Steps to Participate, the Energy Rater must measure envelope and duct leakage, outdoor airflow rates, local exhaust, etc. (pg. vi) (USGBC, 2008). Same in Energy Star, HVAC System Quality Installation Rater Checklist requires airflow measurement of duct/envelope leakage and ventilation airflows (pg. 12) (U.S. EPA, 2011a). PHIUS+ (the new Passive House program in the U.S.) aligns with Energy Star verification requirements (Passive House Institute U.S., 2011).

[3] Gas cooking appliances are a notable exception to this trend towards sealed combustion.

[4] Although uncommon in the U.S., simple exhaust systems with engineered fresh air inlets are commonly used in Europe. Examples include Aldes and FrenchAir.

- Those homes that use balanced mechanical ventilation with heat recovery may be able to achieve much higher levels of air exchange without suffering energy penalties.
- Ventilation systems can be controlled to avoid possible outdoor air pollutant spikes or bad air quality days, and air exchange will be small during these periods.
- Homes that use fully ducted ventilation systems typically supply fresh air in bedrooms and other living areas, while exhausting air from bathrooms and the kitchen. This design may increase ventilation effectiveness and the evenness of distribution of fresh air throughout the home, avoiding short-circuiting, enhancing mixing, and reducing or eliminating under-ventilated zones.

(2) Reasons that high performance, low energy homes may provide compromised IAQ include:

- Increased levels of airtightness, sometimes to extreme levels, and lack of a designed ventilation system can lead to low air exchange rates. This may cause indoor generated pollutants to build up to unacceptable levels.
- In the U.S., ASHRAE Standard 62.2-2010 is often used to calculate required outdoor airflow rates and the 2007 version of the standard is required by Title 24 2008 (California Energy Commission, 2008) in the state of California, but the outdoor airflow stipulated in the standard assumes approximately 0.17 natural air changes per hour due to infiltration[5]. Very tight, low energy homes may be chronically under-ventilated if designed to this standard without accounting for their reduced levels of air infiltration.
- Mechanical ventilation systems are potentially less robust and reliable than natural infiltration, because they can be installed incorrectly, disabled, accidentally or purposefully turned off, suffer from power outages, or become clogged with debris (Crump et al., 2009).
- The usage of complex ventilation systems may confuse homeowners, resulting in a lack of required maintenance or disablement by occupants. Examples include balanced systems with heat recovery, which require the homeowner to change filters, clean heat exchanger materials, etc. Also, kitchen range hoods that use activated carbon filtration require filter changes to have their desired effect.
- Due to extreme envelope airtightness, the resiliency of the house to disturbances in mechanical ventilation is reduced. Occupant misunderstandings about system operation or installation faults may have a disproportionately higher impact on indoor health than they would in a typical home.
- Some high performance green homes use continuous, low-level exhaust ventilation from polluted rooms, such as kitchens and bathrooms, rather than

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[5] More precisely, the standard assumes 0.02 cfm of infiltration per square foot of floor area. For example, the infiltration assumption for a 1,000 ft^2 home with 8 ft ceilings is 20 cfm, or 0.15 ACH.

using intermittent, higher airflows. This strategy may not be sufficient to deal with pollutant peak events such as showers, cooking, etc.

- Homes that use Energy Recovery Ventilators (ERV) are recovering moisture vapor, which could result in the build-up of moisture in high performance green homes[6]. For example, approximately 50% of the moisture vapor generated during bathing may be circulated back into the home. Additionally, some research has shown that ERVs may recover gaseous pollutants, such as formaldehyde, along with water vapor (Offermann et al., 1982). Depending on the recovery rates of other pollutants, they may be expected to build-up in homes with such systems.
- Some high performance green homes do not provide kitchen ventilation using a range hood vented to the outside. A recirculating range hood is provided, often with activated carbon filtration. The efficacy of these systems at removing cooking pollutants is unknown. Cooking pollutants may build up to dangerous levels in such homes. ASHRAE Standard 62.2-2010 requires 5 air changes per hour of kitchen air continuously if a range hood is not provided, and while some exhaust from the kitchen is typically provided, most systems cannot provide the requisite airflows.
- High performance green homes tend to incorporate large amounts of insulation and air sealing materials, which may possibly outgas more pollutants due to their increased volume.
- High performance green homes often use alternative insulation materials, such as polyurethane spray foam insulation, which may emit different pollutants than typical products and proper safeguards to protect occupants may not be used during installation.
- Many low energy homes do not use forced air space conditioning systems, which will sometimes lead to less mixing of the air in a home, as well as reduced deposition of particles during distribution by filtration. This can sometimes increase pollutant exposures and sometimes reduce them.
- Ventilation rates required in the United States, when required at all, are less than standard requirements in other countries, including Belgium, Canada, Italy, Denmark, Finland, Germany (McWilliams & Sherman, 2005), Japan (Sawachi & Tajima, 2008) and Korea (Lee & Kim, 2008).
- The goals of high performance green design and of indoor air quality are contradictory. Without a minimum ventilation rate requirement, an energy-driven design would eliminate all air exchange. Designers pursuing strict energy reduction goals do not have reliable feedbacks in their design process that reflect the impacts of a decision on indoor air quality. Energy impacts are obvious through energy modeling and equipment ratings, but no such feedback

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[6] ERV purposefully recover water vapor as part of their core functionality. This serves to buffer indoor humidity from outdoor levels. Supply and exhaust airstreams are allowed to exchange heat and moisture through a heat exchanger that allows water vapor transmission. This recovers both latent and sensible energies.

exists for air quality. Designers may unwittingly pursue energy reduction at the expense of indoor air quality.

Objectives

In an effort to further our understanding of the effects of energy conservation on IAQ, a study was undertaken of IAQ in Californian homes that were designed to be high performance and green. The objectives of this research were to: (1) identify and assess the ventilation, space conditioning and water heating strategies and equipment being used in a selected sample of Californian homes designed to be high performance and green, (2) create a sizeable data set of air pollutant measurements and occupant activities in these homes, (3) assess the acceptability of the air quality being provided, and (4) identify successful strategies and important variables to provide design and policy recommendations on ventilation and IAQ in high performance green homes.

In pursuit of these objectives, 24 high performance green California homes were recruited as a sample of convenience to participate in a study of indoor air quality. The household occupants, with no further verification, identified the homes as high performance green. This effort was part of a larger LBNL *Healthy Homes* study focusing on IAQ in CA homes with natural gas appliances. *Healthy Homes* is evaluating IAQ through measurements, home characterizations, and occupant surveys. The infrastructure, means and procedures from the larger study were leveraged and adapted to study IAQ in high performance homes, which were identified as a higher risk group for IAQ problems, due to increased airtightness. Electric cooking and heating homes were also recruited to serve as an appropriate control group, which aids in assessing the impact on pollutant levels of indoor combustion for cooking and heating.

In high performance green homes, occupants were surveyed, homes were inspected, and indoor air pollutants were measured, including carbon monoxide (CO), particle number greater than 0.5 micron ($PN_{>0.5}$[7]) and greater than 2.5 micron ($PN_{>2.5}$), ultrafine particle count (UFP), nitrogen oxides (NO, NO_2 and NO_x), formaldehyde (HCHO), acetaldehyde (CH_3 CHO), temperature (T) and relative humidity (RH).

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[7] Particle number values ($PN_{>0.5}$ and $PN_{>2.5}$) should be distinguished clearly from the standard mass concentration measurements of particulate matter ($PM_{0.5}$ and $PM_{2.5}$), which are used to assess compliance with ambient air quality requirements. These values are not comparable.

Literature Review

1.1 IAQ in Energy Efficient Homes

1.1.1 Historical Perspectives on Energy Efficiency and IAQ

The effects of energy conservation on indoor air quality in homes have been sparsely documented in the building science and air quality literatures, but the vast majority of these research efforts are greater than 20 years old. The research efforts in the 1970s and 1980s were spurred by two things: (1) the push for energy reductions in housing, primarily through the reduction of air leakage and the sealing of the building envelope, and (2) the impact of air sealing on radon exposure and its associated health effects on the public conscience. The question being asked in most research efforts was: Is the creation of airtight housing with reduced air exchange rates leading to increased residential pollutant exposures and harmful health effects?

Historical perspectives on energy efficiency and IAQ are discussed in the U.S. and Canadian contexts below. These two national research experiences are handled separately, because the research findings from each country bear direct relationship to the way that energy efficiency and IAQ have been pursued in homes. The Canadian experience is notable for its consistent R-2000 energy efficiency program, which has been continually assessed for its impacts on IAQ and refined accordingly at the national level since 1982. The pursuit of energy efficient homes in the U.S. has been much more piecemeal, with "energy efficient" being defined by individual projects or local jurisdictions, rather than at the national level. While programs like U.S. EPA's Energy Star are national energy efficiency programs, they have lacked the careful ventilation specification of the Canadian program, and they have not assessed impacts on IAQ in program homes. These contrasting approaches explain much of the division between the consistent positive findings in the Canadian research programs and the mixed results in the U.S.

This detailed review has been purposefully limited to the Canadian and U.S. experiences. This was done for three reasons: (1) the unique North American climate, (2) the cultures of the design and construction industries, as well as regulatory agencies, and (3) the trends and conclusions reached are largely indicative of those found internationally. This North American focus allows a more in-depth and detailed reporting of the findings of individual research efforts, and the summaries provided are more informative for those pursuing energy efficiency and acceptable IAQ in California and the U.S. Elements that have emerged as important with international consensus include specification of building airtightness requirements, target air exchange rates, ventilation system design and commissioning, as well as limiting pollutant emissions from materials.

This North American focus is not meant to suggest that international efforts are lacking or irrelevant. The issues of building energy use, indoor air quality and health have been extensively studied and regulated internationally. The Netherlands has implemented ventilation requirements for IAQ in dwellings since 1975, and Belgium has done the same since 1991. Both of these were implemented in response to moisture issues in air-tightened buildings, which did not provide for ventilation and humidity control (Wouters et al, 2008). European Union projects such as Indoor Air Quality & Its Impact on Man have put out reports including *Indoor Air Quality and the Use of Energy in Buildings* since the mid-1990s (Alvarez et al., 1996). These have spelled out the fundamental issues and strategies related to the potential for energy conservation to worsen IAQ, as well as ways to manage these potential liabilities. More recently, the Air Infiltration and Ventilation Centre (AIVC) has published trends in the building ventilation market and drivers for change in 11 countries, including Czechoslovakia, Brazil, Poland, Norway, Japan, Korea and others. These summaries provide national updates on energy performance, ventilation, IAQ and commissioning. Heijmans et al. (2008) have provided an overall summary. Other notable European efforts on energy efficiency and IAQ include the Energy Performance of Buildings Directive (EPBD) and the HealthVent project. The former mandates a framework for the assessment of building energy efficiency throughout the EU, and it has included ventilation and IAQ provisions since its inception in 2002 (European Parliament & Council of the European Community, 2003). The latter is a multi-disciplinary and multi-national effort to develop health-based ventilation guidelines for implementation in Europe (Executive Agency for Health and Consumers, 2012). This international policy, research and development has been occurring in step with North American work, which has not proceeded in isolation by any means.

1.1.1.1 The Canadian Experience in Healthy, Energy Efficient Housing

The majority of Canadian experience in energy efficient housing and indoor air quality is the result of the R-2000 homes program. In 1982, Energy, Mines and Resources Canada created the R-2000 energy efficiency standard for houses. Its goal was the creation of houses that achieved a 50% reduction in heating and hot water energy use over the 1975 National Building Code of Canada baseline. This was achieved through airtight construction, superior insulation, mechanical ventilation with heat recovery and high performance mechanical systems. The R-2000 program was comprised of technical guidelines that exceeded building code, a computer based energy analysis tool, a network of builders and service providers trained in energy efficiency, and close collaboration with the Canadian building industry (Natural Resources Canada, 2010). The R-2000 program probably represents the first large scale, national effort to create high performance green housing, with the explicit inclusion of indoor air quality as a fundamental criterion. It was in fact a requirement of the R-2000 program that the indoor air quality in R-2000 homes be better than the average Canadian home (Gusdorf & Hamlin, 1995).

The requirements of R-2000 homes related to superior IAQ include: (1) high levels of home airtightness, (2) ventilation systems designed to R-2000 specification, and (3) use of low-emitting building materials. R-2000 homes have long had an airtightness requirement of 1.5 air changes per hour at 50 Pascal (Pa), as measured with a blower door test, making them substantially tighter than other Canadian homes (Gusdorf & Parekh, 2000). In 1987, formal ventilation system design and installation guidelines were developed for R-2000 homes, which required the use of Heat Recovery Ventilator (HRV) systems with air supplied to each room. The guidelines specified the following: (1) ventilation system shall provide 5 L/s to each habitable room and 10 L/s to the basement, (2) additional minimum capacity of 25 L/s for high humidity events, (3) capability to exhaust kitchen and bathroom contaminants at 50 L/s and 25 L/s, respectively, (4) the system must not contribute to pressure differences across the building envelope greater than 10 Pascal, (5) provision of make-up air, and (6) requirement that ventilation air be conditioned (M. Riley, 1987). The requirements are designed to ensure adequate fresh air, supplied throughout the home, in order to provide superior air quality. Ultimately, the Canadian Standards Association standard F326 Residential Mechanical Ventilation Systems (*CAN/CSA*, 2010) replaced the R-2000 ventilation requirements. By 1994, R-2000 homes were required to select carpeting, flooring, paints, varnishes, adhesives and cabinetwork from an approved list of low-emission materials and products (Gusdorf & Parekh, 2000). These three elements—strict air tightness levels, fully-ducted HRV ventilation systems and low-emission materials requirements—form the backbone of the IAQ provisions of the R-2000 program.

Beginning in 1984 and continuing for several years on an annual basis, the requirement of superior IAQ in R-2000 homes was tested by the measurement of pollutants and ventilation parameters in hundreds of R-2000 and conventional homes. Measurements included formaldehyde, NO_2 and Radon, as well as ventilation system operation and air exchange rate (Riley & Piersol, 1988). They found that R-2000 homes with mechanical ventilation systems had equal or lower HCHO (formaldehyde) concentrations than conventional houses. HCHO levels in R-2000 homes averaged 69 ppb (85 $\mu g/m^3$) in the first years of the program, essentially equal to the conventional home average concentration of 70 ppb. But the R-2000 average concentration was reduced to 45 ppb (55 $\mu g/m^3$) by 1987, whereas the conventional homes averaged 57 ppb (70 $\mu g/m^3$). This reduction was attributed to revisions enacted in the R-2000 ventilation guidelines, requiring fresh air distribution to each room as well as an air exchange rate of 0.5 $ACH.h^{-1}$. In addition, R-2000 home ventilation systems were commissioned in later years, so that they were actually performing to the program ventilation specification. In the early years of monitoring, approximately 9% of R-2000 homes had HCHO concentrations exceeding the 100 ppb (123 $\mu g/m^3$) exposure limit of Health and Welfare Canada, and 17% of conventional homes exceeded the exposure limit. With the new ventilation requirements and system commissioning in place, less than 1% of R-2000 homes exceeded the limit. This same research found similar HCHO levels in R-2000 homes with forced air heating and with hydronic baseboard heat, suggesting that both system types were compatible with good IAQ. The authors concluded that pollutant source strength, not ventilation rate, is the predominant parameter in determining indoor pollutant levels in R-2000 homes. These research efforts demonstrated that energy efficient homes could have similar or lower HCHO concentrations than conventional homes, provided that ventilation and/or source control measures are put in place. In addition, significant advantage was provided to the energy efficient homes when proper ventilation system specification and commissioning is in place.

Another investigation of IAQ in R-2000 homes was a simulation study intended to assess the impacts of allowing ventilation at 75% of the current requirement in CSA F326 Residential Mechanical Ventilation Systems (Gusdorf & Hamlin, 1995). It was argued that such reduced ventilation rates were already established practice in R-2000 homes, and the adjustment would simply recognize what was already being done successfully. The authors used pollutant source strengths derived from other studies of Canadian housing for HCHO, total volatile organic compound (TVOC), RH and carbon dioxide (CO_2). The 50th and 90th percentile source strengths were used to predict IAQ in 47 R-2000 homes under differing ventilation rates, using the HOT2000 simulation tool (CanmetENERGY, 2011). Four ventilation rates were tested at the 2 source strengths, resulting in 8 concentrations per house. These were compared with measured values in conventional Canadian homes. They concluded that the reduction in ventilation rates would result in an increase in those R-2000 homes exceeding the Health Canada Target HCHO level of 50 ppb (62 $\mu g/m^3$) from 1.7% to 4.7%, with none of them exceeding the Action Level of 100 ppb. They predicted that TVOC are the most likely to cause poorer IAQ under the reduced ventilation scheme in R-2000 homes. When the average source strength was combined with the highest ventilation rate, 91% of houses exceeded the "no effects" TVOC level of 200 $\mu g/m^3$. 9% of R-2000 homes would exceed the Canadian average TVOC concentration under the reduced ventilation scheme, which contradicts the requirement that R-2000 homes have better IAQ than the average Canadian home. When higher source strengths were combined with reduced ventilation rates, the number of homes exceeding the TVOC guidelines increased sharply. So, the authors recommended a decrease in ventilation rate in R-2000 homes only if there was a reduction in VOC emitting materials used in construction. According to data collected from other research projects, average HCHO in R-2000 homes was 26% less than in conventional homes, and TVOC levels were 32% less in R-2000 homes than in conventional homes. Neither of these values were statistically significant, due to fairly large standard deviations. Ultimately, the authors recommended an optional R-2000 package, which included: (1) reduced ventilation rates, (2) restrictions on high emitting construction materials, (3) increased bedroom airflow rates and (4) an extensive monitoring program to assess homes built to the new standard. This simulation study suggested that reducing ventilation rates in R-2000 homes would worsen the IAQ, unless significant counter-measures were employed to reduce pollutant sources.

A more recent survey of energy use and IAQ in the late 1990s was undertaken in 73 conventional new homes and in 24 new R-2000 homes, which revealed significantly lower HCHO and TVOC levels in R-2000 homes compared with their conventional counterparts (Gusdorf & Parekh, 2000). The R-2000 homes were built between 1983 and 1995, and the conventional homes were built between 1990 and 1995. Researchers measured CO_2, temperature, relative humidity, HCHO, TVOC, and Air Exchange Rates (AER) using PFTs. Airtightness measured with a blower door was much better and more consistent in R-2000 homes; air changes per hour at 50 Pascal (ACH_{50})[8] in conventional homes ranged from 2.0 to 4.3 and from 1.14 to 1.44 in R-2000 homes. Over 64% of the conventional homes had no mechanical ventilation systems, which was a major deficit identified by the authors. Formaldehyde in the new conventional homes ranged 8 ppb to 141 ppb (10 to 173 $\mu g/m^3$) with a mean of 53 ppb (65 $\mu g/m^3$), and the R-2000 homes ranged from 12 ppb to 140 ppb

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[8] Air changes per hour at 50 Pascals is a common blower door metric. A calibrated fan is used to depressurize the home to -50 Pa with reference to outside, and the volumetric airflow required to do so is noted. Using this airflow rate, the volume of the home is used to calculate the air changes per hour of the home.

(15 to 172 μg/m^3), with a mean of 27 ppb (33 μg/m^3). The average concentration in R-2000 homes was approximately 51% lower than conventional homes. A few houses of both types exceeded the 100 ppb Health Canada action level. The TVOC levels averaged 571 μg/m^3 in conventional new homes to 388 μg/m^3 in R-2000 homes. Maximum TVOC levels in conventional homes were almost four times greater than maximum levels in R-2000 homes. This research demonstrated that further IAQ advancements were made in R-2000 homes compared with conventional Canadian homes, with a significant performance benefit in the R-2000 homes.

Another report by the Shaw et al. (2001) summarizes more IAQ and energy measurements in R-2000 and conventional homes, but this time, some new homes from the Advanced Houses program were included, as were two other reference Canadian homes—a representative existing home and a "healthy house" (Shaw et al., 2001). The "healthy house" was built purposefully from low-emitting materials and otherwise resembled an R-2000 home. The Advanced Houses program was intended to push R-2000 into the realm of environmental sustainability, in addition to IAQ and energy efficiency. Once again, the R-2000 and Advanced Houses homes were reported as having lower pollutant concentrations than conventional homes. The mean AER of the R-2000 homes was higher than the conventional homes, which contradicts the assumption that low energy houses have less ventilation. The AERs for R-2000 homes were particularly higher during the "shoulder" seasons of fall and spring, when infiltration driving forces were minimal. The TVOC levels were lowest in the Advanced Houses homes, followed by the R-2000 homes, with the conventional new and two reference homes having substantially higher levels. The mean HCHO levels in conventional, R-2000 and Advanced Houses homes were similar. The home with the lowest levels of HCHO was the healthy house, which the authors concluded suggests that appropriate material selection can have major impacts on pollutant concentrations. Once again, the homes in the R-2000 program are shown to have equivalent or superior IAQ to conventional Canadian homes, demonstrating the compatibility of energy efficiency and good indoor air quality.

Recent epidemiological work in conventional and R-2000 homes has been performed by Leech et al. (2004), demonstrating reduced adverse health symptoms in energy efficient homes. Summative symptom scores were determined by telephone survey in 52 new R-2000 and 53 new conventional homes, at occupancy and one year later. Both groups moved into a new home at the start of the research, but details on prior residences were unreported. Summative symptom scores in the R-2000 new homes improved significantly during the first year of occupancy. When compared with control new homes, occupants in R-2000 new homes reported more improvement in throat irritation, cough, fatigue and irritability. Concurrent air quality measurements were not made, so it could not be determined if these epidemiological outcomes related to objective pollutant levels. But symptom scores did not change for health outcomes not thought to relate to air quality, such as nausea or diarrhea. While health improvements were noted, only 76% of occupants in energy efficient homes operated their HRV ventilation systems throughout the winter, and only 58% did so throughout the summer. 10% did not realize they had an HRV installed. These findings cause one to pause; R-2000 homes are very airtight, and a number of them were not mechanically ventilated consistently, though self-reported/perceived health improvements were measured (Leech et al., 2004).

The Canadian experience in high performance green housing has demonstrated that superior IAQ and energy efficiency can be compatible, with either equivalent or reduced pollutant concentrations having been repeatedly measured in R-2000 homes. This achievement was possible due to a coordinated national effort, with requirements and specifications that were refined over time, being informed by actual measurements of pollutants and ventilation parameters in homes that participated in the program. More recently, epidemiological research in R-2000 homes demonstrated an improvement in occupant health in program homes, which has confirmed the benefits of lower pollutant concentrations and better construction quality in these homes. The Canadian experience highlights how important ventilation system design and commissioning can be, as well as the importance of low-emitting materials in making an acceptable indoor environment in high performance green homes.

1.1.1.2 The American Experience in Energy Efficiency and IAQ

Unfortunately, no such long-term, coordinated effort exists in the United States, which can provide the sort of consistent results that R-2000 has in Canada. American programs for energy efficient housing are either significantly less stringent than R-2000—e.g., current Energy Star V 3—or they consist of rating systems with optional credits, rather than enumerated requirements, such as LEED for Homes and other green rating systems. In the United States, the only codified national ventilation standard is ASHRAE Standard 62.2, which does not concern itself with how ventilation airflows are provided. This stands in contrast to the benefits of careful and consistent ventilation system design and commissioning observed in R-2000 homes. Also, no standardized requirements exist in most U.S. jurisdictions that require low-emitting materials, nor is guidance provided for what materials matter most. It may be that when American design and construction professionals pursue high performance green houses, they may not achieve results that reflect the Canadian experience, due to a lack of consistent program support like that provided by R-2000.

The vast majority of research into the effects of energy efficiency on indoor air quality in the United States took place in the 1980s. These efforts were spurred by the emergence of Radon as a pollutant of concern in U.S. homes, as well as in response to the tightening of homes as part of weatherization and energy efficiency efforts. It was thought that homes that were more airtight would experience a build-up of pollutants, resulting from their lower levels of air exchange. Unlike the Canadian R-2000 homes experience, research in energy efficient homes in the U.S. has incorporated a wide variety of house types. These homes have not participated in a consistent, long-term coordinated program like R-2000, and as a result, conclusions have been less reliable and more variable. Research projects have been plagued by small sample sizes and a lack of homogeneity in design and construction specifications. The homes in particular do not have airtightness requirements, nor do they have specifications for ventilation system design and airflow rates. Finally, they lack provisions for low-emitting materials. These three elements were considered crucial to the maintenance of acceptable IAQ in R-2000 homes, yet none are consistently observed in energy efficient U.S. homes.

The U.S. experience in IAQ and Energy Efficiency through the end of the 1980s is surveyed and summarized in the ACEEE book *Residential Indoor Air Quality and Energy Efficiency* by Peter du Pont and John Morrill, published in 1989 (DuPont & Morrill, 1989). They argue strongly that pollutant sources in or under homes, rather than changes in ventilation rate, are the major cause of indoor air pollution. Pollutant source strengths are said to vary by many more orders of magnitude than ventilation rates, and as a result, correlation between ventilation rate and measured concentrations does not exist across a sample of homes. Starting from this assessment, they argue that it is inaccurate to assume that a house with less ventilation will have more polluted air. The authors' review of the literature suggests that pollutant levels found in tight, energy efficient homes are generally no worse than in older, leaky housing. A tight house, they say, without strong pollutant sources will not have a pollution problem, and a leaky house with strong pollutant sources will not necessarily contain healthy air. Yet, it is also admitted that for any given home, a reduction in ventilation rate is likely to increase pollutant concentrations. The counterargument provided to this is that across a sample of homes, no statistical relationship exists between air exchange rates and pollutant concentrations, and that the tightness of a house does not correlate with its pollutant levels. This logic is faulty on many levels. First it assumes that the only reason an energy efficient home could have worse air quality is due to reduced ventilation rate. IAQ could also vary due to the way in which ventilation is provided, how building services are provided, what materials are employed, what spot ventilation is available, etc. Furthermore, if pollutant source strengths are found to be similar in tight and leaky homes, and if AER are lower in tight homes, then their concentrations of indoor generated pollutants will be higher.

The primary argument of the book is that pollutant sources drive indoor pollutant levels, and that ventilation plays a minor, secondary role. That is all well and good, except that we have very few opportunities to manage the sources that end up in any given home, and we have almost no tools available to the designer to aid in assessing the acceptability of design decisions, product choices, etc. Product emission labeling is limited, though not entirely non-existent. Greenguard (GREENGUARD Environmental Institute, 2012), Carpet and Rug Institute Green Label Plus (The Carpet and Rug Institute, 2012), and Scientific Certification Systems (Scientific Certification Systems, 2012) are examples of current voluntary emissions certifications in the U.S. market. Yet, the only mandatory labeling in the U.S. is for OSHA's Hazard Communication Standard (used for MSDS documentation) (OSHA, 2012), and VOC emissions are required on some architectural finish products under the U.S. EPA's Architectural Coating Rule for Volatile Organic Compounds (U.S. EPA, 1998). MSDS documentation is designed for occupational, not residential exposures, and it includes only partial chemical contents, not emissions information. Yet, many pollutant sources in the home are outside the designer's control, including those from durable consumer goods, cleaning products, fragrances, air fresheners and occupant activities, such as cooking. We do not know what is in our homes and therefore we fail to control it. One of the only 'levers' that a low-energy designer has much control over is the ventilation rate and ventilation design. For the given contents of any home, the reduction of its AER will tend to result in higher concentrations of indoor generated pollutants and lower levels of outdoor pollutants.

The following paragraphs will review some of the research presented and argued from in the du Pont and Morris book, as well as other research sources on energy efficiency and IAQ in the U.S.

In the late 1970s, Lawrence Berkeley National Laboratory (LBNL) developed an Energy Efficient Building (EEB) mobile laboratory for studying indoor air quality in buildings. Overall, the goal was to create energy efficient ventilation standards and ventilation designs for commercial and residential buildings, consistent with the health, safety and comfort of the occupants (Hollowell et al., 1978). The primary uses of the EEB were IAQ assessments before and after energy conservation retrofits, and in new buildings that incorporated energy efficient design. The EEB measured time-resolved[9] CO, CO_2, Sulfur Dioxide (SO_2), NO, NO_2, Ozone (O_3), HCHO, total aldehydes, infiltration rate with tracer gas and aerosol particle size distribution. Initial work focused on combustion pollutants in residences. Studies were performed using the EEB in a laboratory room on a gas stove with air exchange rates varying from 0.25 to 10 per hour. It was found that gas stoves generate extremely high concentrations of CO, NO_2, NO and respirable particles and particulate sulfur. Concentrations became unacceptable at 1 ACH or less for CO. For NO_2, an AER of 2.5 did not sufficiently control concentrations, but an AER of 7 did (Hollowell et al., 1978). These initial forays into pollutant measurements in homes led researchers to the conclusion that indoor air can be more polluted than outdoor air, and that ventilation rates were important predictors of indoor air quality.

The mobile test laboratory, EEB, was subsequently used to test the IAQ in three energy efficient homes (Berk et al., 1980). Authors reported that preliminary results showed that energy efficient design features, intended to tighten the building, compromised indoor air quality. The first dwelling tested was called the Minimum Energy Dwelling in Mission Viejo, CA. This was a demonstration project of Southern California Gas Company, which tried to show that good indoor air quality could be maintained in a home that uses at least 50% less energy. The second dwelling tested was the Iowa State University Energy Research House, whose purpose was to obtain data related to active and passive means of reducing household energy consumption. The third dwelling tested was the Energy Research House in Carroll County, MD, which sought cost-effective design strategies for energy efficient homes. Three sample locations were measured in each home, with one outdoor sample. So, a 10-minute sample was taken from each location every 40 minutes. The authors classified the pollutants as follows: (1) generated indoors (low AER is bad), (2) comparable indoor and outdoor sources, and (3) outdoor air pollutants (low AER is good). House number one had an average AER of 0.2; House number two's AER ranged from 0.1 to

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[9] Time-resolved measurements are those that happen repeatedly at a specific period over a length of time. For example, measurements every 10-minutes for one week. This captures the variability in pollutant concentration with activities, time of day, etc. Time-integrated measurements produce average values over a longer period of time, such as a day or week.

0.4, with an average of 0.2; and House number three's AER ranged from 0.05 to 0.3, with an average of 0.15. Reactive outdoor pollutants, Ozone and SO_2, had lower indoor concentrations in all homes. Low air exchange rates shielded the homes from particulate sulfur from power plants. Fine particulates often exceeded outdoor concentrations in all homes. CO in all homes was similar to outside, with slightly higher concentrations in house number one, with gas cooking and heating. Maximum NO_2 in house one was ~200 μg/m^3 (100 ppb). In house one, HCHO hourly concentrations varied from 33 to 104 ppb (41 to 128 μg/m^3), averaging 64 ppb (79 μg/m^3). In house two, HCHO varied from 36 to 97 ppb (44 to 119 μg/m^3), averaging 76 (94 μg/m^3). In house three, HCHO varied from 44 to 148 ppb (54 to 182 μg/m^3), averaging 98ppb (121 μg/m^3). Pollutant sources were not identified in homes, with the exception of gas appliances. The authors concluded that in general, the program provided evidence that indoor concentrations of a wide variety of pollutants increased with lower air exchange rates in energy efficient homes.

A survey was done in the early 1980s of 14 solar homes and 13 conventional homes in Northeastern New York State, in order to assess the indoor radon implications of energy conservation (Fleischer, Mogro-Campero, & Turner, 1982). Researchers found that as a group, the airtight, solar homes had three times the RN222 concentration of the conventional homes. Other specific problems introduced by modern, energy efficient construction techniques also occurred in the solar homes. The authors suggested that the reduction of ventilation rates was the primary problem in the solar homes, but they also asserted that the use of heat storage materials (sand, rock, etc.) in some solar homes, resulted in additional injection of Ra226. During the winter, half of the energy efficient homes had average concentrations of 4 pCi/L, whereas only one room in one conventional home had similarly elevated levels. Concentrations in Solar homes were 3.2 and 2.2 times the concentration in conventional homes, during winter and summer respectively. Energy efficient homes studied were significantly more radon-rich, particularly in the 1st and 2nd floor living areas, where most exposure occurs. Unfortunately, the authors did not report on the airtightness of the homes, nor did they report the AER of the solar homes, which could possibly have been very low. Once again, this research effort demonstrated the potential for energy efficiency measures to compromise IAQ in homes.

IAQ was also tested in the early 1980s in low-infiltration housing in a study in Rochester, New York. 58 occupied homes that incorporated special builder-designed weatherization components, were assessed on (1) the effectiveness of efforts to air tighten, (2) the effect on AER and indoor air quality, and (3) the impact on indoor air quality of homes using mechanical ventilation with heat recovery (MVHR) (Offermann et al., 1982). MVHR was installed in nine of the airtight homes—seven homes with HRV and two homes with ERV—and one relatively 'loose' home was measured as a control. Three homes had gas cooking and six had electric cooking, and one had a smoking occupant. In the MVHR homes, measurements of AER, Radon, HCHO, NO_2, and humidity were made for one week with ventilation running and one week with it off. In all nine homes, AER was relatively low 0.2-0.5 without mechanical ventilation and averaged 0.63 with MVHR installed. Measured pollutants remained below existing guidelines during both test periods, with the 'loose' home having the lowest concentrations of all ten. HCHO concentrations ranged from 7 to 64 ppb (9 to 79 μg/m^3), with an average of 36 ppb (44 μg/m^3). The gas cooking homes had higher average NO_2 concentrations than electric, 15 ppb vs. 4 ppb, but occupants did use outside vented range hoods. Some airtight homes experienced high relative humidity and excessive condensation occurred; one home had mold growth on the walls. MVHR tended to further reduce the pollutant concentrations in the nine homes, with Radon and HCHO having been reduced 50% and 21%, respectively. Yet, NO_2 levels generally increased, due to higher outdoor concentrations. Of note, no reduction in HCHO occurred in the homes with ERV installed, which the authors attributed to potential HCHO transfer through the paper core. The authors concluded that in homes with low pollutant source strengths, good IAQ and low ventilation rates could be compatible. It is worth noting a few things in this research: (1) the airtight homes' average Specific Leakage Area (SLA) was 2.4 cm^2/m^2, which is not particularly tight by today's standards, (2) the ventilation rates in the 'low infiltration' homes were higher than recommended by most current jurisdictions (McWilliams & Sherman, 2005) (3) the ERV failed to reduce HCHO concentrations, (4) condensation and mold occurred in a few airtight houses, (5) the homes did not exceed current exposure standards, but the HCHO standard at the time specified 123 $\mu g/m^3$, which is quite high compared with today's standards, and (5) the 'loose' home had the lowest pollutant concentrations in the study. These factors make the author's conclusion suspect in today's energy efficient homes. This also demonstrates how exposure standards and definitions of airtight and energy efficient vary with time and place, and that the conclusions reached at one time may not remain valid when new exposure standards are put in place, and when new technologies, designs and materials are employed.

In the same time period, other researchers were attaching risk factors to each kWh of energy saved as part of an air tightening energy conservation effort (Burkart & Chakraborty, 1984). The risk factors per kWh saved through air tightening energy conservation, based on linear dose-response relationships, were shown to be orders of magnitude greater than those for a kWh produced by a large, central power plant. The authors attempted to quantify the risk of increased Radon exposure due to reduction in the AER from 1 to 0.3. They concluded that 1,700 deaths per 100,000 people would result from the increased exposure risk of the energy efficient home. NO_2 and HCHO are also singled out for concern by the authors, but they do not have associated risk factors, so no risk factor/kWh saved could be created. The authors concluded that in terms of human health, air tightening is a very expensive way to reduce energy usage.

In the Pacific Northwest, two major research inquiries were made into the effects of energy efficiency on indoor air quality: (1) the examination of the effects of weatherization on IAQ in existing homes and (2) the examination of IAQ in new homes built to the Model Conservation Standards (MCS) for energy efficiency. A useful review of the literature is provided by (Grimsrud et al., 1988) in their presentation of research outcomes on these two questions. A number of the papers referenced are otherwise irretrievable by this author, so the conclusions of Grimsrud et al. (1988) are presented here. For weatherization's effect on IAQ, Grimsrud et al. (1988) argued that little experimental evidence existed to support the claim that weatherization causes a deterioration in IAQ. Other research cited by Grimsrud et al. (1988) found it difficult to attribute changes in pollutant concentrations to weatherization activities, and those that did were laboratory-type experiments, not field research. On the question of IAQ in new, energy efficient homes, the authors identified a number of what they called "small" studies, whose results were inconclusive. They identified the following limitations in the other research: (1) a lack of ventilation measurements, (2) a lack of an adequate control sample, (3) an inadequate justification of the homes as 'energy-efficient', (4) attention to only a single pollutant, and (5) an insufficient number of homes for a statistical analysis. They aimed to overcome these limitations in their work.

Harris (1987) evaluated Radon and HCHO concentrations as a function of ventilation rates in homes built to the MCS for energy efficiency, and reported a very weak correlation between pollutant levels and AER (Harris, 1987). MCS provisions included air tightness to reduce infiltration, as well as the use of MVHR. Radon and formaldehyde measurements were made in 420 MCS residential buildings and approximately 400 conventional new homes. These measured concentrations were compared with ventilation rates measured using the perfluorocarbon tracer gas technique and estimated using fan pressurization tests and an infiltration model. Radon measurements were taken for both 3- and 12-month periods using passive detectors. HCHO measurements were taken over a one-week period during the heating season using a passive detector. A subset of homes was monitored for two consecutive heating seasons, one year apart. The authors reported a very poor correlation between ventilation rates and measured pollutant concentrations, with a maximum correlation coefficient of 0.032. Tests of significance were carried out, which indicated that AER is a statistically significant variable in determining radon, but not HCHO concentrations. This study presented a large statistical sample of both energy efficient and conventional homes, which found that AER was a poor predictor of pollutant levels across a population of homes.

Further details were also reported on this MCS study, with a focus on 29 MCS homes and 32 new, conventional homes (Grimsrud et al., 1988). The SLA was 46% lower in the MCS homes, making them substantially more airtight. Yet, the measured AER were nearly identical, at 0.30 for MCS homes and 0.26 for control homes. Both values were substantially below the 0.6 ACH design target of the MCS program. It was found that pollutant concentrations varied more with region than they did with construction style, or level of energy efficiency. 30% of all homes had HCHO concentrations greater than 100 ppb (123 $\mu g/m^3$), which was considered very high. Homes in the Portland area averaged HCHO concentration were 93 ppb (114 $\mu g/m^3$), while the Spokane homes averaged 60 ppb (74 $\mu g/m^3$). When all MCS homes were compared to all conventional homes, the mean HCHO concentrations were 82 ppb vs. 72 ppb, respectively (101 vs. 89 $\mu g/m^3$). This difference between home types (82 to 72 ppb) was substantially smaller than the difference between regions (93 to 60 ppb). For some reason, the authors did not ascribe significance to the higher HCHO concentrations in the MCS homes. Water vapor concentrations were found to be quite similar between groups and regions, though the MCS homes had spatially uniform concentrations, whereas the conventional homes had significantly higher levels in bedrooms. The MCS homes, which were substantially airtight and used advanced MVHR systems, were reported to have pollutant levels similar to conventional homes.

Researchers in the Pacific Northwest also pursued the question of whether or not house tightening as part of home weatherization efforts would lead to compromised IAQ (Turk et al., 1988). Indoor levels of HCHO, NO_2 and water vapor were measured in 111 homes and were found to be significantly below levels of concern, with NO_2 average concentrations of 5 ppb and HCHO averaging 37 ppb (46 $\mu g/m^3$). Indoor Radon concentrations were elevated in homes with highly permeable soil that encouraged convective flow of radon-bearing soil gas. Forty-eight of these homes were studied to evaluate the effects of house weatherization on indoor air pollutant concentrations. Weatherization reduced the SLA in 40 homes by 12.5%, and house doctoring in five homes resulted in an additional 26% decrease in SLA. Mean AER rates were 0.37 before weatherization and were 0.39 afterwards. This slight increase was counter-intuitive, as one would expect AER to be reduced after weatherization efforts. This likely was the result of low reductions in SLA and varying driving forces. The major change in air quality seen in the sample as the result of weatherization was a substantial decrease in radon concentration in houses having crawlspaces. Respirable suspended particle (RSP) and NO_2 concentrations were low in those homes without tobacco smokers or without frequently used combustion appliances. In general, the changes in AER and in pollutant concentrations were insignificant and uncorrelated, which was expected given the essentially identical mean AER. HCHO was decreased by 3% and water vapor levels increased 8%, neither was statistically significant. The results of this study suggested that with typical weatherization efforts, the AER was not largely affected and therefore the pollutant levels were not increased by the energy conservation efforts. So, when energy conservation does not change AER, then pollutant changes are not to be expected. Even if substantial improvements in airtightness were achieved, mechanical ventilation could be used to maintain ventilation rates and pollutant levels.

Later in the 1980s, researchers in the Pacific Northwest compared the effective ventilation rates of five super-insulated homes using different ventilation strategies—natural, balanced, unbalanced and MVHR[10]—with the assumption that a home with a more consistent ventilation rate was superior (Hekmat, Feustel, & Modera, 1986). The authors concluded that mechanically ventilated homes provided the best IAQ, due to their more consistent effective ventilation rates (spread of 2-13% about the average) versus the naturally ventilated homes (spread 37-47% about the average). The authors reported that ventilation peaks and valleys were reduced with an unbalanced system. This was the result of the empirical method used that added unbalanced mechanical ventilation to infiltration by quadrature[11] (Walker & Wilson, 1993), rather than by direct addition, as with a

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[10] "Natural" ventilation relies on the driving forces of wind and temperature difference alone. "Unbalanced" mechanical ventilation uses a fan of some sort, and either supplies or exhausts air from the building. Make-up air comes through adventitious openings in the building (leaks). Examples include kitchen range hoods and bathroom exhaust fans. "Balanced" mechanical ventilation uses multiple fans to provide simultaneous supply and exhaust of air. All airflow is provided through designed openings, which allows for the source of all ventilation air to be controlled.

[11] A popular method of combining unbalanced mechanical and natural ventilation flows is the use of the quadrature method. Rather than directly adding unbalanced mechanical and natural ventilation flows, the

balanced mechanical system (a spread of 3% vs. 8% or 5% vs. 13% in a colder/windier climate). The naturally ventilated home was criticized as having numerous hours and days with ventilation rates significantly lower than desired. The authors' most questionable conclusion was that unbalanced ventilation systems provided the most consistent ventilation rate and therefore best IAQ. Balanced ventilation systems provided higher rates of ventilation, but they were not as consistent, due to their direct addition to weather-influenced infiltration. It is difficult to understand how a higher, but less statistically consistent ventilation rate would be inferior. Either way, the research demonstrated the clear consensus that emerged at the end of the 1980s—that mechanical ventilation provides superior IAQ, and it is a requirement in energy efficient, airtight residences.

More recently, research and educational efforts concerning indoor air quality in energy efficient homes have demonstrated a number of potential benefits that can result from evidence-based design and careful construction site implementation. It has been demonstrated that the use of building science principles can lead to buildings with fewer IAQ and health problems, in ways that are consistent with energy efficiency. Oftentimes, measures that were shown to improve air quality and occupant health were actually side benefits of durability and energy saving efforts. A major shift in focus has occurred, whereby building airtightness is seen as protecting occupants from pollutants in spaces such as attics, crawlspaces and garages. This stands in sharp contrast to the rhetoric of the past, where airtightness was a liability, potentially leading to increases in pollutant levels. Of course, building airtightness can have both effects. Examples of such effects include sealed crawlspaces in the Southeast and the use of sealed combustion gas appliances. Significant remaining questions have also been explored, such as the impacts of internal mixing and the performance of attached garages.

In the early 2000's, building science professionals and researchers in the Southeastern U.S. were alarmed by a widespread pattern of damp, moldy, vented crawlspaces in air-conditioned homes that they observed. Researchers at Advanced Energy Corporation in North Carolina, undertook a study to assess the liabilities of vented crawlspaces and their impacts on IAQ, as well as to assess the effectiveness of remedial 'closed' crawlspaces (Coulter et al., 2007). 45 homes in North Carolina were selected for mold species testing and building science assessments. 36 new homes were subsequently targeted for demonstration of the advantages of closed crawlspace design. Researchers documented that homes built on conventional crawlspaces had: (1) liquid water, water vapor and associated moisture issues, (2) mold spores, (3) measured holes between the crawlspace and living space, and (4) measured mold spore transmission from the crawlspace to the living space. 62% of homes had visible mold growth, 67% had wood moisture readings in the crawlspace at mold-supporting levels and 36% had wood moisture readings at rot-supporting levels. They determined that occupants were exposed to crawlspace

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square root is taken of their summed squares, and then any balanced flow is directly added:

$$Q_{total} = \sqrt{Q_{unbalanced}^2 + Q_{natural}^2} + Q_{balanced}$$

contaminants through HVAC duct systems and floor leakage. Similar leakage areas were identified between the house and crawl, and the crawl and ductwork, demonstrating that both pathways were allowing for mold and moisture transmission to the house. Moisture and IAQ problems were successfully alleviated through implementation of a closed crawlspace, as well as air and duct sealing of the home. The authors suggested that a moisture management strategy, as well as house air sealing and duct sealing will reduce the moisture and mold transmission problems. This research is a great example of how contaminants outside of the living space can be prevented from reaching occupants through increases in building airtightness and proper moisture management.

The Building Science Corporation (BSC) provides numerous other examples of increased durability and IAQ benefits from energy-efficient building practices, as part of the literature they provide online to contractors and energy designers (Building Science Corporation, 2012). The information provided by BSC is a well-respected source for many of the nation's energy efficiency designers, and they are considered experts on building durability, IAQ and energy use. They recommend sealed natural gas combustion in all climate zones, with dedicated outdoor air intake and exhaust ducts connected directly to the appliance. This is said to disconnect the combustion process from the interior of the home, and it eliminates concerns about back drafting and spillage of combustion pollutants. They add that the elimination of the make-up air duct reduces uncontrolled infiltration and saves energy, as does the sealed-combustion appliance (Building Science Corporation*,* 2009a). The BSC also provides guidance about proper placement of ventilation openings, so as to avoid introducing pollutants into the home. Where ventilation and combustion air comes from and goes to can make a big difference. They urge avoidance of ventilation intakes near roofing materials, plants, snow, etc. They also caution against placement of combustion exhaust outlets near building openings, such as windows, doors and ventilation inlets (Building Science Corporation*,* 2009b).

Debate has recently emerged over the issues of mixing of air in residences and its effects on occupant exposure to pollutants. This has occurred within the context of ventilation standards and best practices development. Sherman and Walker (2011) review the recent literature and debate on this topic, and provide results from new simulation studies. Variations in occupancy patterns and house design can significantly affect the outcomes of mixing. The authors use the notion of relative dose to explore mixing in residences, which is the ratio of the dose at the test condition relative to a reference condition. Mixing can be either beneficial or harmful when a house zone with high concentrations of pollutants, such as the kitchen, is diluted through mixing with the rest of the home. If occupants are in the kitchen, then the dilution is beneficial, but if occupants are elsewhere in the home, then mixing has increased their exposure. When pollutant sources are distributed, then mixing has no impact on relative dose. The authors suggest that if a policy goal is to reduce peak exposure, then mixing is to be encouraged, but conversely, the average exposure is actually increased under well-mixed conditions, which they attribute to higher prevalence of pollutants in zones with local exhaust fans (kitchens, bathrooms and laundry) and resulting increased ventilation efficiencies. For this reason, exhaust systems performed slightly better than central fan integrated supply (CFIS) systems[12]. They add that some amount of mixing, at relatively low levels (0.2-0.3 ACH for exhaust and 0.5-0.7 ACH for supply), which can help reduce the occurrence of high relative doses (M. H. Sherman & Walker, 2010). Mixing, it would seem, is sometimes beneficial and sometimes harmful in occupant exposure levels.

The increased airtightness of energy efficient homes may provide a barrier between occupants and harmful pollutants contained in attached garages. Emmerich et al. (2003) provide an extensive review of the literature on the transmission of pollutants from attached residential garages into living spaces. Pollutant transport occurs as a result of both natural and equipment induced pressure differences across the house to garage (HG) interface. They note that the limited literature on the topic suggests that both acute[13] (carbon monoxide from autos) and chronic[14] (stored chemicals, fertilizers, etc.) exposures result from this transmission. The airtightness of the HG interface is a key element to reducing both chronic and acute exposures. In a small subset of homes tested by the authors, the HG interface was found to be on average nearly 2.5 times more leaky than the rest of the building envelope (Emmerich et al., 2003). Measurements of HG interfaces and pollutant transport have not been made in energy efficient, airtight homes, but they may perform better than average, to the extent that total house air leakage is limited to very low levels, for example in Passive Houses. Airtight forced air ductwork should also limit transmission from garage to house, when air handlers or return ducting are located in the garage.

As suggested in this section's introduction, the results of IAQ assessments in energy efficient homes in the U.S. have not provided consistent results like those reported in R-2000 homes in Canada. Many early research efforts suggested that pollutant levels were elevated in efficient homes, and substantial health costs were said to be associated with these worsening indoor exposures. This research was plagued by small sample sizes and varying definitions of "energy efficient". Later research projects in Rochester, N.Y. and in the Pacific Northwest suggested that acceptable IAQ and energy efficiency might be compatible. Researchers came to the conclusion that AER was not the most important predictor of indoor pollutant levels, and that source strength, geographic location and other elements were more important. Consistent with Canadian findings, these researchers reported that pollutant levels in high performance homes were similar to those in conventional homes. Some consensus was reached around these points, and researchers and practitioners have more or less accepted the compatibility of efficiency and IAQ up to the present.

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[12] CFIS are mechanical ventilation systems that provide outside air through a duct connected from the return plenum of the central air handler to the outside. Outside air is sucked into the return plenum and distributed throughout the home using the existing duct system. This is an unbalanced supply ventilation system.

[13] Acute exposures are intended to describe the risk to humans resulting from once-in-a-lifetime, or rare, exposure to airborne chemicals.

[14] Chronic exposures are intended to describe risk to humans resulting from contact with a substance that occurs over a long period of time.

Nevertheless, results have not been demonstrated for homes built to a national U.S. conservation standard in the present day. Nor does any national program exist in widespread usage that has consistent requirements for ventilation provision, materials emissions, etc. U.S. EPA Energy Star is the closest example, but its requirements are not representative of today's high performance green homes, and IAQ in certified homes has not been assessed to date. This limits the value of the historical findings summarized above, as well as the validity of today's consensus about IAQ in energy efficient U.S. homes. The levels of performance demanded of energy efficient homes have substantially changed with the passing of time, as have materials emissions, and the practices of conventional house construction. As a result, satisfactory conclusions cannot be reached about IAQ in energy efficient homes in the U.S., a market that is characterized by inconsistent regional programs and optional performance criteria.

1.1.2 Current U.S. Consensus on Energy Efficiency and IAQ

Whereas much of the previous research into energy efficient homes and IAQ was concerned with energy efficiency's potential to worsen pollutant levels, current initiatives in the field tend to focus on the potential synergies between health improvements and energy upgrades. These efforts recognize both the liabilities and the benefits that energy efficiency can bring to the indoor environment, and they attempt to minimize the former and maximize the latter. Whereas past efforts questioned if high performance homes had higher pollutant levels, many practitioners today believe these homes are healthier and have lower pollutants than conventional homes. This author has noted a shift in focus to existing and sometimes stressed housing, with most research and policy efforts being directed towards low-income families, who are disproportionately affected by unhealthy indoor environments (Kuholski et al., 2008). Similarly, home performance contractors consider improvements in IEQ to be amongst the key benefits that efficiency improvements provide to homeowners (Sterner, 2011). High performance home programs have been swept along in this belief that efficiency and acceptable IAQ are compatible. This has occurred despite the fact that substantial differences exist between the IEQ impacts of efficiency improvements in existing homes and the very high levels of performance targeted in today's high performance green homes.

Consistent with this consensus, the U.S. DOE and U.S. EPA have produced two documents for the home energy efficiency community pertinent to energy efficiency and IAQ—*Workforce Guidelines for Home Energy Upgrades* and *Healthy Indoor Environment Protocols for Home Energy Upgrades* (U.S. DOE, 2011a; U.S. EPA, 2011b). The first provides standard specifications for home energy upgrade activities, and the second provides practices and procedures meant to ensure that energy upgrades do not worsen IEQ and occupant health. This pair of documents suggests a broad acceptance that efficiency improvements can worsen IEQ in homes, but that this can be managed and reversed if certain protocols are followed.

The National Center for Healthy Housing (NCHH) performed a recent study comparing data on occupant health status before and after energy conservation retrofits. General, respiratory, cardiovascular and mental healths were assessed in 248 treatment households using self-reported health levels. These households received efficiency improvements such as insulation, air sealing and HVAC tuning/replacement. Notably, efforts did not include provision of mechanical ventilation. Health results were mixed. Significant improvements were reported in general health, sinusitis, hypertension and reduced used of asthma medication. At the same time, several respiratory symptoms were reported more frequently, and the number of days reported with trouble sleeping increased due to asthma problems. Pollutants were measured inside the residences before and after, and no significant changes were observed, with low levels of NO_2, CO and CO_2 (National Center for Healthy Housing, 2012). Methodological issues abounded in this study. Outdoor air pollutants were not measured, and health outcomes were simply self-reported. It is possible that activities not related to IAQ improved the general conditions and health in the homes, but air sealing without ventilation provision worsened respiratory health.

The Maine Indoor Air Quality Council has undertaken an assessment of the effects of weatherization on radon concentration in homes. The research question was if weatherization activities increase indoor radon concentrations, and the answer was: “sometimes”. Radon was measured in 50 homes before and after weatherization occurred, and it was found that on average, radon concentrations increased in the homes after weatherization activities. 18% of the homes were beneath the U.S. EPA threshold of 4 pCi/L prior to weatherization, and were above the threshold after work was performed. Notably, the change in air tightness had a marginal impact on indoor concentrations. Rather homes with dirt floor basements and open sump pumps were the cause of most radon increase post-weatherization (Tohn, 2012).

This paradigm, where enhanced IAQ is the result of energy efficiency and sustainability improvements in existing housing is central to current models for green building and high performance new homes as well. All reviewed rating systems for energy efficiency or sustainability in homes explicitly refer to the air quality benefits of certification. For example, a supplemental certification was recently created to the U.S. EPA Energy Star program called EPA Indoor airPLUS, which addresses IAQ through moisture control, radon control, pest management, low-emitting materials, combustion pollutant control and commissioning and verification requirements (U.S. EPA, 2009a). Mudarri (2010) provides an extensive review of building codes, optional certifications and indoor air quality, including Indoor airPLUS, LEED for Homes, and DOE Builder’s Challenge (Mudarri, 2010). These optional programs all explicitly include both energy and IAQ elements. They include moisture management practices, use of low-emitting materials and minimum ventilation requirements, and some existing building certifications require integrated pest management. This suggests that the compatibility of energy conservation and indoor air quality has been almost fully accepted, and it has been integrated into the high performance green building paradigms in the U.S., at least at the program level.

1.1.3 Lingering Concerns with IAQ and Energy Efficient Homes

A consensus has emerged in the high performance homes community in the U.S. that high levels of energy efficiency and IAQ are compatible, and are in fact complimentary of one another. Yet, debate has not been entirely quelled on the subject of air quality in energy efficient homes, particularly when measured improvements are not from a sub-standard baseline, as in low-income housing. Those who continue to be concerned with the IAQ impacts of high performance construction see today's energy efficient homes as posing unique hazards to occupants. They do not consider past research efforts to be sufficient to answer today's concerns. Extreme airtightness, super insulation, innovative HVAC systems, and near total reliance on mechanical means of ventilation are all seen as new reasons for concern. Fear remains that the push to extreme levels of efficiency will result in design and construction professionals who do not sufficiently address IAQ, and who do not recognize how today's best practices may pose new concerns.

Hemsath et al. (2012) explore the potential health concerns associated with zero net-energy homes. They note the increasing policy drive to reduce energy consumption in the built-environment and the lack of knowledge about the outcomes of efforts such as air tightening, mechanical ventilation systems and materials, and their impact on air quality, mental and physical health, and safety of occupants (Hemsath et al., 2012).

Mudarri (2010) suggests that building code protections of indoor air quality in residences are in a perpetual state of "catch-up" to energy provisions, which may be negatively affecting IAQ in homes. He attributes this lag to the institutional momentum and political support that exist in favor of energy conservation, which are not present for IAQ. The primary issue identified in homes is the tendency towards increased air tightness, in a context where mechanical ventilation has not been historically provided. He suggests that increased air tightness can lead to: (1) low ventilation rates and increased pollutant levels, and (2) increased back drafting of natural-draft gas appliances. While building codes and energy codes do often address issues like moisture control and minimum outdoor air rates, they rely on window operation, rules of thumb and forgiving buildings; assumptions which are no longer valid in today's modern energy efficient, air tight homes (Mudarri, 2010).

Bone et al. (2010) discuss the possible health consequences of the UK government's goal to reduce greenhouse gas emissions by 80% by 2050, with housing efficiency improvements seen as a key contributor to the effort. They identify insufficient air exchange rates and over-heating during heat wave conditions as the primary risks. Authors suggest that use of mechanical ventilation in UK homes represents a step-change in practice, which is not without pitfalls. There is no accredited trade body or accredited training available for the commissioning, design and installation of such systems. Reliability of mechanical ventilation systems may be reduced due to poor maintenance, aggravation to occupants due to noise, and lack of awareness of system purpose and operation. The authors conclude that evidence of the outcomes on human health of energy conservation is insufficient (Bone et al., 2010).

The National House-Building Council of the UK has published an extensive review on the current state of knowledge on indoor air quality in highly energy efficient homes. They review literature from Europe and the United States, and they identify a dearth of measurements of IAQ in highly energy efficient homes. The authors identify as a key issue the performance of ventilation systems in highly energy efficient homes, specifically noise, serviceability, installed performance degradation, filtration efficiency and suitability of demand-controlled ventilation. Significant further research on air pollutants and ventilation system performance is urged in energy efficient homes. The authors discuss a research effort in four Passive Houses in the Netherlands, in which IAQ sampling occurred alongside occupant surveys. The mechanical ventilation systems were set to their default speed level one, which is appropriate for use during vacation periods. This low ventilation concerned the authors. The authors concluded that the homes were potentially healthy, but that they required additional care during construction and commissioning and significant occupant education (Crump, Dengel, & Swainson, 2009).

Consistent with these broad concerns, a recent occupant health issue in a Belgian Passive House has been highlighted in the Green Building online community. The home was occupied in 2005, and occupants soon developed a host of health problems, including coughing, shortness of breath, headache, dry throat, pain and weakness in the legs, painful muscles, fever, diarrhea, paleness, nausea, tiredness and a loss of taste. The home was investigated and reported to have a variety of issues including unvented brick-veneer siding, stagnant water and construction debris in earth-tube ventilation system, and ventilation airflow at one third the specified flow rate (Holladay, 2012). These issues are illustrative of the sorts of the problems that can be introduced when low-energy design strategies are used, with a lack of quality and inspection in the construction process and no commissioning of mechanical systems.

1.1.4 Summary of Indoor Air Quality in Energy Efficient Homes

The issue of energy efficiency and indoor air quality is as perplexing as ever. Research has occurred inconsistently over three decades in the U.S., Canada, Europe and Southeast Asia, within a context of changing exposure standards, construction methods and building materials. Results are mixed, and comparisons across time, geography and methods may be invalid. Envelope airtightness and integrity, which seems to be at the heart of most debates, can be both protective and potentially damaging to occupants. The Canadians have demonstrated that with a unified program, containing specifications for low-emitting materials and commissioned ventilation systems, pollutant concentrations in energy efficient homes can be reliably similar to or less than conventional homes. At the same time, American researchers have found mixed results, with some concluding that energy conservation leads to increased levels of indoor pollutants, and others suggesting that pollutant profiles are similar. The current belief in the U.S. argues that IAQ is better in high performance than conventional homes; a complete reversal of previous concerns. The majority of recent U.S. efforts have focused on stressed, low-income housing, and the potential of combined human and health service programs to deliver health and safety benefits alongside efficiency improvements. A similar paradigm exists in the home performance industry, where efficiency interventions are seen as an opportunity to alleviate IAQ problems caused by malfunctioning equipment and unhealthy spaces such as attics, crawlspaces and garages. It is not clear that these findings relate to the unique hazards posed by today's highest performance standards. New building codes and optional sustainability and energy performance standards for homes are coming into use, yet no significant effort has been made to assess their impact on IAQ, though much has been made of their possible failure to reduce energy consumption (Cater, 2010). As nations become serious about reducing the contribution of their buildings to climate change, concerns over the detrimental air quality impacts of high performance green homes have returned to the forefront. This has occurred with much discussion and debate, and very little science.

1.2 Review of the Pollutants to be Measured

A recent hazards assessment of chemical air contaminants measured in residences identified 9 priority pollutants, based upon the robustness of measured concentration data found in the scientific literature and the fraction of residences likely to be impacted. These pollutants are formaldehyde, nitrogen dioxide, $PM_{2.5}$, acetaldehyde, acrolein, benzene, 1,3-butadiene, 1,4-dichlorobenzene and naphthalene. Potential acute health hazards related to household activities included $PM_{2.5}$, formaldehyde, CO, chloroform and NO_2 (J. Logue et al., 2010). A number of the pollutants to be measured in this thesis are part of both the chronic and acute pollutants of concern identified in this assessment, including formaldehyde, acetaldehyde, nitrogen dioxide, $PM_{2.5}$ and CO.

Another recent analysis effort has estimated the chronic health impacts of non-biologic air pollutants in U.S. residences. Using the metric of Disability Adjusted Life-Years (DALYs) per year per 100,000 persons, indoor air pollutants were ranked in terms of their chronic health impacts. $PM_{2.5}$, formaldehyde and acrolein accounted for the vast majority of estimated DALY losses. Radon, ozone, acetaldehyde, NO_2 and CO were also amongst the 17 top contributors to DALYs lost. Chronic NO_2 and acetaldehyde impacts were estimated to be three orders of magnitude less than $PM_{2.5}$, and two orders less than formaldehyde (J. M. Logue et al., 2012). Notably, the potential acute impacts of these pollutants could be substantial and may differ from the chronic results reported. All of these pollutants, except acrolein, radon and ozone are measured in this research, due to their status as key contributors to health impacts in the indoor environment.

Existing standards for the pollutants being measured are presented in Table 1 below, as either 1-, 8- or 24-hour exposure standards, or as chronic or acute reference exposure levels (REL) (CARB, 2011; OEHHA, 2012; U.S. EPA, 2012). Each pollutant is reviewed in more detail below, for its characteristics, sources, health effects and measured concentrations.

Pollutant	Non- Cancer Concentration Criteria	Exposure Period	Agency
CO	9 ppm	8-Hour	U.S. EPA
CO	20 ppm	1-Hour	California EPA
CO	35 ppm	1-Hour	U.S. EPA
Formaldehyde	9 μg/m^3	8-Hour Reference Exposure Level	California EPA
Formaldehyde	9 μg/m^3	Chronic Reference Exposure Level	California EPA
Formaldehyde	55 μg/m^3	Acute Reference Exposure Level	OEHHA
Acetaldehyde	140 μg/m^3	Chronic Reference Exposure Level	OEHHA
Nitrogen Dioxide	30 ppb	Annual	California EPA
Nitrogen Dioxide	53 ppb	Annual	U.S. EPA
Nitrogen Dioxide	100 ppb	1-Hour	U.S. EPA
Nitrogen Dioxide	470 μg/m^3	Acute Reference Exposure Level	OEHHA
Nitrogen Dioxide	250 ppb	1-Hour	California EPA
PM 2.5	35 μg/m^3	24-Hour	U.S. EPA
PM 2.5	15 μg/m^3	Annual	U.S. EPA

Table 1 Indoor Air Pollutants, Reference Exposure Levels

1.2.1 Formaldehyde (HCHO)

The following three paragraphs are a summary of the WHO (2010) description of formaldehyde. Formaldehyde is a colorless, odorless gas that is reactive at room temperature. It is found ubiquitously throughout the environment, with both natural and anthropogenic sources. Natural sources include biomass combustion and decomposition. Anthropogenic sources include industrial emissions, combustion processes, and consumer products, where it is used extensively as a resin, fixative, preservative and disinfectant. Indoor sources include combustion—smoking, heating, cooking, candle/incense use—and building materials and consumer products that contain formaldehyde. This latter group includes furniture, pressed wood products, insulating materials, textiles, paints, sealants, adhesives, wallpaper, household cleaning products, cosmetics, electronic equipment, pesticides, paper products and others. Secondary formation of Formaldehyde also occurs indoors from oxidation of other VOCs and through ozone interactions with terpenes. In terms of inhalation exposure to formaldehyde, indoor exposure contributes up to 98% of time-integrated exposure (WHO, 2010).

The health effects of formaldehyde exposure include cancer and non-cancer effects. Non-cancer effects include odor, sensory irritation of eyes and airway, lung effects related to asthma and allergies, and eczema. The International Agency for Research on Cancer (IARC) has classified formaldehyde as carcinogenic to humans. Sufficient evidence exists for animal carcinogenicity in the upper airway, as well as epidemiological evidence that formaldehyde causes nasopharyngeal cancer in humans, and it may cause myeloid leukemia in humans (WHO, 2010). The OEHHA has set acute, 8-hour and chronic Reference Exposure Levels for Formaldehyde of 55, 9 and 9 μg/m^3 respectively. OEHHA (2007) summarizes the reasoning behinds these determinations (OEHHA, 2007)

Indoor formaldehyde concentrations have been linked with a wide variety of housing factors. Across the literature, the most important factors are house or building material/product age, indoor temperature and relative humidity, presence of formaldehyde resin wood products, smoking, electric heating, air exchange rate, season and recent remodeling activities (WHO, 2010).

The following paragraphs are no longer summarized from WHO (2010). Indoor formaldehyde concentrations have been measured in homes and other buildings for more than 3 decades. Due to its variation with house age, regional variation in building practices, and to reductions that have occurred in formaldehyde levels in consumer products, it is most appropriate to compare measured values from homes of similar ages and regions. For that reason, the focus of this study is on measurements in relatively new homes, made recently. Salthammer et al. (2010) provide an exhaustive international review of indoor formaldehyde concentrations and assessment techniques (Salthammer, Mentese, & Marutzky, 2010).

Table 2 below summarizes several large-scale studies that have measured formaldehyde concentrations in U.S. homes during the past two decades. Offerman (2009) is the most relevant study for assessing new, CA homes. In this research, indoor air quality was measured in 105 new Californian homes (1.7-5.5 years old) using a combination of air pollutant measurements, diagnostic tests and occupant surveys. 28% of homes exceeded the OEHHA acute Reference Exposure Level for irritant effects of 55 µg/m^3, and 59% of homes exceeded the CARB indoor guideline for irritant effects of 33 µg/m^3. 99% of kitchen and bathroom cabinetry were identified as being constructed from composite wood products, and plywood, oriented strand board (OSB) and medium density fiberboard (MDF) were also used throughout most homes (Offermann, 2009). The other studies summarized in Table 2—Avol et al. (1996), Weisel et al (2005) and Gilbert et al. (2006)—sampled homes of all ages, and consistently found lower average indoor formaldehyde concentrations. This was most likely the result of the ages and the air exchange rates of sampled homes. The average concentration across the three studies of non-new homes was 20 µg/m^3, nearly 45% lower than in new CA homes.

Summary of Large-Scale Measurements of Formaldehyde Concentrations in CA Homes							
Source	**House Ages**	**n**	**Minimum (µg/m^3)**	Median (µg/m^3)	Maximum (µg/m^3)	**Sample Duration (days)**	**AER**
Offermann, 2009	New	105	4.8	36	136	1	0.26
Avol et al., 1996	All	99	x	10.1	x	1	0.7
Weisel et al.,2005	All	234	11.1	20.1	53.8	2	Unknown
Gilbert et al., 2006	All	96	9.6	29.5	90	x	Unknown

Table 2 Summary of Large-Scale Formaldehyde Measurements in U.S. Homes

1.2.2 Acetaldehyde

Acetaldehyde is a colorless gas, which is volatile at room temperature. It is used as an intermediate in the production of a number of other chemicals, and its primary indoor sources are sheet vinyl flooring, carpeting, wood building products, such as fiberboard and particleboard, and consumer products, such as adhesives, glues, coatings, lubricants, ink, nail polish remover, detergents, cleansers, deodorant, fuels and mold inhibitors. Combustion processes, such as cigarette smoking, wood stoves and auto exhaust can also contribute to indoor levels, but non-combustion sources dominate indoor concentrations.

Acetaldehyde exposure has been linked in animal studies with respiratory illness, both from chronic and acute exposure. Major non-cancer effects of acute exposure include eye, skin and respiratory tract irritation. Low to moderate air concentrations of 25-200 ppb (45-360 $\mu g/m^3$) can cause eye and upper respiratory tract irritation. Moderate air concentrations of >300 ppb (540 $\mu g/m^3$) cause bronchoconstriction in asthmatics. Acute toxicity has also been demonstrated in animals. Chronic exposure to acetaldehyde can cause inflammation of, and injury to, the respiratory tract. Children, particularly those with asthma, are at an increased risk of impaired pulmonary function and symptoms of asthma after exposure. Acetaldehyde is also suspected of being a developmental and reproductive toxicant. The IARC has found sufficient evidence in animal studies of acetaldehyde's carcinogenicity.

Indoor mean acetaldehyde concentrations in U.S. homes range from 15 to 36 $\mu g/m^3$, with the mean in new manufactured homes reaching 103 $\mu g/m^3$ (OEHHA, 2007). The Offermann study mentioned above also measured acetaldehyde levels and found a median concentration of 20 $\mu g/m^3$, with a minimum to maximum range of 1.9 to 102 $\mu g/m^3$. None of the homes exceeded the OEHHA CREL of 140 $\mu g/m^3$, but 93% of homes exceeded the Proposition 65 no significant risk level for carcinogens of 4.5 $\mu g/m^3$ (Offermann, 2009). A similar result was found in RIOPA homes, with a median indoor concentration of 18.9 $\mu g/m^3$ (Weisel et al., 2005)

1.2.3 Nitrogen Dioxide

Nitric oxide (NO) and nitrogen oxide (NO_2) are the two primary oxides of nitrogen associated with combustion. NO_2 is a volatile, brownish-red gas, which is heavier than air, and it has a pungent odor, perceptible at 188 $\mu g/m^3$. Nitric oxide is quickly oxidized in ambient air to form NO_2, which is considered the primary pollutant. Ambient concentrations of outdoor NO and NO_2 vary widely, due to highly diverse sources and sinks. The most important outdoor source is road traffic, and indoor sources include tobacco smoke and combustion appliances, such as stove, heaters, fireplaces, ovens and water heaters. Indoor combustion appliances have been consistently linked with increased indoor NO_2 concentrations. NO_2 is a criteria pollutant and the U.S. EPA, under the Clean Air Act through the National Ambient Air Quality Standards, regulates outdoor levels.

Respiratory health has been shown to vary with NO_2 levels, independently of other co-exposures. An exhaustive review of epidemiological literature related to health and NO_2

exposure is provided in WHO (2010). Those health effects that have been consistently associated with NO_2 exposure in the built environment include respiratory symptoms, bronchoconstriction, increased bronchial reactivity, airway inflammation, and increased susceptibility to respiratory infection. Those who are sensitized or who are asthmatic are at a particular risk of health effects from exposure. A dose-response effect is found in controlled exposure studies as well as epidemiological studies, but the results of daily peak exposures that can occur from regular use of unvented cooking appliances are not well known. Additionally, these peak exposures from daily cooking are not well characterized, due to the predominance of time-integrated measurements used in health studies (WHO, 2010).

The California Air Resources Board's 2007 *Review of the California Ambient Air Quality Standard For Nitrogen Dioxide* provides an extensive review of NO_2 indoor exposure in California (Kado et al., 2006). Table 3 provides a summary of the findings of the three major assessments of NO_2 in CA homes since 1990. Lee et al. (2002) found that outdoor concentrations, the presence of a gas range and the presence of an air conditioner were positively correlated with NO_2 concentrations in Southern CA homes. Spengler et al. (1994) found a 4 ppb increase in indoor NO_2 was associated with an electronic ignition gas range, and a 15 ppb increase was associated with gas ranges with standing pilots, when compared with an electric range. Wilson, Colome, & Tian (1993) found similar average indoor NO_2 concentrations. These studies suggest that indoor NO_2 levels in CA homes have averaged between 25 and 28 ppb for several decades, with indoor levels exceeding outdoor levels, on average. The presence of a gas range has consistently led to increased levels, with pilot lights contributing substantially to this increase.

Summary of Large-Scale Measurements of NO_2 Concentrations in CA Homes				
Source	**n**	**Indoor Mean (ppb)**	**Outdoor Mean (ppb)**	**Sample Duration (days)**
Lee et al., 2002	119	28	20	6
Spengler et al., 1994	482	25	x	2
Wilson, Colome, & Tian, 1993	293	25	23	x

Table 3 Summary of Large-Scale Measurements of NO_2 Concentrations in CA Homes

1.2.4 Particulate Matter

The following two paragraphs are summarized from U.S. EPA (2009b). Particulate Matter 2.5 ($PM_{2.5}$) and 10 (PM_{10}) are criteria pollutants under the Clean Air Act and are regulated by the U.S. EPA by the National Ambient Air Quality Standard. PM is a broad classification for chemically and physically diverse substances that exist as discrete particles and liquid droplets over a wide range of sizes. Particle pollution is made of numerous components, including acids, organic chemicals, metals, and soil or dust particles. The U.S. EPA has ambient air quality standards for particles 10 microns in aerodynamic diameter and less, and 2.5 microns and less. Particle counts are dominated by smaller particles, whereas particle volume and mass are dominated by large particle fractions. The formation, composition, time suspended in air, deposition processes and rates, and travel distances of particles all vary with particle size. Particles originate from both natural and anthropogenic sources, with the majority of PM coming from outside. PM is generated indoors, from combustion, cooking and some consumer electronics.

The health effects of exposure to particulate matter are linked to the size of the particles. Particles less than 10 microns in diameter can easily pass through the nose and throat and enter the lungs, where they are inhaled deeply into the body; some may even enter the bloodstream. Once in the lungs, particles can affect the heart and lungs, and produce serious health problems. Exposure to particulate pollution has been linked to respiratory irritation, coughing, difficulty breathing, decreased lung function, aggravated asthma, chronic bronchitis, irregular heartbeat, non-fatal heart attacks, and premature death in those who already suffer from heart or lung disease. Health effects of PM are also related to the person's age, with young children and the elderly being most affected by PM-related health issues. Short-term and long-term exposures to $PM_{2.5}$ are consistently positively associated with cardiovascular and respiratory hospitalization rates, as well as mortality levels. Mortality related to cardiovascular issues is causally linked to $PM_{2.5}$ exposure, whereas mortality related to respiratory issues is classified as "likely to be causal". Evidence also exists that is suggestive of a causal relationship between $PM_{2.5}$ levels and low birth weight and infant mortality. There is also evidence suggestive of the carcinogenicity, mutagenicity and genotoxicity of long-term $PM_{2.5}$ exposure. Evidence is suggestive of a causal link between short-term exposures to PM_{10} and cardiovascular, respiratory and mortality effects.

Ultrafine particulate (UFP) are particles of 0.1 micron diameter or less, and while their health effects are potentially serious, they are not regulated as are $PM_{2.5}$ and PM_{10}. In addition, UFP levels are inefficiently controlled by the ambient mass-based PM standards, because UFP contributes little to and correlates poorly with $PM_{2.5}$ mass (Bhangar et al., 2011). Evidence is suggestive of causal relationships between short-term UFP exposure and cardiovascular and respiratory effects, but evidence is inadequate to link short-term exposure to central nervous system effects and mortality. Inadequate evidence exists to link long-term UFP exposure to health outcomes (U.S. EPA, 2009b).

Particle levels indoors are the result of a complex array of variables including outdoor levels, air exchange rates, penetration efficiencies, deposition rates, rates of internal mixing, indoor suspension and indoor particle generation (Nazaroff, 2004). Wallace (1996) summarizes and compares three major studies (>150 homes) of particle pollution in U.S. homes, and also provides analysis on a number of small studies. All studies indicated cigarette smoking as the primary contributor to indoor PM. Several studies identified cooking as an important source of indoor particles, with an increased indoor concentration of 10-20 $\mu g/m^3$ for homes reporting cooking during sampling. A substantial portion of indoor particles were from unexplained indoor sources. Air exchange rates were significant variables, either increasing or decreasing indoor particle concentrations, depending upon outdoor levels. Without indoor particle sources, an average AER from the literature (0.76) was used to estimate the proportion of outdoor particles found indoors, with 66% and 43% for fine and coarse particles, respectively. The review also highlights the effect of the "personal cloud", whereby personal exposures are consistently higher than indoor or outdoor measurements. Other studies have gone to great effort to characterize indoor sources of indoor particles using air sampling and detailed occupant activity logs, including cooking, cleaning, personal grooming and smoking activities (Abt et al., 2004).

Indoor particle levels can be controlled through air filtration, which can be achieved by furnace air filters, supply ventilation filters, the building envelope and stand-alone filters. PM levels in residences (Rodes et al., 2001) as well as health risks of ambient $PM_{2.5}$ (Janssen et al., 2002) have been shown to be lower in the presence of central air conditioning, presumably due to furnace filtration. Enhanced filtration has also been shown to reduce indoor particle levels (Burroughs & Kinzer, 1998). Macintosh et al. (2009) modeled indoor exposure to ambient $PM_{2.5}$ under three scenarios: (1) natural ventilation, (2) forced air with 1" media filter and (3) forced air with a high-efficiency electrostatic air cleaner with HEPA-like aerosol removal efficiency. Median 24-hour indoor-outdoor ratios were 0.57, 0.35 and 0.1 in these homes respectively, with indoor particle mass concentrations from outdoor sources in high-efficiency homes 82% less than in the natural ventilation baseline homes. The ventilation-air cleaning configuration was the most powerful determinant of indoor levels (Macintosh et al., 2009). Fugler (2000) found that PM_{10} concentrations were lower in residences with varying levels of filtration by 9-31% in active periods and 13-71% in non-active periods, as measured from a no-filter baseline. Personal exposure to indoor PM_{10} was dominated by occupant activity-related particle generation and suspension, and while filtration led to lower particle levels, it was not considered significant (Fugler, Bowser, & Kwan, 2000). In a modeling exercise, Fisk et al. (2002) reported that cat and dust mite allergens can be substantially reduced (50% or more) if filtration airflows are a few indoor volumes per hour. Fine-mode outdoor particles could be reduced by 80% using practical filtration technologies and airflows ($4\ hr^{-1}$) (Fisk et al., 2002). In addition to mechanical filtration, Fugler (2003) demonstrated the particle filtration effect of the building envelope while using an exhaust only ventilation fan. Particle removal efficiencies for PM_1 and PM_{10} were measured at 0.43 and 0.37, respectively. The envelope was a little less than half as effective as HEPA filtration for balanced and supply-only filtration scenarios (0.81 to 0.99) (Fugler, 2003).

Short-term measurements of UFP were carried out in seven Northern Californian residences, and the contribution to indoor UFP exposure from indoor episodic sources, such as cooking, was 150% that of outdoor contribution. Cooking on gas or electric stoves was the most notable indoor episodic source, with the highest peak concentrations of 200,000-600,000 particle count per cm^3 (pn/cm^3), and cooking activities drove most of the variation in the average levels in the seven homes. Ironing clothes and candle use also always results in UFP peaks. Indoor-outdoor ratios were reliably below 1 when the homes were vacant, but periods of high I/O ratios corresponded with occupants being at home and awake (Bhangar et al., 2011).

1.2.5 Carbon Monoxide

Carbon Monoxide is a colorless, odorless, tasteless, non-irritant, toxic gas, which is generated through the incomplete combustion of carbon-based fuels. Carbon monoxide exposure occurs through breathing. Outdoor CO exposure can occur near traffic, as CO is a constituent of car and diesel exhaust. Indoor sources of CO include unvented or poorly maintained gas appliances, infiltration of outdoor CO, car exhaust from attached garages, incense and candle burning, and cigarette smoke (WHO, 2010). CO exposure guidelines are set by the California EPA of 9 ppm at 8-hours and 20 ppm at 1-hour, and the U.S. EPA 8-hour guideline is 35 ppm (OEHHA, 2012; U.S. EPA, 2012).

While CO is fatal at high concentrations, chronic exposures to lower concentrations (between 0 and 9 ppm) can also cause headaches, dizziness, disorientation, nausea and fatigue. CO poisoning is the result of CO binding with blood hemoglobin, which blocks the body's ability to deliver oxygen. The most important variables are the concentration and duration of exposure. Acute CO exposure has also been linked to reduced exercise tolerance, as well as symptoms of ischemic heart disease. The severity of health effects from CO exposure varies with the health and age of the individual. WHO (2010) suggests that chronic CO exposure has far wider ranging health impacts than acute exposure. Chronic effects include sensory-motor changes, cognitive memory deficits, emotional-psychiatric alterations, cardiac events and low birth weight.

Carbon monoxide exposure from poorly tuned natural gas appliances has received serious attention by the home performance industry in the U.S. Standard energy audit protocols from the Building Performance Institute (BPI) require several CO-related measures: (1) auditor carries a CO sensor with him/her at all times, (2) combustion appliances are tested for CO production and (3) vented water heaters and furnaces undergo Combustion Appliance Zone (CAZ) testing (BPI, 2012). As CO in homes results from incomplete combustion and improper combustion appliance venting, levels measured in most homes are non-problematic. In a CEC study of 105 new Californian homes, CO was measured on a one-minute basis, with 8-hour indoor concentrations ranging from 0.4 to 3.7 ppm, and one-hour indoor concentrations ranging from 0.4 to 6.8 ppm. All homes were below the relevant indoor standards (Offermann, 2009).

1.3 Cooking and Indoor Air Quality

Cooking is a contributor to indoor concentrations of a variety of indoor pollutants of concern including formaldehyde, NO_x, particulate matter, UFP, carbon monoxide, Polycyclic Aromatic Hydrocarbons (PAH's) and others. I hypothesize that in high performance or green homes, cooking may represent the primary indoor contributor to pollutant levels inside the home. Other gas combustion appliances will tend to be either forced draft or sealed combustion, because of their increased levels of efficiency, and homes that use healthy and low-emitting materials can limit the amount of chemicals that would otherwise off gas from building products.

1.3.1 Gas vs. Electric Cooking Appliances

Cooking contributes substantially to indoor pollutant levels, and it is an area of concern with respect to human health worldwide (Kim et al., 2011). Pollutants and their indoor concentrations vary widely with fuel type, cooking methods and kitchen parameters. Early research into indoor NO_2 concentrations led to the conclusion that NO_2 levels were higher in kitchens with gas appliances as opposed to electric (72.3 ppb vs. 9.5 ppb) (Melia et al., 1978). Substantial epidemiological evidence suggests that respiratory health can be impacted by the presence of a natural gas cooking appliance (WHO, 2010). A detailed investigation into the generation of oxides of nitrogen and ultrafine particles by gas and electric cooking found that gas combustion, frying and cooking of fatty foods resulted in high levels of UFP. In addition these emissions, electric cooktops and grills may also generate particles from their surfaces. Substantial concentrations of NO_x were generated during gas burner operation; four burners operating for 15 minutes resulted in five-minute peaks of 1,000 ppb NO_2 and 2000 ppb NO (Dennekamp et al., 2001). Another study of indoor contributions to particle levels in homes found that frying, grilling, stove use, toasting, and cooking pizza led to indoor submicrometer particle number concentrations 5 times greater than background levels, and $PM_{2.5}$ levels could be 30 and 90 times above background for frying and grilling, respectively (He et al., 2004).

In a California Air Resources Board study of residential cooking pollutants, a test house was instrumented for continuous pollutant sampling and 32 cooking tests were performed on gas and electric appliances, as well as a microwave. Cooking on gas or electric appliances was shown to generate high concentrations of particles and gaseous toxic air contaminants. Routine cooking activities resulted in kitchen $PM_{2.5}$ concentrations greater than 1,000 $\mu g/m^3$, which were expected to result in exceedences of 24-hour outdoor standards. CO and NO_2 levels increased substantially during gas range usage. Formaldehyde exceeded the then-current acute REL during oven cleaning and fish broiling in both gas and electric ranges, and acetaldehyde was elevated during gas oven fish broiling. Variability was significant, making conclusions about specific cooking methods, foods and other kitchen parameters impossible. Nevertheless, cooking was shown to contribute substantially to exposures, irrespective of appliance fuel type (Fortmann, Kariher, & Clayton, 2001).

Both gas and electric cooking appliances contribute significant levels of pollutant to the indoor environment. Combustion pollutants, such as CO and NO_x, are most directly linked with gas cooking, but pollutants of all types can also be generated from cooking activities themselves, as well as electric burners. The method of food preparation can have a large impact on the pollutant emissions.

1.3.2 Kitchen Ventilation

Cooking, whether using a gas or an electric appliance, contributes harmful pollutants to indoor air, both from combustion and cooking processes. These pollutants must be removed from the home to ensure good IAQ. Kitchen ventilation by a range hood that exhausts to outside is the primary method of expelling cooking pollutants. Other methods include downdraft exhausts and wall/ceiling exhausts without capture hood. Nagda et al. (1989) demonstrated that kitchen exhaust fans can substantially reduce the peak combustion pollutant levels during cooking with a gas range by approximately 50%, but this effect was greatly reduced if the exhaust fan was not turned on upon commencement of cooking and used throughout. In addition, a kitchen range hood was shown to be more effective at reducing cooking pollutants than either window/door operation or a whole house ventilation system (Nagda et al., 1989). Dispersion of UFP into the home during cooking events has also been shown to be significantly reduced through operation of a kitchen exhaust fan, with higher airflow rates leading to greater removal rates (Rim et al., 2011). Unfortunately, a recent survey of cooking appliance usage in California homes suggests that kitchen range hoods are used an average of only 34.2% of the time (Klug, Lobscheid, & Singer, 2011). Nevertheless, kitchen range hoods exhausted to outside have been recognized for their essential role in mitigating cooking pollutants, and they are required by the ASHRAE residential ventilation standard 62.2, at a minimum airflow of 100 cfm (ANSI/ASHRAE, 2010a)[15]. This practice is now California law, as ASHRAE 62.2-2007 has been incorporated into the 2008 Title 24 building code.

Singer et al. (2011) measured the installed performance of 15 kitchen range hoods and found that at a given airflow, pollutant capture efficiency varied substantially. They suggest that meeting a minimum airflow requirement, such as the 62.2 level, is not adequate to ensure sufficient removal of cooking pollutants, but at least 200 cfm was required to achieve 75% capture efficiency. In addition, only 5 of 15 units delivered airflow at >70% of its rated value. Performance varied on type of exhaust fan, airflow, front vs. rear burner usage, presence and shape of capture hood and coverage of burners. The devices that performed the best removed 75% of cooking pollutants when operated on medium speed or higher, but microwave units, flat bottom units and those that did not cover the in-use cooking surface suffered, with capture efficiencies as low as 25% or less (Singer et al., 2011). Seven new residential range hoods were also tested in the laboratory, and capture efficiencies ranged from <15% to >98%. It is notable that all fans that met the Energy Star requirements for fan efficiency and noise level had capture efficiencies of <30% for front burners and oven operation. Airflow performance in a lab setting was better, with 6 of 7 hoods tested performing at 80% or above the manufacturer’s rated airflow (Delp & Singer, 2012). Clearly, performance issues with range hood fans can act as a significant barrier to pollutant removal, even when installed and used properly.

Kitchen range hoods exhausted to outside should be standard practice, particularly in high performance and green homes, which are typically required to comply with or exceed ASHRAE 62.2 requirements. Code-built homes in California are also required to comply. There are two notable contradictions to this trend.

First, deep energy retrofits are not required to comply with CA Title 24 ventilation requirements, unless 1,000 ft^2 or more are added during renovation. It is advisable to add a kitchen range hood during renovation; in particular, deep retrofits almost always include significant air tightness improvements, which could increase pollutant concentrations.

Second, the Passive House movement in the United States regularly employs a kitchen ventilation system that relies on either no range hood or a recirculating range hood with carbon filtration, and a 35 cfm continuous extraction from the kitchen zone using a central ventilation system, such as HRV or ERV. Significant discussion and debate can be found on this topic in on-line forums, such as Green Building Advisor, where building energy

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[15] An alternative compliance path exists for kitchens lacking a range hood. An exhaust fan elsewhere in the kitchen can comply with the standard if it provides 5 kitchen air changes per hour continuously.

professionals argue about the energy use, safety and code-compliance of these systems (GreenBuildingAdvisor.com, 2010a; GreenBuildingAdvisor.com, 2010b). A significant disconnect appears in such discussions between cooking pollutant and health issues presented in the research literature and practitioner understanding. Traditional kitchen ventilation is seen as incompatible with the extreme airtightness and envelope performance required of a Passive House. A recent interpretation request was submitted by the Passive House Institute U.S. to the ASHRAE 62.2 committee asking for interpretation of Passive House kitchen ventilation compliance with the standard. The committee responded that the 35 cfm continuous kitchen exhaust recommended by Passive House U.S. only complies with the standard if 35 cfm equal 5 kitchen air changes per hour (ANSI/ASHRAE, 2011). 5 kitchen air changes per hour is the 62.2 requirement for continual kitchen ventilation when lacking a range hood. With standard 8' ceilings, this would limit a Passive House kitchen to 52.5 ft^2. Needless to say, such systems installed in Passive Houses do not meet ASHRAE 62.2, nor are they aligned with the scientific research on the subject.

1.4 Statement of the Problem

Today's high performance green homes are using strategies, technologies and materials that have the potential to worsen IEQ and occupant health, and the past research summarized above has not assuaged these concerns. Past research efforts measured air pollutants and ventilation in homes that were considered "high performance" in comparison to standard practice at the time, which was approximately 20 years ago. The results varied from comparable levels of indoor pollutants to increased levels in the low energy homes. These studies measured selected pollutants—namely formaldehyde and radon—but not necessarily those most harmful to occupant health or most likely to be elevated in high performance green homes, such as PM. Today's most advanced homes are achieving previously unheard of levels of airtightness, energy use and purported sustainability, using new materials and methods. Yet, they have not been assessed for IAQ. The results of past research efforts have guided the development of today's exemplary programs, but the resulting buildings have not been tested and verified. Today's high performance homes may control some pollutants very well, such as formaldehyde in homes that have eliminated pressed wood products or selected low-emitting substitutes. While at the same time, energy reduction strategies may worsen other indoor exposures, such as NO_2 and PM emissions from unvented gas ranges in Passive Houses.

Have the lessons from the past been successfully transformed into practice? Do today's high performance homes, which look so good on paper, actually perform as intended—limiting pollutant sources, ventilating at appropriate levels, commissioning equipment, etc.? These high performing homes attempt to achieve maximum efficiency; are they performing as intended or have the problems of installation quality, system commissioning and occupant behavior caused other potential problems to arise? In the context of this specific research effort in high performance green existing and new CA homes, what design/construction strategies are used in today's homes, what equipment has been installed, how do occupants operate this equipment, and what are the indoor concentrations of select pollutants? Finally, what elements of the high performance green design, if any, are contributing to the pollutant levels observed? This research is a preliminary effort to answer these questions.

Approach/Methods

This investigation of IAQ in homes designed to be high performance green homes was carried out as part of a larger LBNL research study titled Healthy Homes. The broad goal of the Healthy Homes study was to investigate and quantify the relative influence of several factors on occupants' exposures of unvented combustion gases in homes in California, using both statistical and physical approaches. This was accomplished by measuring the concentrations of CO, NO_X, NO_2, formaldehyde and acetaldehyde over 6-day periods in 155 California homes, by either mailing air quality sampling materials to participants or having a researcher visit and deploy samplers. Information regarding physical characteristics of the home and household activities relevant to indoor air quality was collected via two participant surveys administered before and after the sampling period, and a home characterization protocol administered by researchers at homes that were visited. Homes with characteristics expected to result in elevated pollutant concentrations based on physical considerations were disproportionately selected for participation.

As part of the Healthy Homes study, the same basic measurements were made in high performance green and standard CA homes—formaldehyde, NO_x, CO, temperature, relative humidity and occupant surveys—but additional measures were performed in high performance green homes, including home inspection, air exchange rate, stove top testing, CO_2, and ventilation and airtightness diagnostics.

The overall strategy of this research was to recruit as participants some of the most advanced low energy homes in the state of California. Many of these homes also had features intended to improve IAQ, principally low-emitting materials or product use, and we therefore refer to them as high performance green homes. These homes used a variety of building systems, design strategies and materials. Homes in which occupants smoked cigarettes were screened and not included in the research. An assessment of indoor air quality was undertaken in the homes, which relied upon occupant survey responses, a home visit/inspection and measured pollutant concentrations.

The author of this work personally performed all high performance green home recruitment, survey administration, home visits, data analysis and reporting presented herein. The author contributed to the development of the sampling methodology in high performance green homes, namely VOC and tracer gas testing, with the assistance/guidance of LBNL staff, including Brett Singer, Marion Russel, David Faulkner, Erin Hult and Randy Mandalena. The following were performed by or developed by others at LBNL, namely Nasim Mullen and Brett Singer: Healthy Homes surveys, quality control/quality assurance (QA/QC) procedures, sensor calibration, chemical analysis (Marion Russel) and funding.

1.5 Recruitment

High performance green homes were recruited for this project using a variety of contact methods, including phone, email and list serve announcements. Targeted recruitment was essential for this research, due to the rarity of high performance green homes. Numerous individual homebuilders, building science consultants, homebuilding organizations and other personal contacts in the high performance housing industry were contacted as part of the project recruitment effort. Wherever practical, outreach was not directed to homeowners or occupants of potential projects, rather third party contacts were used to start the process. An email introducing the project and the types of homes being sought was sent to these third parties, and attached to this email were materials appropriate for forwarding directly to homeowners or occupants. Some examples of those contacted are provided in Table 4 below.

Contact	***Contact's Website***
The Splinter Group	http://www.splintergroup.info/
Passive House California	http://passivehousecal.org/
Bay Area Living Building Challenge Collaborative	https://sites.google.com/site/bayarealbccollaborative/home
Davis Energy Group	http://www.davisenergy.com/
Consol	http://www.consol.ws/
Net Zero Energy Certified	http://nzen.info/index.html
The Thousand Home Challenge	http://thousandhomechallenge.com/
PassivWorks	http://www.solar-knights.com/
Clarum Homes	http://www.clarum.com/
Arkin-Tilt Architects	http://www.arkintilt.com/index.html
Community Land Association of Marin	http://www.clam-ptreyes.org/
Solar Community Housing Association	http://schadavis.org/
Paul Welschmeyer Architects	http://www.pwarchitects.biz/
Bevilacqua-Knight, Inc.	http://www.bki.com/
Living Homes	http://www.livinghomes.net/primer.html

Table 4 Examples of Businesses and Organizations contacted as part of project recruitment.

1.6 Defining 'High Performance Green' Home

The term 'high performance green building' is formally defined by ASHRAE as part of its Standard 189.1-2009 as: "A building designed, constructed, and capable of being operated in a manner that increases environmental performance and economic value over time, seeks to establish an indoor environment that supports the health of occupants, and enhances satisfaction and productivity of occupants through integration of environmentally preferable building materials and water-efficient and energy-efficient systems".

Project homes were identified as high performance green homes using flexible criteria, so as to allow for inclusion of a variety of house types. There are many ways to design, construct and operate a high performance green home, and the following designations were recognized in this research as representing homes that would qualify under the definition above. Homes could be either officially certified or the occupants reported that these systems were used as formal tools in design and construction.

- LEED for Homes (USGBC, 2008)
- GreenPoint Rated new home (Build It Green, 2012)
- GreenPoint Rated existing home (Build It Green, 2012)
- National Green Building Standard (NAHB/ICC, 2009)
- Earth Advantage (Earth Advantage Institute, 2012)
- Living Building Challenge (International Living Future Institute, 2012)
- Passive House (Passive House Institute U.S., 2011)
- Earthcraft (Southface Energy Institute, 2012)
- Net-Zero Energy Certified (Zero Net Energy Network, 2012)
- CA Title 24 Tier II or greater (California Energy Commission, 2012)
- Energy Star for Homes (U.S. EPA, 2011a)
- ACI Thousand Home Challenge (Affordable Comfort, Inc., 2012)
- Deep Energy Retrofit (Fisher, Less, & Walker, 2012)
- U.S. DOE Building America (U.S. DOE, 2012)

Evaluating the actual energy performance of the project homes was not within the scope of this research. While it is recognized that building certification or the use of certain design methods does not automatically lead to low energy use or high performance, these designations are sufficient to qualify a home for this research. This is because each designation listed above suggests that a home's energy performance was intended to be superior to a standard, code-built home.

The classification of a home as high performance green was dependent upon the occupant's responses to survey questions. During the initial screening survey, the occupants are asked: "To your knowledge, was your home designed, constructed or remodeled to be any of the following (check all that apply)?" Possible response categories are:

- Passive House
- Net-zero energy home
- Green certified home
- Very high performance home
- Very low energy home
- None of these
- I don't know

These categories were intended to be both specific and flexible. As a screening survey question, it was essential that respondents did not feel overly constrained by the categories available. Initial versions of this question did not include the "Very high performance home" and "Very low energy home" designations, nor was remodeling mentioned in the question. It was initially felt that these designations were not specific enough and may simply cause confusion. Yet, some respondents to the screening survey who lived in homes appropriate for the study did not respond positively to this question, because they felt their home did not fit exactly into the categories provided. For example, a homeowner called the research team for further information, and they indicated during this conversation that their home had been remodeled to be net-zero energy. Yet, "net-zero energy" was not selected in the survey. The question was quickly adjusted to its present form to allow for more flexible interpretations. Further details about a project home's certifications, design methods or other achievements were ascertained during the more detailed initial survey questionnaire. It should be noted that these details were as reported by the occupants; no effort was made to verify certification, for example.

Given the variety of classifications and certifications listed above, four broad categories were developed to categorize homes for analysis: deep energy retrofit, net-zero energy, green certified and Passive House. A project home could fall into multiple categories, such as a net-zero energy and green home. Deep retrofits were a separate category, because the strategies used and results achieved may be different when working in existing homes, as opposed to new construction. Passive House was called out individually, because the standard stipulates very specific requirements for airtightness and ventilation, which could impact IAQ. Net-zero energy is the highest energy performance that a home can target, which sets these projects apart from green homes, which may have attained average levels of energy performance and garnered certification through other optional program credits for sustainable materials, urban infill, etc.

1.7 Occupant Participation Sequence

The following sequence was followed for each study home:

1. The home occupant filled out online screening survey at: http://healthyhomes.lbl.gov/
2. Respondents that indicated one of the categories noted above were contacted by the researcher in order to administer the oral consent statement and to answer any questions that arose about participation, study goals, methods, etc. A hard copy of the consent statement was mailed to occupants once oral consent was received.
3. An initial survey questionnaire was administered over the phone by the researcher, asking questions about home characteristics, equipment and occupant activities related to indoor air quality, such as cooking, window operation, occupancy, etc.
4. An initial site visit included inspection of home, stovetop testing and pollutant sampler installation. Samplers and equipment were deployed for six days by the researcher.
5. A final site visit included removal of pollutant samplers.
6. An exit interview survey was administered either in person, during sampler collection, or over the phone. Questions were designed to collect information about how the home was operated during the week of sampling.

1.8 Home Visit Protocol

The purpose of the home visit, in addition to deployment of the pollutant samplers, was to further characterize the project home, beyond what was possible through the initial survey questionnaire. The full home visit protocol is included in Appendix II of this document. The activities performed during the home visits included:

- Sketching of the home layout. This may have included measuring the home where necessary. Project drawings and plans were also used. Items to be indicated on the sketch include room locations, appliance locations, ventilation equipment locations and any other elements worth noting, such as signs of mold/mildew, excessive pet dander/hair, partly burnt candles, plug-in air fresheners, etc.
- All major appliance characteristics were noted, particularly nameplate information, condition and location of heating and cooling, ventilation, domestic hot water, cooking and laundry equipment. This was typically done by photograph.
- Gas combustion appliances were subjected to further assessments:
    - A cooking test was performed with temporary ultrafine particulate, CO, CO_2, temperature and relative humidity sensors in the kitchen. All gas burners were ignited and checked for flame consistency and color.
    - Appliance defects such as inappropriate combustion venting, cracked heat exchangers and flame rollout were also looked for during inspection.
- The airflow of accessible ventilation equipment was measured in all homes wherever it was feasible and time permitted using either an Energy Conservatory powered flow hood or non-powered flow hood. If measurement proved infeasible due to time or space constraints, manufacturer quoted airflow rates were looked up and recorded.
- House airtightness was measured using blower door depressurization in a manner similar[16] to ASTM E779-2010 Standard Test Method of Determining Air Leakage Rate by Fan Pressurization (ASTM International, 2010). Tests were not performed in some homes due to time constraints. Where possible, test results were retrieved from other sources, such as HERS raters, energy auditors and the like. Airtightness was ascertained in 19 of 24 homes.

1.9 Stovetop Testing Protocol

In each project home, a standard stovetop testing protocol was performed with coincident one-minute measurements of carbon monoxide, carbon dioxide and ultrafine particles

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[16] Blower door tests performed in this research did not comply with ASTM E779-2010. The test procedure was similar, in that a multipoint test was performed and ordinary least squares regression was used to generate a flow coefficient and exponent. Baseline pressure was measured and deducted from all pressure readings. Indoor/outdoor temperature corrections were not made, and homes were measured using only fan depressurization, not pressurization.

(UFP). Instruments used are indicated in Table 5 below. In addition, notes were taken on the functioning of the gas appliances, including flame assessment for noise, color and shape. These were intended to identify malfunctioning appliances with improper combustion, broken ignition, etc. Photos were taken of the cooking appliance, with burners ignited, off and during the test procedure. The purpose of the test was to put each cooking device—cooktop and oven—through similar steps, so that cooking emissions for the varying appliances can be compared.

The measurement equipment was placed approximately 0.91 m (36 in) to the side of the cooktop surface, preferably with some slight elevation above the countertop surface. A typical set-up is pictured in Figure 1 below (note the “1201” designation is the research project code), with the case for the UFP counter being used as a platform for all three instruments. Two pots from the occupant’s kitchen were filled with cold water and used for the testing protocol. There are four stages to the stovetop test. Times are noted at the start of each phase and photos are taken. The phases are as follows:

(1) Turn on all cooktop burners, photograph and inspect flames for noise, shape, and color. Turn off after 1-2 minutes.
(2) Place pots on front-right and rear-left burners, ignite and allow to heat. Turn off after 5 minutes.
(3) Move pots to the front left and rear right burners, ignite and allow to heat. Turn off after 5 minutes.
(4) Set oven to 177°C (350°F) and allow to heat up. Turn off after 5 minutes.

Figure 1 Example of Stove Top Test Set Up, Project 1201

A variety of cooking devices were tested using this protocol. Varieties included combined gas or electric range, separate gas cooktop with gas oven, separate gas cooktop with electric oven, or separate electric cooktop with electric oven. Within the electric designation exist two types of electric cooktop: electric resistance and electric induction. The induction type cooktop does not use a traditional electric resistance element (hot surface); rather it heats the pot directly using magnetic induction.

Test results were produced for UFP and CO. CO_2 logger timestamps were found to be incorrect after completion of fieldwork, and could not be adequately corrected[17]. . UFP log files contain time stamps and UFP counts per cubic centimeter. The minimum UFP level for the sampling period was taken as a background, non-cooking related value, and was deducted from each measurement. The maximum of this adjusted UFP count was then compared between cooktop types—natural gas, resistance and induction. Minimum and adjusted maximum UFP counts are reported in table format. A time series plot of each test was also created. The same calculations and reporting are done for CO measurements. Invalid UFP results occurred in one project home, due to battery failure of the logger, and CO data loss occurred in seven homes, due to battery failure issues. Any burner issues were noted and reported on a frequency basis.

1.10 Occupant Surveys

Occupants were surveyed three times, once online and twice by phone. Full texts of the three surveys are located in Appendix III. The online survey acted as a screening tool, and it was deployed through the project website (http://healthyhomes.lbl.gov/). The survey was designed to provide sufficient information to the research team to determine whether or not to include the home in the research. Those homes that indicated that their home was in one of the "high performance" categories were contacted for further details and recruitment. The two phone surveys were carried out, one prior to sampling and the other immediately after sampling. The forms tool embedded in Google Documents was used to create the surveys. Researchers filled in the online form while administering the phone survey. Responses were stored in a matrix, which was used for analysis purposes.

The first phone survey's purpose was to characterize the building, appliances, household demographics and some activities. Questions included variables such as housing type and characteristics (floor area, number of bedrooms, age, presence of moisture problems, etc.), presence of and detailed information about appliances (heating system type, operation, fuel, maintenance, age, location, etc.), occupant demographics (number of occupants, age, race, income), and household activities (amount of cooking, use of bath exhaust fans, actions taken to improve air quality, etc.). Survey questions were intentionally designed so as to not lead occupants to certain activities during sampling, such as increasing their usage of kitchen exhaust fans. Though an indoor air quality study in homes with natural gas appliances does imply some concern about indoor pollutants, so some occupant reaction and behavioral modification cannot be ruled out.

The second survey was completed after the sampling week was complete. The survey was either administered in person during sampler retrieval or over the phone within one week

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[17] The CO_2 data was rendered unusable, because data values could not be assigned to an event or timestamp. Loggers recorded data over long periods of time, including periods spent in the lab, in transit and during testing events. Data was not downloaded immediately after each event, rather the exact date/time of the testing was recorded, and it was assumed that the pertinent data could be extracted from the full time series at a later point. There was no means of determining where the logger was at any given data point. Rather than guessing, the data were discarded.

afterwards. Two homes did not complete the exit survey due to extenuating circumstances. The purpose of the exit survey was to ask questions about the sampling week, including occupancy, activity levels, appliance operation and questions about kitchen exhaust fan usage. This latter category was asked in the exit survey so as to not influence occupants to use their kitchen exhausts more than normal during sampling. Activity logs were considered as an option for tracking occupant behavior, but they were ultimately rejected, due to concerns over the demands being placed upon research subjects.

Three open-ended questions were asked during the survey, whose results had to be interpreted. Responses were categorized by topic—for example airtightness, ventilation, healthy products, etc.—and they were eventually filtered into summary statements that represented what the occupant said. This process led from specific reports from occupants, such as "Our cabinetry does not contain added formaldehyde" to general summary statements presented in the finding, such as "Use of low-emitting materials".

1.11 Pollutant Measurements

The Healthy Homes study began by targeting CO and NO_2, as the two pollutants most expected to be elevated when exhaust from natural gas appliances enters a home. Other pollutants that are indicative of natural gas combustion and are easy to measure were also included—formaldehyde and NO_x. CO_2 and UFP can also come from gas combustion, but could not be mailed to all participating homes, so they were selected for inclusion only in high performance green homes, which were visited by the research team. Finally, it was felt that air exchange rate and particle pollution measurements would add value to round out the IAQ assessment of high performance green homes. The methods for monitoring were selected because they were measurable using existing passive technologies that were affordable and would not cause major disruption to the home's occupants, and the technologies used could be transported by U.S. Postal Service or FedEx at minimal effort by the home occupants.

Home inspections and pollutant measurements were made in homes from January through April of 2012. Summarized in Table 5 below are the indoor air pollutants that were measured in each participating home. Whenever possible, completely silent and passive samplers were used, in order to avoid unnecessary annoyances to the occupants. The exception to this general rule was the Dylos DC1700 particle counter, which had to be plugged in and emits a very subtle, constant "white noise".

While the results are not reported in this thesis, a full-spectrum sampling of volatile organic compounds was also performed in each project home, as part of the air exchange rate measurement. Passive samplers were placed for six days—four indoor and one outdoor—at each project home. 45 individual VOCs were measured.

A detailed account of the sample handling and quality assurance/quality control procedures used in the Healthy Homes study is provided in Appendix IV. This description is copied in-full from a pre-publication version of the year-one summary of the Healthy

Homes study: *Impact of Unvented and Improperly Vented Combustion Appliances on Pollutant Levels in California Homes* (Mullen, Li, & Singer, *Pre-print*).

Measurement	***Method***	***Type***	***Location(s)***
Temperature (T)	HOBO T/RH Data Logger Indoor: U10-003 Outdoor: U23 Pro v.2	Time-resolved (min)	Kitchen and Bedroom, Outdoor
Relative Humidity (RH)	HOBO T/RH Data Logger Indoor: U10-003 Outdoor: U23 Pro v.2	Time-resolved (min)	Kitchen and Bedroom, Outdoor
Carbon Dioxide (CO_2)	Extech SD800 CO_2, Temperature and Relative Humidity data logger	Time-resolved (min)	Bedroom
Carbon Monoxide (CO)	Lascar CO Logger	Time-resolved (min)	Kitchen
Nitrogen Oxides (NO_x) and Nitrogen Dioxide (NO_2)	Ogawa Passive Sampler, Ion Chromatography analysis	Time-integrated average	Kitchen and Bedroom, Outdoor
Formaldehyde (HCHO) and Acetaldehyde (CH_3 CHO)	Passive Aldehyde (Waters, Sep-Pak XPoSure) Sampler with DNPH, HPLC analysis.	Time-integrated average	Kitchen and Bedroom, Outdoor
Number concentration of particles larger than 0.5 and 2.5 µm ($PN_{>0.5}$ and $PN_{>2.5}$)	Dylos DC1700 True Laser Particle Counter	Time-resolved (min)	Kitchen
Air Exchange Rate (AER) - Hexafluorobenzene (HB)	Passive Sorbent Tube with Tenax TA, analyzed on GC/MS	Time-integrated average	Four interior locations, including Kitchen and Bedroom, plus outdoor
Ultra Fine Particulate Count, $PM_{0.1}$ (stove top test during site visit)	TSI P-Track 8525 Ultrafine Particle Counter	Time-resolved (min)	Kitchen

Table 5 Indoor air quality parameters, measurement methods, type and location

Pollutant samplers were deployed in three main locations in each home—kitchen, bedroom and outdoors. Sampling tins (see Figure 2 below) were placed at each indoor location, and a sampling bell (see Figure 5 below) was placed in one outdoor location. Examples of kitchen, bedroom and outdoor sampling set-ups are pictured in Figure 3, Figure 4, and Figure 5 below. Kitchen tins were typically attached to the refrigerator by magnet, or were set-up on an available countertop space as in Figure 3 below. Bedroom tins were typically placed on either a bedside table or a dresser. Each location had a 2,4-dinitrophenylhydrazine (DNPH) aldehyde sampling cartridge, an Ogawa NO_x / NO_2 sampling cartridge, a temperature/relative humidity HOBO data logger, and a steel passive sorbent sampling tube with Tenax TA sorbent for VOCs (Figure 3, middle object). One bedroom in each project home also had an Extech CO_2/Temp/RH logger (Figure 4), and the kitchen in each home was outfitted with a Lascar CO data logger (Figure 2, far right) and a Dylos DC1700 Particle Count logger (Figure 3, far right). Two additional VOC sampling tubes were deployed elsewhere in the project home, and tracer gas emitters were evenly spaced throughout conditioned space. All sampler placements were documented through photographs.

The date and time of deployment and repackaging was recorded for each sampler type. These values were used to calculate total deployment time and for selection of time-series data.

Figure 2 Sampling Tins, Bedroom Location (Left) and Kitchen Location (Right)

The bedroom sampling tin contains (left Figure 2 above)—Aldehydes sampler (upper left), HOBO temperature and relative humidity logger (center, labeled "Bedroom") and two NO_x samplers (bottom). The kitchen sampling tin contains (right Figure 2 above)— NO_x sampler (top left), Aldehydes sampler (top middle), HOBO temperature and relative humidity logger (bottom left) and Lascar CO logger (right).

Figure 3 Example of Kitchen Sampler Set-Up, Project 0601

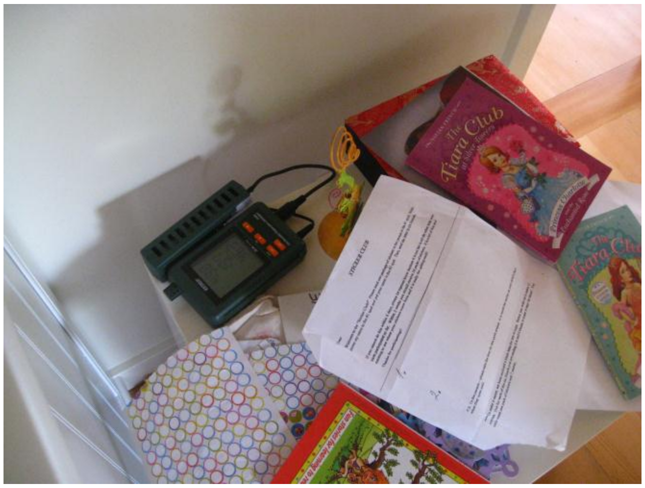

Figure 4 Example of Extech CO_2 Logger Set-Up in Bedroom, Project 1911

Figure 5 Sampling Bell Outdoor Location

1.11.1 Formaldehyde and Acetaldehyde

Formaldehyde and acetaldehyde were measured in each home using a commercially available DNPH sampling cartridge. These samplers were analyzed using high performance liquid chromatography (HPLC). Analytical blanks were used with each batch of cartridges analyzed, and the average blank value was deducted from the in-home sampling cartridge. The sampling duration and sampling rate were then used to calculate air concentrations (μg/m^3). Method Detection Limit (MDL) and Limit of Quantitation (LOQ) for the HPLC were calculated according to the U.S. EPA procedure found in Title 40 Code of Federal Regulations Part 136 (40 CFR 136, Appendix B, revision 1.11). Formaldehyde MDL was 1.741e-3 ng and LOQ was 5.539e-3 ng. Acetaldehyde MDL was 3.883e-3 ng and LOQ was 1.236e-2 ng. MDL and LOQ data and calculations can be found in Table 59.

The accuracy of formaldehyde and acetaldehyde concentrations was assessed using replicate samples in homes participating in the larger Healthy Homes study. These replicates consisted of two samplers being deployed in parallel in a single home. A total of

30 homes deployed paired replicate samples, and the Relative Average Deviation (RAD) was calculated for each co-located pair. The average RADs of formaldehyde and acetaldehyde samples were ±5.2% and ±5.5%, respectively.

As passive sampling was used in this research, the sampling rate of passive cartridges is of great importance in calculating concentrations. In order to determine this rate, passive cartridges are deployed in parallel with actively pumped samples, and the resulting concentrations are used to calculate the sampling rate of the passive cartridge that would lead to the same concentration. The samplers used in this research are intended by the manufacturer to be used actively, not passively. Shinohara et al. (2004) reported that they could be used passively and provided passive sampling rates of 1.48 mL/min for formaldehyde and 1.23 mL/min for acetaldehyde (Shinohara et al., 2004). In 2010, LBNL initially conducted an experiment to confirm this rate using a laboratory set-up with constant HCHO injection rate, measured by both active and passive means. This gave rates of 1.26 and 0.97 for formaldehyde and acetaldehyde, respectively. This was prior to start of field sampling. Subsequent to field sampling, we conducted a side-by-side (active and passive) assessment in an occupied home, which revealed significant inconsistencies. Four subsequent tests have been conducted, one in the lab and three in homes, and the results are reported in Table 6 below. Further validation is ongoing. For the purposes of the analyses presented in this thesis, revised sampling rates of 1.068 mL/min and 0.890 mL/min have been used to calculate formaldehyde and acetaldehyde concentrations, respectively. This may have introduced a positive bias in the reported concentrations relative to those that would have resulted from the published value from Shinohara et al. (2004). A more detailed description of the full validation procedure, which incorporated six experiments in total, is contained in Appendix IV.

Experimental Results for Determining the Passive Sampling Rate of the Waters DNPH Aldehyde Samplers			
Data Source	**Date**	**HCHO sampling rate (mL/min)**	**Acetaldehyde sampling rate (mL/min)**
Shinohara et al.	2004	1.48	1.23
LBNL lab study	Jun-10	1.26	0.97
ML house	Mar-12	1.03	0.77
MR house	May-12	0.86	0.71
JL house	Jun-12	1.03	1.04
MM house	Jun-12	1.16	0.96

Table 6 Passive Sampling Rates for Waters DNPH Aldehyde Samplers

1.11.2 Nitrogen Dioxide

Nitrogen dioxide was measured in each home using a commercially available Ogawa sampler cartridge, with a NO_2 and a NO_x pad. These samplers were analyzed using ion chromatography. NO_2 samples were corrected for temperature, relative humidity and atmospheric pressure, and analytical and travel blanks were analyzed with each batch of samplers. The blank values for each batch were averaged and deducted from the in-home sampler values. If the sampled value was less than the blank, "not detected" was reported, rather than a negative concentration. Air concentrations were then calculated in parts per billion (ppb). MDL and LOQ for the ion chromatograph were calculated according to the

U.S. EPA procedure referenced above. NO_2 and NO_x share the same values, with an MDL of 7.855e-3 ng and an LOQ of 2.499e-3 ng. MDL and LOQ data and calculations can be found in Table 58.

The accuracy of NO_2 and NO_x concentrations was assessed using replicate samples in homes participating in the larger Healthy Homes study. These replicates consisted of two samplers being deployed in parallel in a single home. A total of 30 homes deployed paired replicate samples, and the RAD was calculated for each co-located pair. The average RAD's of NO_x and NO_2 samples were ±4.1% and ±6.3%, respectively.

In addition to reporting the simple concentration of NO_2, the Indoor-Outdoor ratio (I/O ratio) was calculated, in order to aid in comparisons between groups of homes, such as those with gas cooking and those with electric cooking appliances. The indoor concentration is simply divided by the outdoor concentration to produce this value. Outdoor NO_2 concentrations vary significantly with location, which makes straightforward comparisons of indoor concentrations difficult. Some homes with no indoor NO_2 sources may have elevated levels, due to outdoor concentrations, and some homes with substantial indoor sources may have low levels, due to low outdoor concentrations. The I/O ratio in homes without indoor sources should be less than 1, as outdoor NO_2 is deposited/removed by indoor surface reactions. So, levels near and greater than 1 suggest significant indoor sources, such as a gas stove, vehicle exhaust from attached garage or candle/incense use. I/O ratio is used to compare gas and electric cooktop homes, as well as homes with mechanical ventilation.

1.11.3 Carbon Monoxide

Carbon monoxide was measured using a combined sensor and data logger from Lascar Electronics (EL-USB-CO) with one-minute time resolution in parts per million (ppm). The unit's measurement range is 0-1000 ppm, with an internal resolution of 0.5 ppm. Manufacturer's stated accuracy is ± 6% of the reading, and repeatability is ± 2% of the reading. Response time to reach 90% concentration is advertised as one-minute. CO was logged for six days in each project home's kitchen, and in addition, CO logging was employed during the stovetop testing procedure.

During the data collection phase, CO sensors were calibrated roughly every 2 weeks. The CO calibration involved exposing 6 to 10 sensors to concentrations of roughly 0, 25 and 50 ppm in a 3.8 L chamber. The calibration spans were achieved by titrating a CO concentration of 0.1%, with ultra zero air using a Dynacalibrator (Valco Instruments Co. Inc., Model 760). The precise span level was calculated by measuring the flow rate of each gas at the beginning and end of the exposure period. For the CO loggers, an intercept adjustment was calculated based on the loggers response at zero and a slope was calculated from a best-fit linear regression of the logger's response to the 3 tested spans. In November 2011, prior to the start of data collection, the CO data loggers exhibited a mean ア one standard deviation slope and intercept (calculated across loggers) of 1.09 / 0.02 and -0.02 / 0.05 ppm, respectively. In April 2012, at the completion of data collection, the CO data loggers exhibited a mean slope and intercept of 1.12 / 0.05 and -0.19 / 0.39 ppm, respectively. Data collected at each home were adjusted using an average of the slope and intercept calculated from the calibration experiment that took place immediately before and after the sampling period at that home. In some cases, only a pre- or post-measurement calibration was performed, and in those cases, the single set of calibration coefficients were used.

CO levels were assessed in the project homes using two variables—maximum one-hour concentration and maximum 8-hour concentration. These are calculated by averaging the data for one hour and eight hour time periods and then looking at the maximum values of those averages. The U.S. EPA and CalEPA have one-hour and eight-hour standards against which these values are compared (see Table 1 above). For stovetop testing, the one-minute maximum CO concentration, minus the minimum background level, was calculated and reported.

1.11.4 Particle Count

Time resolved, one-minute particle count concentrations were measured in the kitchen of 21 of the 24 homes using a Dylos DC1700 true laser particle counter, and in two of 24 homes using a Met One Instruments BT-637 Bench-Top Particle Counter. Met One instruments were used in the first week of sampling (week 5), because the Dylos units were not yet available. The Dylos logger counts particles in two size bins—>0.5 micron and >2.5 micron. The Met One counts in 6 size bins—>0.3, >0.5, >0.7, >1.0, >2.0 and >5.0 micron. Count values include all particles of the specified size and larger. Dylos data are multiplied by 100 to get the number of particles per cubic foot, per manufacturer's instructions. Only $PM_{>0.5}$ counts are reported from the Met One homes, as $PM_{>2.5}$ levels were not measured.

The manufacturer provides no estimate of the Dylos unit's accuracy. One report was found on an investigation of second hand smoke in an apartment building, and the Dylos DC1700 was operated alongside the particle mass monitor (TSI AM510 Sidepak, aerosol photometer). The two devices were reported to give "nearly identical results", which presumably referred to the time and magnitude of the particle peaks caused by second hand smoke events (Klepeis, 2010). A basic experiment was performed by LBNL to test how well Dylos particle counts tracked the results obtained using the Met-One instrument with manufacturer reported accuracy of ±10%. The two counters were operated in a home side-by-side for 400 minutes, and comparisons were made between the >2.5 micron Dylos output and the >2 micron output of the Met-One, as well as the >0.5 micron counts from both machines. Results are plotted in a time series in Figure 6 and Figure 7 below. General trends and peaks were in very good agreement. Correlation coefficients of 0.888 and 0.979 were calculated for the >2.5 & >2 micron data and the >0.5 micron data, respectively. The >0.5 micron size bin is the only one where both instruments are actually intended to measure the same thing, and a regression equation of the Met-One on the Dylos data was produced—$y = 0.975x - 99{,}542.146$. The slope was almost unity, with the Dylos consistently over-reading by approximately 100,000 particles per ft^3. These results suggest that the Dylos unit can provide an estimate of particle levels in a space consistent with that provided by the Met-One, with greatest accuracy in the >0.5 micron size bin.

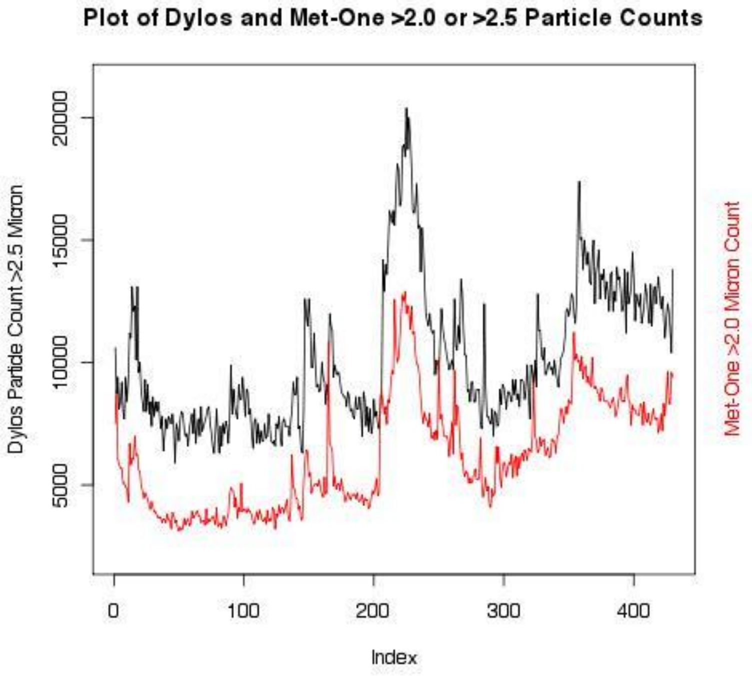

Figure 6 Plot of Dylos >2.5 micron and Met-One >2 micron particle counts

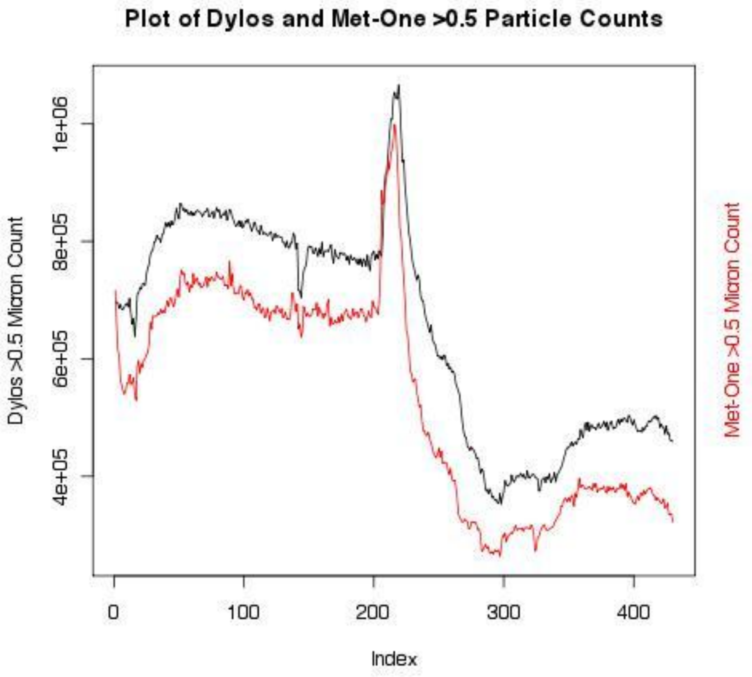

Figure 7 Plot of Dylos and Met-One >0.5 micron particle counts

It should be noted that the Dylos particle counters were used in an exploratory spirit, in an attempt to learn if there was value in measuring particle pollution in high performance homes. The results the Dylos devices report are imprecise, in that they have only two particle size bins, and they were not calibrated in chamber testing with known particle levels. The results of particle counts are not used to assess compliance with ambient air quality standards or guidelines. They provide no indication of the acceptability or health implications of particle levels reported in this research, rather they simply allow for coarse comparisons to be made between homes, and to point towards future research areas.

Three Dylos particle counters (named Dylos 1, Dylos 2 and Dylos 3) were used throughout the study, and all were purchased new for this research. At the end of sampling, all three Dylos units were operated in parallel for a period of 5 days in an LBNL office. Linear regressions were performed between all three loggers for the two particle size bins. The outputs of Dylos 1 and Dylos 2 were most accurately corrected to match those of Dylos 3 readings ($PM_{>0.5}$: Dylos2-to-Dylos3 R^2=0.9919 & Dylos1-to-Dylos3 R^2=0.9739; $PM_{>2.5}$: Dylos2-to-Dylos3 R^2=0.7974 & Dylos1-to-Dylos3 R^2=0.6342). Regression coefficients were applied to Dylos 1 and Dylos 2 prior to analysis. The Met One instruments were not available for this side-by-side calibration, so their values are unadjusted (homes 0501 and 0502).

The U.S. EPA standards for PM_{10} and $PM_{2.5}$ in Table 1 above are in μg/m^3. The count data collected in this research cannot be reliably transformed into mass concentrations[18]. Therefore, comparison to an objective standard was not possible to assess particle levels in project homes, but comparisons were nevertheless useful between groups, such as gas and electric cooking, mechanically ventilated homes and natural ventilation, forced air heating/cooling and radiant systems, etc. In order to enhance the validity of these comparisons, outdoor $PM_{2.5}$ mass concentrations were downloaded from the California Air Resources Board's Air Quality and Meteorological Information System (AQMIS). Representative AQMIS sites were found, which are most similarly situated to the project homes of this research (Table 7). Addresses provided in Table 7 are for the AQMIS stations, not participant addresses. Issues of geographic location, level of urban density and proximity to major roadways were balanced in determining these stations. Past research has shown that central ambient monitoring sites can adequately represent a town or small city, in terms of $PM_{2.5}$ and PM_{10} (Wallace, 1996). $PM_{2.5}$ mass concentrations were averaged during the sampling week for each project home. These values are used to verify if groups being compared by particle count had substantially different outdoor particle pollution levels.

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[18] The mass of particles contained in any size bin is far too variable depending upon the actual constituents of the aerosols that make up the particulate. Furthermore, the size bins measured by the Dylos logger are too large to allow a reasonable approximation. Tittarelli et al. (2008) reported good correlation between particle counts and particle mass measurements (R^2=0.734 and R^2=0.856) for PM_{10} and $PM_{2.5}$, but the particle counter used had much greater resolution, with six particle size bins. The two bins of the Dylos counter do not allow for such transformations.

Station Address	ARB Number	House ID's
50 Natoma St, Folsom CA 95630	34311	1301, 1802
9th and Princevalle, Gilroy CA 95020	43389	1501, 0802
837 5th St, Santa Rosa CA 95404	49893	0601, 0602, 1402
Campbell Rd, Davis CA 95616	57577	1302, 1303
9925 International Blvd., Oakland CA 94603	60347	1502, 1901
1100 21st Street, Oakland CA 94607	60349	0501, 1201, 1401
158 E Jackson St, San Jose CA 95112	43383	0801, 1601
534 4th St, San Rafael CA 94901	21451	0502
897 Barron Av, Redwood City CA 94063	41541	0902, 1202, 1801, 1911
170 Pierce Point Rd, Point Reyes CA	21453	1001, 1002
18330 Gault St, Reseda CA 91702	70074	1902

Table 7 CARB AQMIS Stations Used to Estimate Outdoor Particle Mass Concentrations

1.11.5 Carbon Dioxide

Carbon dioxide concentrations were measured in stovetop testing and in the bedroom of each project home using an Extech SD800 CO_2, Temperature and Relative Humidity data logger. Data was logged on a one-minute basis. Unfortunately, the internal time stamps of the Extech units were incorrect, which made assigning values to a project home difficult and to a stovetop testing event, impossible. As a result, the CO_2 data will not be presented here. CO_2 was not a key pollutant in this research and temperature and relative humidity data were logged with different sensors. The CO_2 data could have been useful in examining the effectiveness of different ventilation strategies, in terms of the effectiveness of distributed supply ventilation and air exchange rates. Some homes had ventilation systems that delivered fresh air to each bedroom, and presumably CO_2 levels in those bedrooms would have been better controlled during sleeping hours, particularly with doors and windows closed. CO_2 data would also have provided a means for calculating intermittent AER values using CO_2 decay. Overall, the loss of the CO_2 data does not limit the findings of this research.

1.11.6 Temperature and Relative Humidity

Temperature and relative humidity were measured using an Onset HOBO U10-003 data logger on a one-minute logging interval in the kitchen and bedroom, and an Onset HOBO U23-001 data logger outside of each home. Mean temperatures and relative humidities were calculated and reported for each location and project home. The reported accuracy of the indoor temperature sensors is ± 0.53°C from 0° to 50°C (± 0.95°F from 32° to 122°F), and relative humidity accuracy is ± 3.5% from 25% to 85% over the range of 15° to 45°C 59° to 113°F). The outdoor sensors have reported accuracy of ±0.21°C from 0° to 50°C (±0.38°F from 32° to 122°F) for temperature, and ±2.5% from 10% to 90% RH (typical), to a maximum of ±3.5% including hysteresis for relative humidity (Onset Computer Corporation, 2012).

1.11.7 Air Exchange Rate

The average air exchange rate was measured in test homes using a passive tracer gas technique similar to the Brookhaven National Laboratory BNL/AIMS method described in

Dietz et al. (1986), wherein passive samplers and emitters are used to measure time-integrated, whole house air flows. Dietz et al. (1986) reported that this method has been shown to give results comparable to SF_6 decay testing. The method calculates the infiltration rate of a building as the ratio of the tracer emission rate divided by the average tracer concentration (Dietz et al., 1986). The method used in this research did not assume a constant emission rate of the tracer, because the emission rates vary with temperature, which could not be controlled. Rather a time-averaged tracer emission rate was calculated from the total mass emitted and total duration of deployment.

Tracer gas emitters and samplers were deployed at the same time as home inspection and other IAQ sampling equipment, and they remained in place for approximately six days. This method was used to determine the average airflow rate of outside air during the monitoring period, and the building volume was used to generate an average AER. During data analysis, 8 homes were identified as corrupted, due to significant amounts of the chemical tracer being found on outside samples, which should have been free of tracer chemical. It is hypothesized that tracer chemical was deposited on lab gloves and transferred to the outside sampling tubes. AER data were eliminated from analysis if greater than one nanogram of tracer chemical was detected on the outdoor sample. While this does not guarantee that no corruption existed on the other samples, it has eliminated the obviously problematic homes.

As discussed in Section 1.16.2 of the Findings, substantial levels of inconsistency in tracer gas concentrations were found between the four indoor locations in nearly all homes. Average relative error between the minimums and means was 14.8% (range of 1.9% to 33.0%) and 21.5% between the maximums and means (range of 1.1% to 50.2%). Bedrooms were identified as measurement points that might skew the average, due to closed doors, which could cause an accumulation of tracer chemical. With bedroom samples removed from analysis, min-to-mean relative errors averaged 11.8% (0.4 to 34.3%) and mean-to-max relative errors averaged 9.6% (0.1 to 22.0%). This tighter distribution suggests an accuracy of ±10.7% for tracer gas air exchange rate measurements. This is consistent with accuracy estimates provided in the literature by Dietz et al. (1986) and Sherman (1988).

1.11.7.1 Description of Passive Emitters and Passive Samplers

Tracer gas emitters are 2 mL Agilent glass vials with a screw-cap lid with a diffusion septum. The liquid tracer chemical—Hexafluorobenzene—was placed inside the vials, and it diffused through the septum as a gas at a fairly consistent rate. 22 emitters were assembled for this research, and they were labeled HH1 through HH22. A line-up of emitters to be placed in home 0902 is pictured in Figure 8 below.

Figure 8 Eight Passive Emitter Tubes with Tracer Gas, Project 0902

The passive samplers are comprised of a steel Thermal Desorption Unit Tube, with a wire mesh diffusion cap placed on the sampling end and a stainless steel union and PTFE ferrule on the other end. A Tenax TA sorbent medium is packed into the tube, onto which gaseous compounds are adsorbed and absorbed. These samplers were used to sample a full-range of VOCs in addition to the tracer chemical. An image of the passive sampling tube is included in Figure 9 below, installed on a steel stair railing using a wire mesh basket. The effective sampling rate of these samplers was determined by laboratory staff at LBNL in controlled chamber tests (Parra, 2010).

Figure 9 Example of Passive Sampling Tube Installed on Stair Rail with Wire Mesh Basket, Project 0902

1.11.7.2 Weighing of the Passive Emitters To Determine Tracer Gas Emission

The mass of the tracer that was emitted over any given time period was determined by weighing the vial at the beginning and end of that time period. A Metler-Toledo digital scale, accurate to 1/10,000th of a gram was used to weigh each tracer vial. The scale was auto-calibrated prior to each use, and the scale was allowed to zero prior to each weighing. The exact time of the weighing was recorded, so that changes in mass could be combined with the time interval in order to calculate the average mass emission rate in grams per hour. When vials were not deployed in test homes, they were placed in a ventilated fume hood at LBNL, inverted with the septum cap facing downwards, so that all samples were treated the same when not in use.

The vials were weighed prior to being deployed in a test home, and they were then reweighed as soon as possible after being retrieved from a test home. The time that the tracer vials entered and exited the home was recorded. The mass of tracer that was emitted during transport was determined using each vial's average mass emission rate, along with the number of hours between the last weighing and entry into the test home. A similar correction was made for the time period between when the vials left the home and when they were reweighed at the laboratory. The mass of tracer emitted into the home during the test period was determined using the following equation.

$$m_{\mathrm{inhom}e} = m_{before} - m_{after} - (\dot{m}_{tracer} * T_{transit})$$

Equation 1

$m_{\text{in home}}$ = Mass of tracer chemical emitted in the test home (g)
m_{before} = Total mass of tracer vial prior to deployment (g)
m_{after} = Total mass of tracer vial upon return (g)
m_{tracer} = Mass emission rate of the tracer vial (g/hr)
T_{transit} = Number of hours between weighings when vial was not in test home (hr)

1.11.7.3 Determining the appropriate number of passive emitters

Prior to testing in a home, the appropriate number of emitters was determined for each home. Loading either too much or too little tracer gas mass onto the sampling medium must be avoided. Unfortunately, the primary parameter that determines how much tracer is loaded onto the sampling medium—air exchange rate—is exactly that which we seek to measure. Other important parameters were known imprecisely, such as the building volume, which was not ascertained prior to the first site visit, and the tracer gas emission rate. As a result, the mass of tracer was calculated using a variety of reasonable inputs for these unknown parameters, and the number of emitters used is based on the average result. It was assumed that the concentration of the tracer gas was equal throughout the home.

The mass of tracer loaded on the sampling medium is calculated using the following equation.

$$\frac{n_{emitters} * \dot{m}_{emitters}}{Q_{ventilation}} * Q_{sampler} * T = m_{tracer}$$

Equation 2

$n_{emitters}$ = Number of passive emitters
$m_{emitter}$ = Emission rate of a single emitter [μg/hr]
$Q_{ventilation}$ = House total ventilation rate [L/hr]
$Q_{sampler}$ = Sampling rate [L/hr]
T = Total deployment time [hours]
m_{tracer} = Total mass of tracer gas on sampling medium [μg], not to exceed 0.2 μg

$Q_{sampler}$ varies with the amount of time that the sampler is deployed by the following relationship (Parra, 2010).

$$V_{sampled} = 0.0572 * T^{0.6416}$$

Equation 3

$V_{sampled}$ = Apparent sample volume [L]
T = Total deployment time [hours]

Rearranging this equation and dividing by the total deployment time gives the average sampling rate.

$$Q_{sampler} = \frac{V_{sampled}}{T}$$

Equation 4

$m_{emittters}$ varies with indoor temperature, but indoor temperature cannot be predicted ahead of time, so two values of $m_{emitters}$ are tested for temperatures typical in indoor environments: 15 and 25°C (59 to 77°F). Emission rates vary between 450 and 550 μg/hr at these temperatures.

$Q_{ventilation}$ could not be accurately determined ahead of time, so some assumptions were made for the purposes of predicting the total tracer mass load on the sampler. An AER of 0.2 was assumed in all homes as a base case, but values of 0.35, 0.5, 0.7 and 1.0 were also evaluated. The volume of the home was estimated from the floor area value provided by the homeowner during the initial survey, using average ceiling heights of 2.44 m (8 ft), 2.74 m (9 ft) and 3.05 m (10 ft). $Q_{ventilation}$ was determined as follows.

$$Q_{ventilation} = V_{home} * AER_{home}$$

Equation 5

$Q_{ventilation}$ = House total ventilation rate [L/hr]
V_{home} = Total volume of the home [L]
AER_{home} = Air exchange rate of the home [hr^{-1}]

The parameters identified above—AER, ceiling height and emission rate—were varied in order to determine the mass of tracer on the sampler at various conditions that might be encountered in the field. The maximum mass was not to exceed 200 ng and could not be less than 0.02 ng. The target level was an average for all combinations of parameters between 20 to 30 ng. A minimum of 5 emitters was used in each home.

1.11.7.4 Placement of the Tracer Gas Emitters in the Home

Tracer gas emitters were placed to whatever extent possible to achieve the well-mixed zone assumption of ASTM Standard E741-11 Standard Test Method for Determining Air Change in a Single Zone By Means of a Tracer Gas Dilution Standard test method for determining air change in a single zone by means of a tracer gas dilution (E741-11). The passive tracer gas method makes the assumption that the home is a well-mixed zone, where concentrations of the tracer are equal throughout. In reality, this idealization is never fully achieved—different rooms and zones always experience different ventilation rates and internal mixing and therefore tracer gas concentrations vary. This is true unless the rate of internal mixing is substantially greater than the rate of air exchange. The placement of the passive samplers further complicates this issue, as tracer gas concentrations have been shown to vary substantially within a room, depending on the sampler's distance from a point-source emitter—1.5 to 2 times the concentration predicted by a well-mixed zone assumption (Furtaw et al., 1996). With these issues in mind, the goal of emitter placement was to most closely approximate this well-mixed zone assumption. Tracer gas concentration in the home will vary with mixing of the air from zone to zone, location of fresh air supply, location of stale air exhaust, interior door positions, operation of local exhaust equipment, microclimate temperature of the passive emitter, etc. The passive emitters should be brought into the test home and distributed prior to deployment of the sampling tubes, so as to minimize the period during which the tracer gas concentration is out of equilibrium. It is also very important to avoid cross-contamination between emitters and samplers.

Emitters are evenly distributed throughout the test home. Emitters are placed in each major zone of the home, with distribution that is approximately proportional to the floor area of the zone. For example, a two-story home of 1800 square feet, with 1200 square feet on the ground floor and 600 hundred on the second level, would have 67% of the emitters placed on the ground level. Consistent with this, effort was made to place a single emitter in each interconnected room with a door or zone of interconnected rooms, and to place multiple emitters in each large, undifferentiated space, again proportional to floor area.

Foreseeable obstructions to even mixing were accounted for to whatever extent possible in emitter placement. Closed doors limit even mixing, so all doors should be left open in the home whenever feasible; it was requested of the occupants that interior doors remain open in the home whenever possible, though lifestyle preferences were always respected. Operation of the central forced air system, if it existed, also facilitates even mixing, as does use of oscillating fans. These were similarly encouraged.

Emitters are either strapped to a wire mesh basket and placed on furniture, or they are strapped directly to the vertical furniture or other household items. Examples include, cable wires, table legs, candle sticks, etc. An example is included in Figure 10 below.

Figure 10 Passive Emitter Vial Attached to Table Leg, 0902

1.11.7.5 Placement of the Tracer Gas Samplers in the Home

The tracer gas samplers serve two purposes in this research: (1) to measure the tracer gas concentration and (2) to measure the concentration of other volatile organic compounds in the air. Five passive samplers were used at each test home, with four placed inside the home and one outside. Two of the interior samplers were located along with the aldehyde and NO_x samplers in the kitchen and bedroom (see Figure 2). In the context of where the kitchen and bedroom samplers were located, the two other interior samplers were placed in locations that were most representative of the well-mixed home. At least one sampler was placed in each main building zone, and in multi-story homes, a minimum of one passive sampler was placed on each floor. Samplers were preferentially located in large, interconnected family rooms, kitchen areas, etc. In accordance with ASTM Standard E741-11, samplers were located at approximately mid-zone height (approximately 4’-5’ from floor height). The sampling tubes were placed in a vertical position, with the diffusion cap towards the sky. They were either strapped to a wire mesh basket or to furniture, such as a table leg.

1.11.7.6 Chemical Analysis

After in-home sampling was completed, sampling tubes were stored in a freezer at LBNL until chemical analysis was performed. Tubes were analyzed by LBNL staff using a gas chromatograph mass spectrometer. Full VOC analysis was performed on five tubes per home. Analysis results included the mass of tracer gas on the tenax medium. The lab “blank” value was deducted from the mass on the sample tube, and this value is reported as the mass sampled ($m_{tracer,sampled}$).

1.11.7.7 Calculating the Average Air Exchange Rate Over the Sampling Period

Once the passive sampling tubes were analyzed, the mass of tracer chemical sampled, $m_{tracer,sampled}$ was used to determine the average air exchange rate during the sampling period. Four sampling tubes were used in each home, and the $m_{tracer,sampled}$ varied with tube placement due to imperfect mixing conditions. The average ventilation rate, $Q_{ventilation}$ was calculated using the following formula for each of four $m_{tracer,sampled}$ values.

$$Q_{ventilation} = \frac{Q_{sampler} * m_{tracer,emitted}}{m_{tracer,sampled}}$$

Equation 6

$Q_{ventilation}$ = House total ventilation rate [L/hr]
$Q_{sampler}$ = Sampling rate [L/hr]
$m_{tracer, emitted}$ = Total mass of tracer emitted in test home [ng]
$m_{tracer, sampled}$ = Total mass of tracer collected on sample tube [ng]

As described above, $Q_{sampler}$ varies with the amount of time that the sampler is deployed according to Equation 3. The average sampling rate was determined using Equation 4 above.

The $m_{tracer, emitted}$ was calculated using the measured weights of the tracer vials before and after the deployment. They were corrected for the amount of time spent in transit using each vial's average emission rate for that measurement period. The following equation was used.

$$m_{tracer,emited} = \sum_{i=1}^{n} m_{tracer,emitted,i} = \sum_{i=1}^{n} m_{before,i} - m_{after,i} - (\dot{m}_{tracer,i} * T_{transit})$$

Equation 7

i = Tracer gas emitter
n = Total number of emitters in test home
$m_{tracer,emitted}$ = Total mass of tracer chemical emitted in the test home [ng]
m_{before} = Total mass of tracer vial prior to deployment [ng]
m_{after} = Total mass of tracer vial upon return [ng]
m_{tracer} = Average mass emission rate of the tracer vial [ng/hr]
$T_{transit}$ = Number of hours between weighings when vial was not in test home [hr]

Once the four $Q_{ventilation}$ values were calculated, they were averaged. This average ventilation rate was combined with the building volume to calculate the average air exchange rate AER_{home} using Equation 5. The minimum and maximum ventilation values in each home were used to calculate an AER range.

1.12 Data Analysis

All data analysis was carried out in the R statistical package version 2.12.1 (2010-12-16). Summary statistics were calculated for all pollutants, including minimum, 1st quartile, median, mean, 3rd quartile and maximum. Also reported is the number of samples (n). Summaries were disaggregated by location (Kitchen, Bedroom and Outdoor), by cooktop fuel type (Gas and Electric), and by a combination of the two. Summaries are reported in table format and sometimes visually using boxplots. In cases where in-home concentrations were below the minimum detection limit (MDL), a 0 was substituted for this value, for the purposes of summary statistic calculation and generation of boxplots. This avoids the undesirable positive skewing of the data, if very low values are removed from analysis. In table summaries, the 0 is not reported as a minimum value, because 0 was not measured. Rather "bd" is used to represent "below detection". As nearly all data distributions were non-normal according to the Shapiro-Wilk Normality Test (p-value > 0.05), medians are reported and are used for comparing distributions between groups. Statistical significance between groups of homes was tested using the non-parametric Wilcoxon Ranked Sums test, and results were considered significant with P-values less than 0.05. W and P-values are reported for individual tests highlighted in this report. Single and multivariate regression analyses were also performed on some pollutants, which were tested for assumptions of normality using the Shapiro-Wilk Normality Test. Data are considered normally distributed if the p-value is greater than 0.05. If data were not normal, then they were log-transformed and retested, if necessary, prior to modeling. Model P-value, F-statistic and adjusted R^2 were used to assess models, and P-value of each parameter was used to determine its significance.

1.13 Grouping and Analysis of Project Homes

A number of indoor air quality comparisons are made between groups in this research. Statistically significant differences between pollutant levels in these two groups were sought as evidence of degraded or improved air quality in high performance green homes with different characteristics. The homes were grouped based upon fuel usage and upon the strategies and ventilation equipment employed. The groups considered included but were not limited to subsets based on cooktop fuel type, presence of mechanical ventilation, presence of air filtration, presence of kitchen exhaust fan, energy/sustainability classification, heating system type, etc.

Further multivariate modeling and significance testing was out, in order to identify important variables from field measurements and survey responses that explained some of the variance in the high performance green home pollutant measurements. Examples of variables included the amount of cooking reported during the week, the use of the range hood (when present) during the test week, and the type of ventilation system.

Findings

1.14 Summary Characteristics of Project Homes

1.14.1 Housing Characteristics and Energy/Sustainability Classification

24 homes were recruited and measured as described in the Methods section above. Each project was identified by a four-digit number. The first two digits represent their week of measurement, and the latter two digits represent their order in the week. For example, 0501 was week five, house number one.

All of the project homes were located within a 161 km (100 mile) radius of Berkeley, CA, with the exception of a single home in Southern California, which could not be visited and was measured under a reduced protocol. General housing characteristics for the 24 homes are summarized in Table 8 (House-by-house data are in Table 40 in Appendix). Housing age was determined using either the year that home construction was completed or the Deep Energy Retrofit (DER) completion year. Changes in the DER homes were substantial, including almost all new interior finishes, insulation, appliances, etc., making them equivalent to a new home for the purposes of this research. The average age of the homes was 4.3 years from the date of measurement. 23 of the homes were less than eight years old, and 18 homes were five years old or less, making the sample mostly representative of new homes. A single outlier was a DER completed 28 years ago. The average home size in the sample was 198±79.5 m^2 (2,128±856 ft^2) and the average number of occupants per house was 2.8±1.2. These values compare to California statewide averages for single-family homes of 175 m^2 (1,882 ft^2) and 3.2 persons per household (KEMA, 2010). Sample homes are slightly larger and less populated than the California average.

The demographic characteristics of project home occupants are summarized in Table 9 below. Occupants were well educated, with a minimum education level in each home of a college degree, with 14 homes having a graduate degree. Occupants predominately identified themselves as “White, Caucasian” with 21 of 25 responses in this category. Very small populations of “Black, African American”, “Asian or Pacific Islander, East Asian”, and “American Indian, Alaskan Native” were also reported. Only one project home did not answer this question. It should be noted that multiple race/ethnicity classifications could be indicated for each home, so values reported in Table 9 do not sum to 24. Project homes also tended to be fairly wealthy, with 12 homes reporting greater than $100,000 in combined annual income, and only three homes at less than $50,000. Six homes did not report a combined annual income.

The energy and sustainability classifications of the project homes are summarized in Table 10 (House-by-house data are in Table 41 in Appendix). These classifications are the result of survey responses by the occupants, and minimal effort was made to further confirm actual energy performance or formal certification. Multiple designations were sometimes applied to a single home, where applicable. For example, home 0502 was both a Deep

Energy Retrofit and a Passive House, and 1601 was both a Net-Zero Energy home and a Passive House. The primary energy and sustainability classifications used for project comparisons were Deep Energy Retrofit, Net-Zero Energy, Green Certified and Passive House.

The sample is exactly one half Deep Energy Retrofits and one half newly constructed homes. 11 of the homes reported being certified or were undergoing certification in a green building rating system, while another two homes reported using green building systems in design and construction, but not pursuing certification. Four homes achieved the highest levels of sustainability certification, with three homes achieving Platinum certifications by the U.S. Green Building Council's LEED for Homes rating system, and another home pursuing the Living Building Challenge, arguably the most demanding sustainable building certification in existence. Seven Passive Houses were included, which included both certified projects and those projects that were substantially modeled after the standard and that marketed or declared themselves to be "Passive Houses". These homes are characterized by extreme airtightness and balanced ventilation systems with heat recovery. Six homes claimed to be net-zero energy, either in design or operation. This included some overlap with the other main categories—Deep Energy Retrofit, Net-Zero Energy and Passive House. One of these projects will be the first home in California to be certified by CalCERTS[19] with a HERS index of 0. A number of the project homes have participated in building energy research projects, and have been monitored or commissioned by Building America or DOE National Laboratories teams.

Airtightness as measured with a blower door varied substantially across the 19 homes with values reported, from a minimum value of 0.4 air changes per hour at -50pa (ACH_{50}) to 10.3 ACH_{50} (House-by-house data are in Table 42 in Appendix). The median airtightness in homes was 2.8 ACH_{50}[20], which is well below the median value for new California homes built between 2001 and 2011 of 3.95 ACH_{50} (Wanyu Chan, personal communication, 5/24/2012). Homes pursuing the Passive House standard were reliably the tightest homes, with ACH_{50} values ranging from 0.4 to approximately 2 (homeowner recollection from contractor testing). Other homes had substantially higher values, reflecting the reduced emphasis placed on airtightness of those outside the Passive House circles. Deep retrofits were assessed separately, due to the relatively increased difficulty of achieving airtightness in existing versus new homes. Average airtightness in Deep Retrofits versus other homes was 4.7 versus 3.3 ACH_{50}. Nine homes were leakier than the median new California home, as noted above.

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[19] CalCERTS is the largest Home Energy Rating System (HERS) provider in the state of CA. They certify homes using the RESNET HERS score, which is a national standard for energy efficient home construction certification. A score of 0 indicates a net-zero energy home, according to the rating method.

[20] This median includes two Passive House style homes that were not directly measured. Instead, estimates were used for these two homes (one based upon Passive House certification requirement of 0.6 ACH_{50} and the other from homeowner recollection of 2 ACH_{50}). If these two data points are eliminated, then the median increases to 4.7 ACH_{50}.

Housing Statistic	Average Value
Age (years)	4.3
Floor Area (m^2)	198
Conditioned Volume (m^3)	569.1
# of Stories	1.8
# of Bedrooms	3.4
# of Bathrooms	2.3
# of Occupants	2.8

Table 8 Project Home Characteristics Summary

Highest Education Level of Anyone in Household	# of Homes
Graduate Degree	14
College Degree	10
Race/Ethnicity of Anyone in the Household	**# of Homes**
White, Caucasian	21
Black, African American	2
American Indian, Alaskan Native	1
Asian or Pacific Islander, East Asian	1
Prefer not to answer	1
Combined Annual Income of Household Residents	**# of Homes**
>$150,000	7
$100,000 - $150,000	5
$75,000 - $99,999	2
$50,000 - $74,999	1
$25,000 - $49,999	3
Prefer not to answer	6

Table 9 Project Home Demographics Summary

Energy and Sustainability Classification	# of Homes
Deep Energy Retrofit	12
Green Certified	10
Passive House	7
Net-Zero Energy	6
“Very High Performance”	3
Green (not certified, but used rating system)	2
Living Building Challenge	1
EPA Indoor Air Plus	1
Building America	1

Table 10 Energy and Sustainability Classifications Summary

1.14.2 Heating, Cooling and Domestic Hot Water Characteristics

The heating, cooling and domestic hot water system characteristics of the project homes are summarized in Table 11, Table 12, Table 13 and Table 14, respectively (Project by project summaries can be found in
Table 43, Table 44, Table 45, Table 46 in appendix). As with Table 10 above, some projects fall under multiple designations. For example, project 0501 uses natural gas and solar for heat, and this is a combination or “combi” system, serving both space heating and domestic hot water.

Primary heating systems are summarized in Table 11 below. Nearly two-thirds of the homes were primarily heated by natural gas, with nearly another one-third using electricity; one off-grid home used exclusively solar energy for space heating. Very few homes had traditional heating equipment; in fact, there were only four traditional forced air natural gas furnaces. Most projects had complex systems incorporating multiple sources of energy and means of distribution. Solar energy was incorporated into nine of the home heating systems, being paired with tankless water heaters, gas boilers, and heat pumps in single and multiple storage tank configurations. In fact, exactly one half of the projects used combi systems. This combination seems to be a trend in high performance green Californian homes. One half of the projects used hydronic distribution for heat, using wall, floor and in-room radiators. Another three homes used point-source heating, relying solely on centrally located natural gas fireplaces. Two projects used a system pioneered in Passive Houses where heat is distributed using the ventilation air from an ERV or HRV, using a heat exchange coil in the supply air stream.

Supplementary heating systems were used in 15 project homes and are summarized in Table 12 below. System types included a mix of portable and fixed electric space heaters, natural gas and wood burning fireplaces, and denatured alcohol heaters.

All natural gas primary heating systems used either power vented or direct vented appliances, limiting any potential leakage of combustion pollutants into the homes. These were mostly high efficiency, condensing gas appliances with dedicated outdoor combustion air ducting, connected to a combustion chamber that is sealed from the indoor space. Three homes used natural gas fireplaces for primary space heating, with direct venting technology. The combustion safety features of the primary heating equipment should contribute to enhanced occupant safety in these homes. We were not able to verify the sources of combustion air for all supplementary gas fireplaces, so these remain a potential liability, if they are atmospherically drafted.

Heading Fuel / System Type	# of Homes
Natural Gas	16
Electric	7
Solar	9
Combisystem	12
Heating Equipment Type	**# of Homes**
Gas boiler	9
Gas furnace	4
Air-to-air heat pump	3
Gas fireplace (primary system)	3
Air-to-water heat pump	1
Geothermal heat pump	1
Heating Distribution Type	**# of Homes**
Hydronic-radiant, in-floor	7
Hydronic-radiant, in-wall	1
Hydronic-radiant, wall radiators	1
Forced air	10
Point-source	3
Baseboard heaters	1
Portable space heater	1
HRV supply duct	2

Table 11 Primary Heating System Types Summary

Supplementary Heater Type	# of Homes
None	9
Electric Space Heater	7
Woodstove	3
Gas Fireplace	3
Denatured Alcohol Heater	2

Table 12 Supplementary Heating System Types Summary

Cooling systems were installed in seven homes (see Table 13). Only those homes that used forced air distribution provided mechanical cooling. Notably, five of seven homes employed advanced technologies in conjunction with their air-to-air heat pumps, such as nighttime ventilation cooling and evaporatively cooled outdoor condensers.

Cooling System Type	# of Homes
None	17
Air-to-air heat pump	7
Night ventilative cooling	3
Evaporatively cooled condenser	2

Table 13 Cooling Types Summary

Domestic hot water systems were varied similarly to the space heating systems and are summarized in Table 14 below. 19 of the projects used natural gas as a primary water heating fuel and five used electricity. 14 homes used solar energy to assist in water heating, and as mentioned previously, half of homes used combined space heating and hot water systems. The majority of homes used some configuration of single or multiple hot water tanks, though six homes used tankless systems. The predominance of tank-based systems is likely due to two things, first the incorporation of solar energy demands storage capacity, and second the output of heat pump water heaters cannot service tankless applications. The vast majority of water heating systems were located outside of the conditioned, living space. Only four homes used interior closets or conditioned attics for water heating equipment. 14 of the gas hot water homes used either direct vent or power vent appliances. Three water heaters were atmospherically drafted, two of which were in attached garages and one of which was in a conditioned basement closet with a make-up air duct to outside. In general, the combustion safety of water heating systems in the project homes was high, due to advanced combustion technologies and the location of heaters outside the living space.

Two homes were notable for their hot water systems. 0802 uses a 3,785 L (1,000 gal) solar storage tank to supply space heating, and it acts as a domestic hot water preheat for a direct-vent 151 L (40 gal) natural gas tank heater. Heat is delivered using hydronic tubing in the above grade walls, and water delivery is entirely buoyancy driven, with not a single pump in the distribution system. 1801 uses solar to heat water and a geothermal heat pump as a back-up heat source; rainwater is stored and treated in two 3,785 L (1,000 gal) storage tanks, and an additional four smaller storage tanks serve as solar storage, pre-heat, buffer and chilled water tanks. Heated water is distributed to in-floor radiant tubing and to domestic hot water fixtures.

DHW Location	**# of Homes**
Basement	7
Garage	4
Unconditioned attic	3
Interior closet	2
Conditioned attic	2
Garage closet	2
Outside closet	2
Outside	1
DHW Fuel Type	**# of Homes**
Natural Gas	19
Electric	5
Solar	14
Combisystem	12
DHW Equipment Type	**# of Homes**
Air-to-water heat pump	4
Geothermal heat pump	1
Tank	18
Tankless	6
Boiler	1
DHW Combustion Type	**# of Homes**
Direct Vent (Sealed Combustion)	11
Power Vent	3
Atmospheric Draft	3

Table 14 Domestic Hot Water Types Summary

1.14.3 Ventilation—Continuous, Bathroom and Windows

1.14.3.1 Continuous Ventilation System Characteristics

Continuously operated ventilation systems are summarized in Table 15 (Project by project summary in Table 47 in appendix). Continuously operated ventilation systems were installed in 13 of the project homes, and 11 homes were naturally ventilated. The average airtightness as measured by a blower door of mechanically and naturally vented homes was 2.3 and 6.7 ACH_{50}, respectively[21]. This suggests that designers generally understood that mechanical ventilation becomes more important with increased airtightness.

Of homes with mechanical ventilation systems, Heat (HRV) and Energy Recovery Ventilators (ERV) were by far the most popular, with six and three systems, respectively. Most of these systems were installed in the Passive Houses, where heat recovery ventilation is considered a key aspect of performance (Schnieders, 2003). The majority of these systems were stand-alone, with ductwork independent from any larger forced air heating and cooling system. Exceptions included, 0502 and 0902. All HRV and ERV systems were fully ducted, with multiple supplies and returns distributed throughout the home. A pattern emerged, consistent with manufacturer recommendations, to supply air to bedrooms and living areas, and to exhaust air from bathrooms, laundry and kitchens. This remained true with the units integrated with other forced air systems. Some variety emerged with specific systems. 1601, for example, did not use an HRV return duct in the kitchen, because the builder felt that a range hood was absolutely essential to remove cooking pollutants. 1801 was not built to the Passive House standard, but used a series of ERVs to provide ventilation; this system operated 25% of the time, rather than continuously.

Other ventilation systems included CFIS and one home used a simple exhaust fan in the laundry room. The CFIS systems were operated on a runtime schedule ranging from 17% to 25% operation per hour. The reliability of some CFIS systems installed in California has been seriously questioned due to controls, sizing and balancing issues (Offermann, 2009). The runtime schedules are as reported by the occupants and were not measured. Although operation was not verified as part of the research, all CFIS homes ostensibly were set-up to operate regularly throughout the day, which would avoid the problem of non-operation observed by Offermann (2009).

CFIS, HRV and ERV systems all have the added benefit of filtration and fresh air distribution, which cannot be achieved with simple exhaust systems.

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[21] The difference in airtightness between mechanically and naturally vented homes was much greater than the difference between house types, Deep Retrofits and other homes, for example.

Continuous Ventilation System Type	# of Homes
None	11
Heat Recovery Ventilator	6
Energy Recovery Ventilator	3
Central Fan Integrated Supply	3
Exhaust Fan	1

Table 15 Continuous Ventilation Systems Summary

1.14.3.1.1 Observed Performance and Installation Problems in Mechanical Ventilation Systems

Of the 13 mechanically ventilated homes in this research, 12 of them had what could be characterized as “complex” systems. Project 0601 was an exception, which operated a continuous exhaust fan in the laundry room. Other systems were either fully-ducted HRV/ERV or CFIS systems. These system types were prone to installation and performance issues, due to their increased complexity[22], and they require careful measurement, verification and commissioning in order to function properly. Their proper performance is all the more essential in an airtight home, where the vast majority of air exchange can be mechanical.

A number of alarming performance issues were noted in project home ventilation systems, which are summarized in Table 16. All faults identified were in ERV/HRV systems. CFIS systems may have suffered from similar problems, but their airflows were not measured due to access limitations to the fresh air intakes. Past research in California homes suggests that these systems may be extremely unreliable in delivering proper airflows (Offermann, 2009). The prevalence of ventilation system faults was disconcerting given the “high-end” nature of these homes, both in terms of cost and performance. These systems represent the quality of work being employed in those projects most dedicated to “doing it right”.

Project 0501 used an ERV with supply air fully ducted to all living spaces and exhausted from bathrooms and the kitchen. During the home inspection, measured airflows in the bathrooms were significantly less [23]than expected. The unit was inspected, and it was discovered that three of four duct connections to the unit itself had come loose and were only partially attached to the appliance. The plastic duct collars came from the manufacturer with a double-sided adhesive foam gasket, which is normally supplemented with sheet metal screws. No screws were installed in this system. This fault is pictured

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[22] In this case, “complexity” means that systems have multiple fans and controllers, and they are connected to fully distributed duct systems, with multiple supply and exhaust duct runs. This contrasts with a single fan, with one controller and a single duct going to outside. Complex systems are prone to similar errors that are experienced in forced air heating and cooling systems—leaks, improper design, hardware failure, control issues, etc.—but faults are not immediately obvious to occupants, and they can have detrimental effects on IEQ and health when they go unnoticed.

[23] A total of three return ducts were provided in project 0501, and two of these were measured with the system on High. Airflows were 23 and 14 cfm in the half bathroom and full bathroom, respectively. Total system airflow on high is reported by the manufacturer as 201 cfm. The kitchen return duct was the same size and presumably provided similar airflow to the bathroom ducts, for an approximate total of 56 cfm.

below in Figure 11. This fault was repaired by the installer during the sampling week. Needless to say, such poor workmanship does not inspire confidence in the integrity of the rest of the forced air system hidden within floors and walls. Project 0501 was a Passive House, whose airtightness was 0.6 air changes per hour at -50 Pa or better, and the ERV was its only ventilation source.

During inspection of project 0902, the HRV airflows were measured and were much lower than expected. This HRV was connected to a central air handling system using a shared duct system, but the central air handler and conditioning system was not being operated in parallel with the HRV. Rather the occupant used portable electric space heaters to provide heat. When set to high, the summed exhaust airflows totaled 98 cfm, which compares poorly with the manufacturer's rated airflow of 191 cfm. When set to low, the total exhaust airflow was only 34 cfm. While the exact problem was not identified in this home, it is suspected that without air handler operation, a significant portion of the HRV airflow was short-circuiting between the supply and exhaust connections to the duct system. Rudd (2009) identifies this common performance issue as one of the ten most common issues with residential ventilation designs (Rudd, 2009).

Project 1201 was inspected during sampler deployment by the research team, and it had also undergone major commissioning and diagnostic testing by the Building Science Corporation. Issues that emerged with the HRV installed in this home were so severe that the whole unit was eventually abandoned as a continuous ventilation system and now only operates as a very expensive bathroom exhaust fan. When initially installed, Building Science Corporation (BSC) measurements revealed that the unit was extremely unbalanced, with total supply flow on low being 84 cfm and total exhaust flow being 48 cfm. Commissioning revealed that the ductwork was installed backwards, requiring that the entire unit be torn out and rotated to properly align exhaust and supply inlets and outlets. The HRV did not provide sufficient bathroom exhaust airflow to meet ASHRAE 62.2 requirements, so an additional in-line exhaust fan was installed on the roof at the exhaust outlet. Controls, relays and additional fans were combined on-site in order to control this system and have proven unreliable (Ueno, 2012). During our own diagnostic testing the unit was so unreliable as to be untestable, with airflow exhausting and supplying from the same bathroom register on different days. Ignoring all of these performance issues, Figure 12 below shows the closet where the HRV was rendered inaccessible for maintenance. Ventilation was provided in the home using a CFIS system, in which BSC programmed and verified airflow.

Project 1901 used a fully ducted ERV (Figure 13), which functioned properly during measurement. The occupant noted during the initial survey that for the ERV's first year of installation, the ducting had been attached incorrectly. The unit acted as a recirculating system that just reintroduced house air back into the home, rather than exhausting it. Eventually the problem was identified and fixed, and clear labels had to be applied to the unit, as in the photo below, in order to avoid future errors and confusion.

Project 1911 used a fully ducted HRV to provide 24/7 mechanical ventilation in an extremely airtight Passive House. Performance issues with the duct system have lingered for more than a year. Problems reported on this system by a performance contractor hired by the owner included large air leaks near HRV connection, unsealed duct connections, improperly drained condensate pipes, broken balancing dampers, ruined filters and incomplete duct connections resulting in air dumping into wall and floor partitions rather than into the home (Wahl, 2011).

In all cases except project 0902, it appeared that installation and operation errors were responsible for these faults, rather than the piece of equipment itself. The complex interactions of installers, users and technology have been noted in the literature for problems with ventilation systems, with particular focus on HRV (Hasselaar, 2008).

One specific brand of HRV encountered in several project homes was notably free of detected faults. A manufacturer's representative commissioned each of these systems after installation, and occupants were able to provide a written record of the measurement and verification process. Commissioning consisted of measuring every supply and exhaust inlet and outlet in the home; supplies and exhausts were summed to compare system balance and total airflow. This knowledgeable professional remedied any problems with distribution or controls. This is the level of commissioning required to verify the performance of complex ventilation systems.

Unfortunately, such efforts are expensive, time-consuming, and potentially inaccurate and impossible/implausible. In my experience measuring these systems, inlets and outlets are often placed in such a way as to make them impossible to measure with a flow hood, or nearly so. Furthermore, multiple flow hoods of differing shapes are often required, unless provision for measurement was made in design, which is uncommon. This makes determination of total system airflow impossible. In addition, summing measurements of individual registers can be inaccurate, due to changes in the duct system pressures as a result of added flow resistance of the flow hood itself (Walker & Wray, 2003)[24]. Total airflow measurements should be made at the outside inlets and outlets, which are not always accessible (e.g., on the roof). Finally, flow hood measurement devices are not currently rated for accuracy in a consistent way, and the results they produce are not always reliable, particularly in the field where flow asymmetry, flow angle and flow direction can have significant impacts (Stratton, 2012). In combination, these issues make the measurement and verification of ventilation system performance in airtight homes difficult and unlikely to be done correctly, which creates liabilities in these homes.

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[24] Use of a powered flow hood eliminates this issue, as duct system pressures and airflows through other registers are unchanged.

Project ID	System Type	Problem Identified	Reason or Cause
0501	ERV	Airflows measured at bathroom inlets were significantly less than expected.	Installation errors. Three of four duct connections to the ERV unit had failed, due to reliance on double-sided gasketing without sheet metal screws.
0902	HRV+CFIS	Airflows measured throughout the home were less than expected.	Central fan on duct system was not operated during HRV operation, leading to recirculation within duct system.
1201	HRV	Ductwork was connected to the unit backwards. Supply/exhaust airflows were extremely imbalanced (84/48 cfm). Fan could not provide sufficient bathroom exhaust airflow, requiring booster fan added to the roof.	Installation errors. Unreliable, custom controls, relays and additional fans. Low quality hardware.
1901	ERV	Ductwork was connected to the unit backwards (1st year only), resulting in a unit that only recirculated outside and indoor air.	Installation errors. Was not obvious which airstreams connected to which inlets/outlet on the unit.
1911	HRV	Imbalanced airflows. Air leakage in ventilation duct system.	Installation errors.

Table 16 Summary of Observed Mechanical Ventilation System Faults

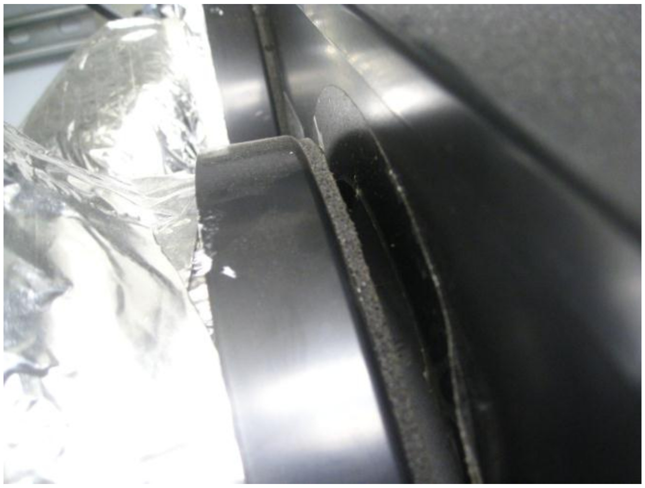

Figure 11 Failed ERV Duct Connection, Project 0501

Figure 12 Failed HRV in Closet, Project 1201

Figure 13 Airflow Labels on ERV, Project 1901

1.14.3.2 Bathroom Exhaust Fans

In addition to continuous ventilation systems, nearly all homes provided kitchen and bathroom exhaust fans. Kitchen fans are discussed in section 1.14.5 below. 23 of 24 project homes had at least one bathroom exhaust fan, with an average of 1.9 bathroom fans in each home. One home had no bathroom exhaust fans, and four homes had more than three. The number of bathroom fans usually corresponded perfectly with the number of bathrooms, though five homes did not provide exhausts in half-bathrooms and two homes did. All bathroom exhaust fans were reported to work well. Several of the homes with fully ducted ERV or HRV used those central systems to provide bathroom exhaust. In those cases, an ERV/HRV return grill was considered a bathroom exhaust. These exhausts operated continuously and most were automatically controlled to ramp temporarily to high speed using humidistat controllers. The reported usage of the exhaust fan in the most used full bathroom is summarized in Table 17 below. Some homes provided multiple responses, such as "always when showering or bathing" and "as needed to remove odors". In general, occupants reported high levels of bathroom exhaust fan usage. Only four occupants reported that bathroom exhaust fans were used "not very often or never".

In the Most Used Full Bathroom, How is the Exhaust Fan Used?	# of Homes
Always when showering or bathing	11
Fan operates continuously	7
As needed to remove odors	5
Not very often or never	4
As needed to remove steam when showering or bathing	3
Used by some but not everyone when showering or bathing	1
No fan in bathroom	1

Table 17 Occupant Reported Usage of Exhaust Fan in Most Used Full Bathroom

1.14.3.3 Window Usage

Window usage was also assessed in project homes through survey questions, during the initial and exit surveys. Initial survey question asked about average window operation during "this time of year", and the exit survey asked about actual window operation during sampling. Initial survey responses are summarized in Table 18 below. Just more than half of project homes reported that windows were usually closed all day, with another three reporting window operation less than one hour per day. The remaining eight homes reported substantial window usage.

Average Window Operation During This Time of Year	# of Homes
Usually closed all day	13
Less than an hour each day	3
Several hours per day	6
More than half the time	2

Table 18 Average Window Operation During This Time of Year

Window usage during the sampling week is reported in Table 19 below. The most window usage was reported during the daytime, with only six homes reporting no daytime window usage during the sampling week. Overnight, morning and evening time periods had more than half of project homes reporting no window usage. Only four homes reported no window operation at any time period during the entire week; all four of these homes did provide continuous mechanical ventilation. Seven homes had at least one window open on at least one day during every time period.

Number of Days During Sampling Week That At Least One Window Was Open During Time Period	**# of Homes**
Overnight	
None	15
Some	1
Most	1
All	5
Morning	
None	13
Some	4
Most	1
All	4
Daytime	
None	6
Some	9
Most	1
All	6
Evening	
None	13
Some	4
Most	3
All	2

Table 19 Occupant Reported Window Usage During Sampling Week, by Frequency and Time of Day

1.14.4 Filtration

A variety of air filtration methods were employed in these project homes: (1) no filtration, (2) central forced air system filtration, (3) supply air ventilation filtration, (4) stand-alone in-room filtration, and (5) kitchen range hood carbon filtration. Some projects used a combination of these filtration methods. For example, project 1801 used a HEPA filter on the ventilation supply air and two stand-alone room air filters. The filtration types are summarized in Table 20 below (Project by project summaries in Table 48 in appendix). One-third of homes provided no mechanical filtration whatsoever, with the remainder being split nearly evenly between central forced air systems and ventilation supply systems.

Filtration details for each home were ascertained from a mix of on-site visual inspection and manufacturer specifications. These details are summarized in Table 48 in the appendixes. Filter varieties used in full forced air systems included electrostatic precipitators, 4" and 2" pleated filters, with MERV ratings from 8 to 14. Some systems were recirculation-only and others included intentional outside air ducts, through either CFIS or night ventilation systems. CFIS systems were operated on fixed schedules providing regular periodic filtration, whereas the recirculating systems only filtered during a heating/cooling call from the thermostat. A notable exception was home 0601, where the central air handler was operated 24/7 beginning on the 3rd day of monitoring. Filters in supply air ventilation systems were typically part of the ERV or HRV unit itself, with MERV ratings of either 7 or 12. For example, the same ERV unit was used in homes 0501 and 1901, and this unit type uses an enthalpy exchange material that acts as a MERV 12 air filter. A notable exception was home 1801, which used a HEPA filter in the supply airstream, independent of its three individual ERV units. Ventilation filtration systems operated either continuously or on a regularly schedule.

Occupants were questioned about maintenance they performed on their home's ventilation systems. 12 occupants reported either replacement or cleaning of air filters as maintenance they or someone else performed. This provides encouragement that the benefits of air filtration will not be outweighed by the liabilities of sensory irritant emissions from soiled filters observed in commercial buildings (Clausen, 2004).

Filtration Type	Total Count
Full forced air filtration	9
Supply ventilation filtration	8
Stand-alone filtration (in-room)	1
Kitchen range hood carbon filtration	4
No mechanical filtration	8

Table 20 Summary of Filtration Techniques

1.14.5 Cooking Equipment and Kitchen Ventilation Characteristics

The cooking equipment and kitchen ventilation characteristics are summarized in Table 21 and Table 22 (Project by project summaries are in Table 51 and Table 49 in appendix). Cooking appliances are summarized below in Table 21. 15 of the homes used either natural gas or propane for cooktop fuel. Of the remaining electric cooktops, four were traditional resistance heating elements and five homes used induction heating elements. Gas usage was more prevalent for cooktops than for ovens, with six of the gas cooktop homes switching to electricity for the oven. Two-thirds of homes had combined appliances and the other third had cooktop and oven as separate appliances. Three homes had appliances that used pilot lights for burner ignition, but two of these home disabled the pilots and instead used matches to light burners on demand. The remaining 12 homes used modern electronic ignition for burners. Cooktop burners varied from four to six. The vast majority of cooking appliances were less than ten years old, but a few exceptions were observed. Gas ranges in 0801, 0802 and 1302 were notable for their age. All three were "historic" ranges, which the author estimates to be at least 50 years old. These unique appliances are pictured below in Figure 14, Figure 15 and Figure 16.

Figure 14 Historic Gas Range in Project 0801

Figure 15 Historic Gas Range in Project 0802

Figure 16 Historic Gas Range in Project 1302

Cooktop Fuel Type	**# of Homes**
Gas	14
Propane	1
Electric - Resistance	4
Electric - Induction	5
Oven Fuel Type	**# of Homes**
Gas	8
Electric	15
Propane	1
Cooktop and Oven Together	**# of Homes**
Together	16
Separate	8
Burner Ignition Type	**# of Homes**
Electronic	12
Match light	2
Pilot	1
# of Cooktop Burners	**# of Homes**
4	13
5	8
6	3
Age of Cooking Appliance (years)	**# of Homes**
0-5	16
6-10	4
16+	4

Table 21 Cooking Equipment Summary

Kitchen ventilation systems of some sort were installed in every one of the project homes, and they are summarized below in Table 22. 18 of the homes had a range hood installed, though a number of these units installed in Passive Houses were recirculating and did not exhaust to outside.

In the homes with recirculating hoods, either an HRV or ERV return duct or multiple ducts were located in the kitchen ceiling. These systems provided continuous ventilation, but at relatively low airflow (35 cfm per Passive House requirements); less than the minimum airflow of 100 cfm required of a intermittent operation range hood ducted to outside in ASHRAE Standard 62.2. 62.2 also provides guidance on the required level of continuous kitchen ventilation, if a range hood exhaust to outside is not installed. The number specified in the standard is 5 kitchen air changes per hour. Kitchen exhausts of this sort were performing dramatically below this requirement when measured. For example, project 1901 uses this system type, and based upon kitchen size (using only the outline of the cabinets to calculate the minimum possible size; kitchen is actually entirely open to a large volume of the home), would require 241 cfm of continuous kitchen exhaust. Measurement of exhaust airflow from the kitchen was performed with the ERV turned to high, and the total airflow from the kitchen was 48.1 cfm. The system operates continuously on low with estimated kitchen exhaust airflow of 28 cfm, nearly a factor of 10 less than required by the standard. Home 1202 used a similar system and according to kitchen volume, 62.2 would require 103 cfm of continuous airflow. On setting 3, the total exhaust airflow from the kitchen was 67 cfm, but the system operates on setting 2 continuously, with an estimated airflow of 35 cfm—a factor of three less than required by the standard. These examples are typical of the installed systems in Passive Houses.

The connection between kitchen and the rest of the home, with one exception, was characterized in all project homes as either “Kitchen is very open” or “Kitchen is mostly open”. In such kitchens, pollutants can easily disperse, potentially making continuous kitchen ventilation even less effective at removing cooking pollutants. In addition to low-flow continuous HRV and ERV exhausts from the kitchen, most Passive Houses provided a recirculating range hood, with some sort of carbon filtration. Filter types varied from granular carbon to carbon-impregnated media filters. Such gas phase air cleaning is not likely to be effective or reliable in residential applications. Most occupants were not clear about whether or not they had this technology or how to access it if they did, and they did not understand its operation. Carbon filters must be replaced or recharged periodically; otherwise, they cease to remove pollutants. One homeowner who was eager to do the right thing actually reported regularly rinsing his range hood carbon filter in the sink and then reinstalling it. This is illustrative of how such technology is not reliable in a residential context where maintenance is unreliable at best.

Five of the 18 range hoods installed were of the recirculating type described above. The other 13 range hoods were all exhausted to outside. Five additional homes used either an exhaust fan in the ceiling or wall above the cooktop, or a microwave exhaust. In one case, within the limits of this study, it was not possible to determine if the microwave system exhausted to outdoors.

Occupants were asked to assess the noise level of their kitchen exhaust systems, both on the lowest and highest fan speeds. On low, only four systems were reported to “interfere” with conversation or television/radio usage. But on high, 11 systems were said to interfere, but could be talked over, and two systems were reported to be so loud, that conversation was impossible during operation.

Kitchen Ventilation Type	**# of Homes**
Range Hood	18
HRV / ERV Exhaust	6
Exhaust fan in wall / ceiling	3
Microwave Exhaust Fan	2
Kitchen Exhaust to Outside?	**# of Homes**
Yes	**17**
No	**6**
# of Kitchen Ventilation Fan Settings	**# of Homes**
1	2
2	5
3	8
4	4
5	2
Continuously Variable	3
Noise on Lowest Fan Setting	**# of Homes**
Quiet, barely noticeable	10
Noticeable but does not interfere with conversation	10
Interferes with conversation or radio or TV but can talk over it	4
Loud; can't have conversations or hear radio or TV	0
Noise on Highest Fan Setting	**# of Homes**
Quiet, barely noticeable	0
Noticeable but does not interfere with conversation	9
Interferes with conversation or radio or TV but can talk over it	11
Loud; can't have conversations or hear radio or TV	2

Table 22 Kitchen Ventilation Technologies Summary

Occupants were asked during the exit survey about their frequency of use of their kitchen exhaust fan and typical fan speed selected. The responses are summarized in Table 23 below. Kitchen exhaust behavior was widely variable, with a fair number of occupants reporting either 75% of more usage or infrequent usage. 10 respondents indicated that they used their kitchen exhaust “infrequently, only when needed”. Another three reported using it 75% of the time during oven or cooktop operation, and three reported 75% usage only during cooktop operation. Another three reported using it half of the time and one occupant reported never using their kitchen exhaust. The majority of occupants reported using the lowest or only available fan speed. Eight occupants reported preferentially using the lowest speed, and another four occupants only had one fan speed. The rest were split between medium, high, variable and never.

The reasons that occupants reported using kitchen ventilation fans are summarized in Table 24 below. Odor removal, smoke removal and no response were the most popular choices. Four reported steam/moisture removal and two reported heat removal. These findings, coupled with the frequency of kitchen exhaust usage, suggest that occupants were most aware of pollutants from cooking during particularly smelly and smoky events.

Occupants casually reported that there was no reason to use the exhaust fan during water boiling or other apparently innocuous cooking activities. In aggregate, these findings suggest that most occupants do not judge cooking to be a major source of pollutants under normal operating conditions, and they assume its intended use is in ”outlier” situations.

Average Kitchen Exhaust Fan Usage	**# of Homes**
Never	1
Infrequently; only when needed	10
About half the time	3
Most times when cooktop is used but not when oven is used	3
Most times (75% or more) when cooktop or oven is used	3
Continuous Kitchen Exhaust Only	2
No Answer	2
Most Common Speed Setting Selected When Using Kitchen Exhaust	**# of Homes**
Only one speed available	4
Lowest setting	8
Medium setting	3
Highest setting	1
Varies or changes depending on what is being cooked	3
Continuous Kitchen Exhaust Only	2
No Answer	2
Don't know or prefer not to say	1

Table 23 Kitchen Ventilation Usage Summaries

Reason You Use Kitchen Exhaust Fan	**# of Homes**
Remove Odors	11
Remove Smoke	8
Remove Steam/Moisture	4
Remove Heat	2
Continuous Kitchen Exhaust Only	2
No Answer	7

Table 24 Reasons for Kitchen Exhaust Fan Usage Summary

1.15 Occupant Assessments of Indoor Air Quality in Their Home

During initial and exit surveys, occupants were asked some qualitative questions about the air quality in their homes, both generally and during the sampling period. Three qualitative questions were intended to assess what occupants thought contributed to air quality and what sort of actions they took to manage or improve air quality in their homes. The responses to these three free-response questions are summarized in Table 25. By far, the most frequently cited elements of a home that were perceived to contribute to good IAQ were the ventilation system and healthy building materials and furniture. At least four occupants reported that the following contribute to good IAQ in their homes: being “very airtight”, a lack of forced air heating and cooling, safe combustion appliances, all hard surface flooring, and operable windows. This feedback suggests that these occupants were reasonably well-informed, on average, of the elements of a home that are considered to affect IAQ. A popular maxim in residential high performance green construction is “build tight, ventilate right”. In addition, source control through use of low-emitting materials is considered essential to IAQ in high performance homes. These elements constituted the top three responses to this survey question. Significant confusion was still reported. Three occupants reported that the insulation levels of their home contributed to good IAQ, and two occupants reported that plants in their lawn contributed to good IAQ. Oddly enough, despite 10 homes having been certified as "green", only one occupant reported perceiving that such a certification contributed to good IAQ.

Occupants generally found it much more challenging to report elements of their home that contributed to poor IAQ. The most frequent response was "Nothing". The primary reported contributor to poor IAQ was off-gassing new furniture or equipment that was brought into the home after construction. Other reported contributors were gas cooking, pets and kitchen ventilation system issues, including missing systems and occupant's lack of operation of installed systems. Once again, some confusion was evident. A lack of curtains or drapes was reported to contribute to poor IAQ, as were houseplants. But in general, cooking was seen as a potential source of trouble. It is noteworthy, that the published purpose of the study was to measure pollutants in homes with gas appliances, which may have primed respondents to these types of responses.

The final free-response question concerned what actions the occupant took to manage or improve IAQ in their home. By far, the most frequent response was to operate windows whenever necessary, with 11 homes responding such. The next most frequent response, with eight homes, was that on an ongoing basis, they purchased healthy products, such as cleaners, furniture and paint. Occupants also reported increasing ventilation rates during cooking and frequent use of bathroom/laundry exhaust fans. Other examples included equipment maintenance, regular cleaning and use of air cleaners/filters. Some confusion was evident here as well, as one occupant reported that water filtration was an activity they pursued to improve or manage IAQ.

Element of home that contributes to good IAQ	**# of Responses**
Ventilation system	16
Healthy building materials and furniture	11
Very airtight	6
No forced air system	5
Combustion appliance safety	4
No carpeting, all hard surfaces	4
Operable windows	4
Kitchen ventilation	3
Insulation level of walls, floor, window, etc.	3
Heating system	2
Air filtration	2
Exterior plants	2
Green/IAQ certification	1
Good construction quality	1
Furniture is old and has already outgassed	1
Avoid keeping toxic products in home	1
Crawlspace is sealed from house	1
Automated exhaust fans, bathroom	1
Ceiling fans for circulation of air	1
Central vacuum, scrape off matts	1
Element of home that contributes to bad IAQ	**# of Responses**
Nothing	7
Off-gassing furniture or new equipment	5
Gas cooking	3
Pets	3
Missing or badly installed kitchen exhaust	3
No ventilation system, tight house, lack of window operation in winter.	3
Failure to use kitchen exhaust fan	2
Off-gassing from new equipment (fireplace, furniture)	1
Lack of maintenance, filters	1
House plants	1
Lack of curtains/drapes	1
Air leakage from basement	1
Total reliance on ventilation system in very tight house	1
Actions taken to improve/manage IAQ in home	**# of Responses**
Operate windows when necessary	11
Purchasing healthier products (cleaning, furniture, paint, etc.)	8
Increase ventilation during cooking	6
Use of exhaust fans in bathrooms/laundry	3
Equipment maintenance	3
Use of ventilation for cooling or moisture	2
Extra air cleaning or filtration	2
Cleaning	2
Avoid outside debris on shoes	2
Nothing	2
Seal up house in response to outdoor event	1
Water filtration	1

Table 25 Open-Ended IAQ Questions Summary

Occupants were also asked to report on their subjective evaluation of the indoor air quality in their home during the sampling week. All occupants reported either "very good" or "acceptable" air quality. Results are summarized in Table 26 below.

How would you rate the air quality in your home over the past week?	# of Homes
Very good	16
Acceptable	6
Barely Acceptable	0
Poor	0

Table 26 Occupant Reported Perceived Air Quality During Sampling Week

1.16 Pollutant Measurements

1.16.1 Stovetop Testing Measurements

Stovetop testing was performed in all project homes except 1301, where the ultrafine particle counter failed to record data during the test. One-minute measurements of ultrafine particles, carbon monoxide, carbon dioxide, temperature and relative humidity were made during standardized operation of cooktop burners and oven.

Results of the ultrafine particle measurements are summarized in Figure 17 using maximum particle counts, adjusted for the minimum count encountered in the home. A clear distinction existed between electric induction cooktops and either electric resistance or gas burner cooktops. The median values for the maximum UFP concentrations for gas and electric resistance cooktop homes were 181,265 and 231,583, respectively, whereas the median in induction cooktop homes was 5,430. The difference in maximum UFP concentrations between induction cooktop and other types was highly significant (Wilcoxon Ranked Sums, W = 0, P = 7.595e-5). Similarly, multivariable regression revealed induction to be a significant variable, while electric resistance was not statistically different from gas burners (P-values of 0.00101 and 0.70610, respectively). This test procedure did not include any UFP emissions directly from the material being cooked (aside from water boiling), and these emissions could be substantial depending on the food/preparation type. Induction burners operate by using a magnetic field to generate heat in the pan itself, and the cooktop burner does not become hot. Potentially dust on the cooktop surface does not volatilize under these circumstances, which could explain the difference observed. Another explanation is that potentially a buildup of carbon occurs on pot bottoms with resistance and gas burners, but this does not occur with induction. This analysis was repeated using a three-minute simple moving average of the maximum adjusted UFP concentration, and the r^2 of the linear model of the one-minute and three-minute adjusted maximums was 0.9938, suggesting the metric used for comparison is reasonably robust.

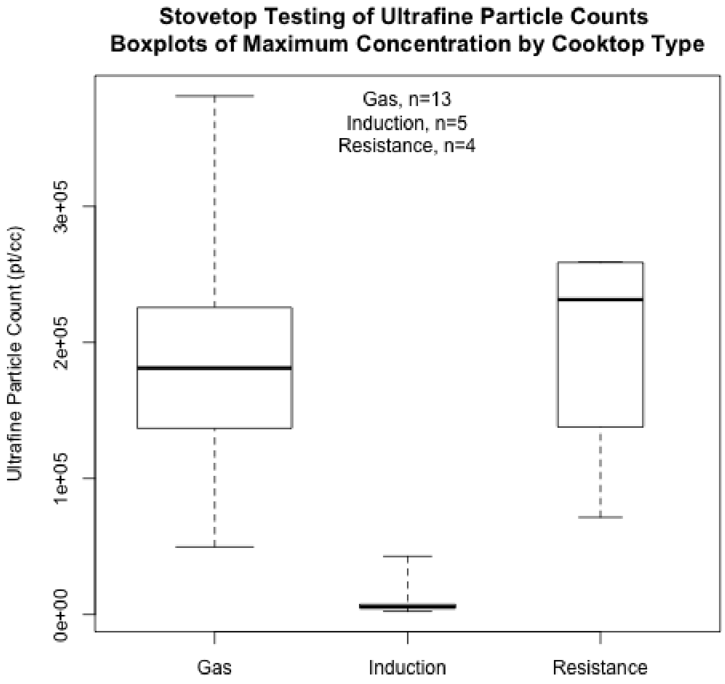

Figure 17 Adjusted Maximum Ultrafine Particle Concentrations by Cooktop Type

The CO results are summarized in Table 27 below, by minimum background CO and maximum one-minute and five-minute concentrations. The sampling rate was one-minute, and data files included short time periods prior to igniting the first burner (1-5 minutes), as well as decay periods of ~15-minutes after burners were extinguished. Significant CO concentrations were generated near the cooktop during stovetop testing in some project homes. The one-hour CalEPA limit of 20 ppm was reached in five homes for one-minute concentrations, but only in one home at a five-minute average. While one-hour and five-minute averages cannot be directly compared, the CalEPA threshold provides some reference for what are considered acceptable and unacceptable levels of CO on a short timeframe. The CO stovetop testing results in home 1202 are inexplicable. This home used an electric induction cooktop and electric oven; the only combustion in the home was a sealed combustion, direct vent water heater in the attic. The home was located in a rural setting, without nearby thoroughfares, parking facilities, etc. Yet, this home achieved the highest CO peak concentrations, of 44 ppm and 33 ppm at one- and five-minute averages. No explanation can be offered for this, and it is notable that CO logging in the home during the 6-day monitoring period revealed 0% of the time was spent >5ppm, with an one-hour peak concentration of 0.7 ppm.

	Minimum Background CO (ppm)	Maximum One-Minute CO (ppm)	Maximum Five-Minute CO (ppm)	Number of Observations
501	NA	NA	NA	NA
502	NA	NA	NA	NA
601	0	22.1	14.0	40
602	0	0	0	31
801	1.7	20.0	19.4	37
802	2.9	5.7	5.7	35
902	0.0	3.4	1.5	31
1001	NA	NA	NA	NA
1002	NA	NA	NA	NA
1201	-0.8	21.2	13.6	35
1202	-0.3	44.2	33.1	44
1301	1.4	4.7	4.3	28
1302	0.0	14.3	12.4	43
1303	0.0	1.7	1.3	26
1401	0.0	2.8	2.5	34
1402	0.8	3.6	3.2	37
1501	NA	NA	NA	NA
1502	NA	NA	NA	NA
1601	0.0	1.2	1.2	36
1801	1.0	3.7	2.4	27
1802	0.0	1.7	0.5	35
1901	0.0	25.1	9.4	35
1902	NA	NA	NA	NA
1911	0.0	2.2	1.9	32

Table 27 Stovetop Testing CO Summary

1.16.2 Air Exchange Rate Measurements

The air exchange rates were measured by passive tracer gas technique and non-corrupt results were obtained in 16 homes, with results having been corrupted in 8 homes, as discussed in the methods section. Median and mean AER were 0.304 and 0.339 for all homes, ranging from 0.141 to 0.80. AER in mechanically ventilated homes were similar to AER in naturally vented homes (Figure 18) with the group of naturally vented homes having more homes with high AER. Median AER was 0.324 in naturally ventilated homes and 0.304 in mechanically vented homes.

Significant levels of inconsistency in tracer gas concentrations were found between the four indoor locations in nearly all homes. The minimum, mean and maximum AER calculated for each home are presented in Table 28 below. Average relative error [25]between the minimums and means was 14.8% (range of 1.9% to 33.0%) and 21.5% between the maximums and means (range of 1.1% to 50.2%). Some homes, such as 1201

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[25] "Relative errors" were calculated as the proportional difference (See below) between the minimum and mean as well as the maximum and the mean in each home. These relative values were then averaged.

$$\mathrm{Re}\,lativeError_{\min\text{-}to\text{-}mean} = \frac{AER_{\min} - AER_{mean}}{AER_{mean}}$$

had very consistent results, and a number of others had ranges of greater than 1/10 of an air change. The precision of these and other single-point air exchange rate measurements are called into question by the variability in these results.

The minimum and maximum tracer gas concentrations were identified in each project home, and they are counted and summarized by their location in Table 29 below. Samplers placed in a bedroom were most often the highest or lowest values in a home, with a much more pronounced effect on the maximum concentration counts. This makes sense, as a maximum concentration would tend to occur in a zone with low air exchange in a well-mixed home. Bedrooms are most likely to have a door closed for sleep and privacy, and unless ventilation is provided to the room, its AER will be low. Alternatively, the home may not be well-mixed and a tracer gas source in a bedroom could disproportionately accumulate on the bedroom sampler, despite open doors. Kitchen samplers were placed in the kitchen, which were mostly or entirely connected to other large volumes of the home in the vast majority of cases. Samplers labeled “I” or “J” were placed in other central areas of the home. Due to this issue with Bedroom samplers, all bedroom values were removed, and means, minimums and maximums were recalculated. Min-to-mean relative errors averaged 11.8% (0.4 to 34.3%) and mean-to-max relative errors averaged 9.6% (0.1 to 22.0%). This tighter distribution suggests an approximate accuracy of ±10%. The new mean value was 0.334 (vs. 0.339) and median was 0.296 (vs. 0.304), each less than one hundredth of an air change different from the value including the bedroom samplers. The new range was 0.140 to 0.75 (vs. 0.141 to 0.8).

House ID	Min AER	Mean AER	Max AER
501	0.210	0.260	0.308
502	0.261	0.331	0.398
601	NA	NA	NA
602	NA	NA	NA
801	0.328	0.371	0.491
802	0.179	0.206	0.228
902	0.237	0.276	0.323
1001	0.226	0.278	0.417
1002	0.359	0.536	0.747
1201	0.329	0.335	0.339
1202	0.339	0.379	0.460
1301	0.157	0.170	0.179
1302	0.744	0.800	0.900
1303	0.338	0.412	0.526
1401	NA	NA	NA
1402	0.111	0.141	0.180
1501	0.173	0.182	0.207
1502	0.359	0.496	0.657
1601	NA	NA	NA
1801	0.227	0.245	0.279
1802	NA	NA	NA
1901	NA	NA	NA
1902	NA	NA	NA
1911	NA	NA	NA

Table 28 Minimum, Mean and Maximum Weekly AER in Project Homes

	Count of Minimum and Maximum Tracer Concentrations by Location of Passive Sampler		
Location	Total	Minimum	Maximum
Bed	18	7	11
Kitchen	12	6	6
I	10	8	2
J	6	2	4

Table 29 Count of Minimum and Maximum Tracer Gas Concentrations in Each Home by Location of Passive Samplers

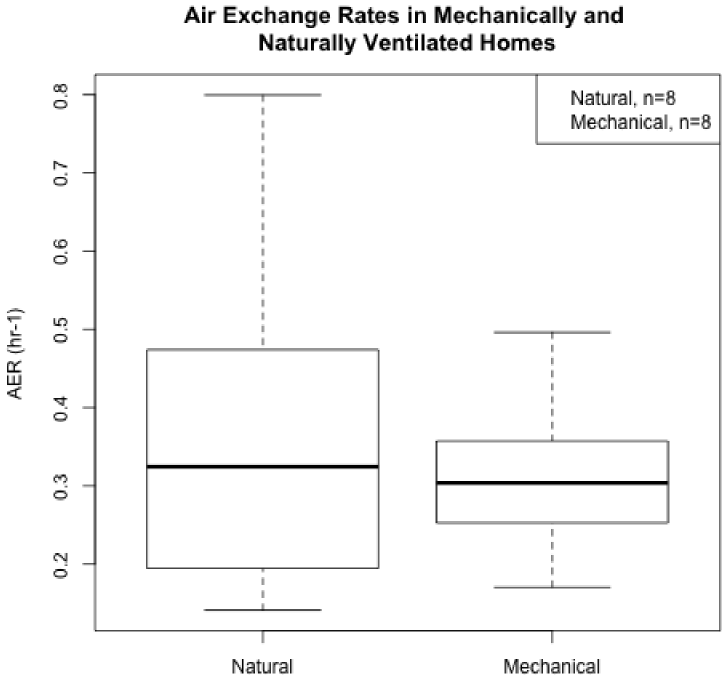

Figure 18 Weekly Average Air Exchange Rates in Mechanically and Naturally Ventilated Homes

1.16.3 Formaldehyde Measurements

Weekly average formaldehyde concentrations were measured in the bedroom and kitchen of 24 project homes. Concentrations are summarized in Table 30 and Figure 19 below (House-by-house data is in Table 55 in Appendix). The kitchen concentrations were normally distributed (Shapiro-Wilks test, W = 0.9549, p-value = 0.3445), but the bedroom and outside concentrations were not (Shapiro-Wilks test, W = 0.8511, p-value = 0.002289 & W = 0.7088, p-value = 1.32e-05, respectively). As a result, the median values are of most interest. Only a single home had an indoor concentration below the California EPA Chronic Reference Exposure Level of 9 μg/m^3, but all homes were significantly below the OEHHA Acute REL of 55 μg/m^3 (represented in Figure 19 as the green and red dashed lines, respectively). Bedroom concentrations were higher than outdoor in all homes, and kitchen concentrations were higher than outdoors in 23 of 24 homes. Median indoor-to-outdoor ratios were 4.9 and 4.8 in the bedrooms and kitchens, respectively.

	One-Week Formaldehyde Concentration (μg/m^3)						n
Location	**Minimum**	**1st Quartile**	**Median**	**Mean**	**3rd Quartile**	**Maximum**	
Bedroom	11.68	15.46	17.54	22.31	29.73	47.02	24
Kitchen	8.121	13.79	20.08	20	27.21	33.18	24
Outside	0.5089	2.845	4	4.366	4.514	13.2	24

Table 30 One-Week Average Formaldehyde Concentrations Summary, in Kitchen, Bedroom and Outside

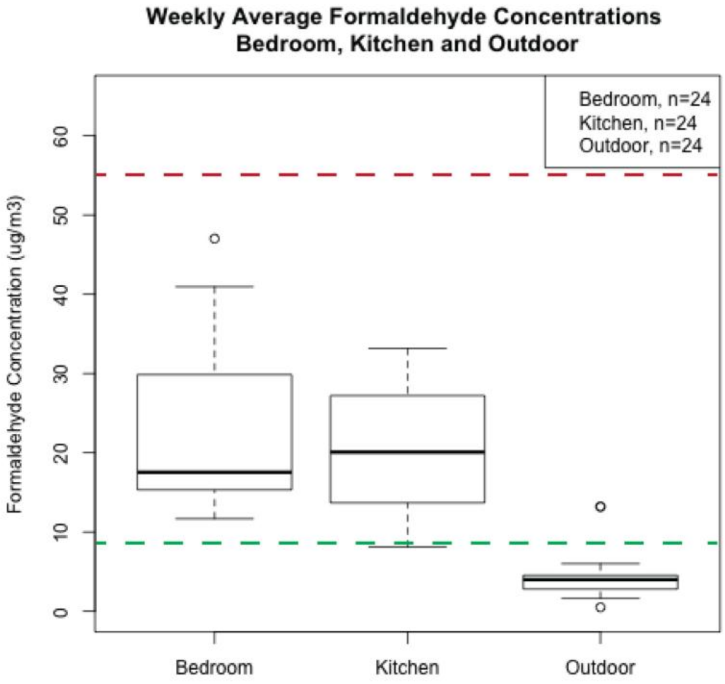

Figure 19 Weekly Average Formaldehyde Concentrations, Bedroom, Kitchen and Outdoor

Kitchen formaldehyde concentrations were compared in homes with gas cooktops and electric cooktops (Figure 20). A significant difference between the two groups was not observed (Wilcoxon Ranked Sums, W = 73, p-value = 0.7702)

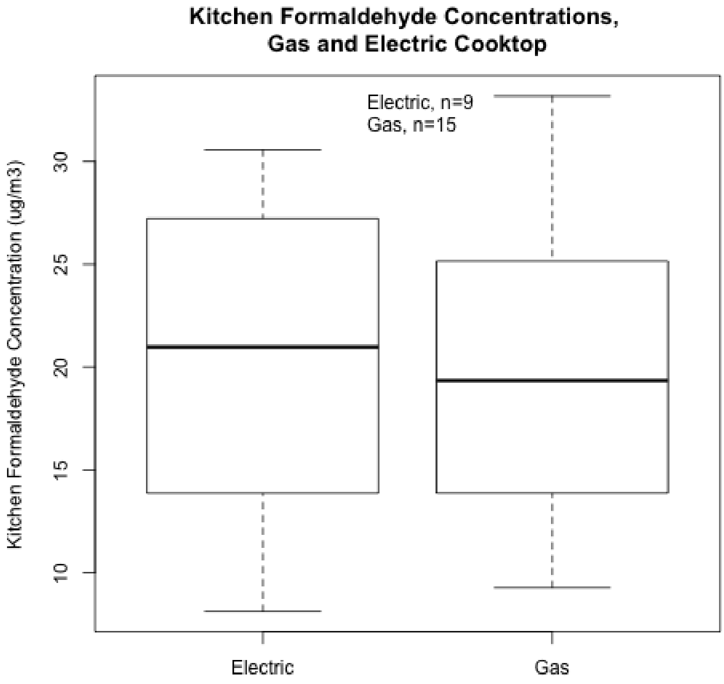

Figure 20 Kitchen Formaldehyde Concentrations, by Gas and Electric Cooktop

No correlation was found between measured air exchange rates and formaldehyde concentrations in kitchens and bedrooms, with correlation coefficients of r = -0.09 and r = -0.04, respectively (Figure 21). Similarly, significant differences were not found between homes with and without continuous mechanical ventilation (Wilcoxon Ranked Sums: Kitchen, W = 81, p-value = 0.6085 and Bedroom, W = 85, p-value = 0.4585). These groups are pictured in Figure 22 below.

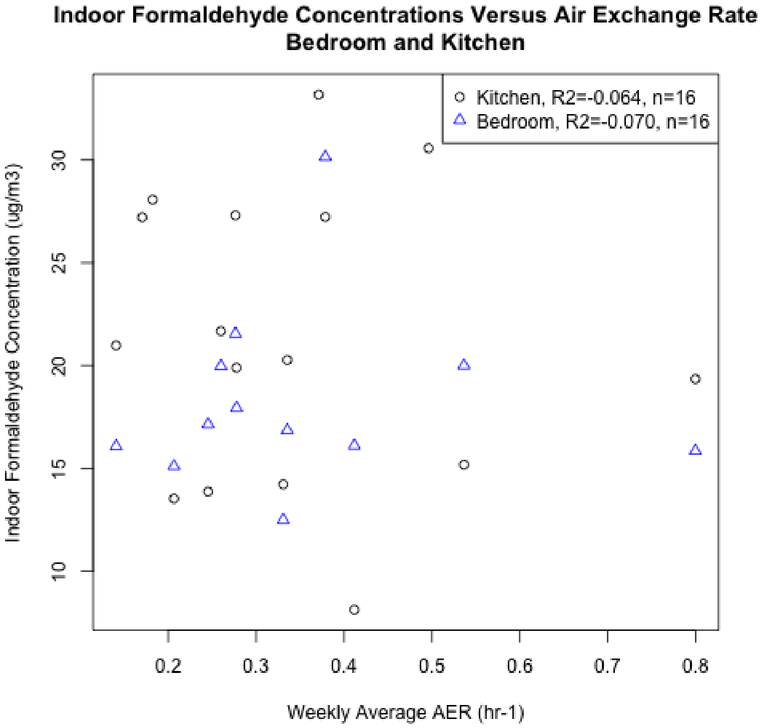

Figure 21 Formaldehyde Concentration Versus Air Exchange Rate, Bedroom and Kitchen

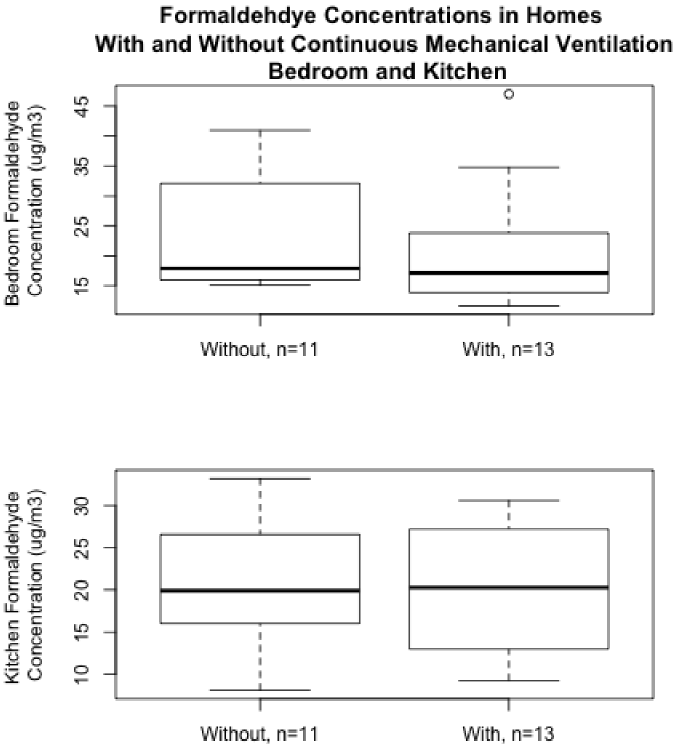

Figure 22 Formaldehyde Concentrations in Homes With and Without Continuous Mechanical Ventilation, Bedroom and Kitchen

Presence of new materials from recent remodeling activities has been associated with increased formaldehyde levels in homes. Homes with and without new materials within the past year were compared, and no significant differences were observed between them (Bedroom, W = 80, p-value = 0.482 and Kitchen, W = 81, p-value = 0.446). These groups are pictured in Figure 23 below. Homes without new materials in the past year reported no new carpeting, furniture, cabinetry, paint, sheetrock, siding, or flooring. Those with new materials reported one or more of these items.

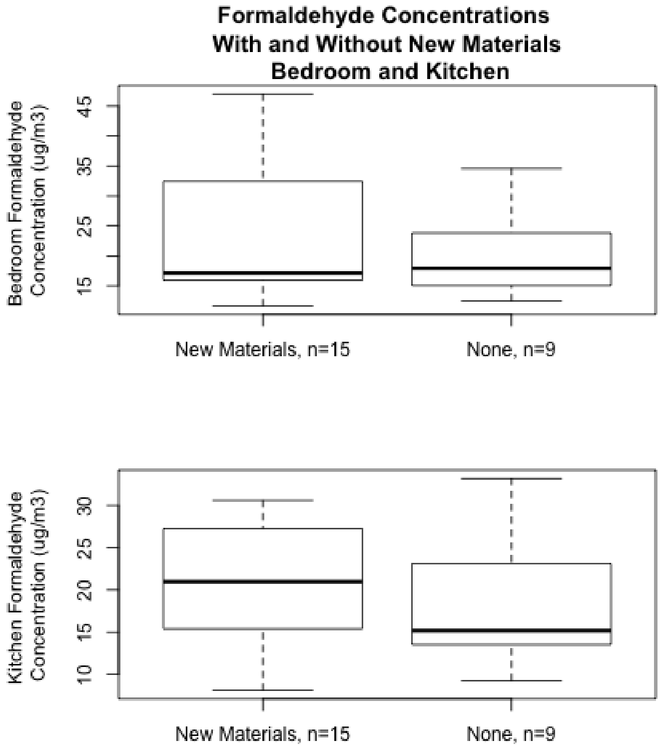

Figure 23 Formaldehyde Concentrations With and Without New Materials, Bedroom and Kitchen

Formaldehyde concentrations were also compared between homes with different energy or sustainability classifications. Bedroom and kitchen formaldehyde levels are plotted by Passive House, Net-Zero, Deep Energy Retrofit and Green Certified designations in Figure 24 below. The distributions and medians are similar between groups.

Multivariate modeling was performed using the kitchen formaldehyde data. A model was developed using house age, average relative humidity and presence of any new materials (see Figure 23 above). The adjusted R^2 was 0.3366 (F-statistic: 4.89 on 3 and 20 DF, p-value: 0.01040). Age was significant (p= 0.00478), presence of new materials was significant (p=0.02367), and average relative humidity was nearly significant (p=0.05803). The AER was not significant in any models tested, nor was the presence of continuous mechanical ventilation.

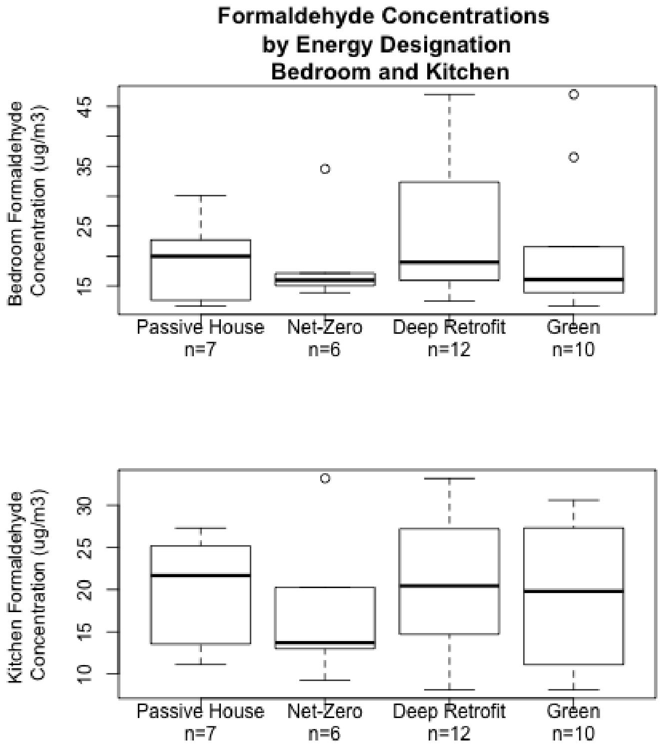

Figure 24 Formaldehyde Concentrations by Energy/Sustainability Designation, Bedroom and Kitchen

1.16.4 Acetaldehyde Measurements

Weekly average acetaldehyde concentrations were measured in the bedroom and kitchen of 24 project homes. Concentrations are summarized in Table 31 and Figure 25 below (House-by-house data is in Table 55 in Appendix). Bedroom, kitchen and outdoor samples were not normally distributed (Shapiro-Wilk Test, W = 0.8163, p-value = 0.00055, W = 0.8195, p-value = 0.0006234, and W = 0.8996, p-value = 0.02113, respectively). Bedroom and kitchen levels were log-normally distributed (W = 0.9652, p-value = 0.5521 and W = 0.9696, p-value = 0.6572, respectively). As a result, the median values are of most interest. All homes exceeded the Proposition 65 No Significant Risk Level for carcinogens of 4.5 μg/m^3, but all homes were well beneath the OEHHA Chronic Reference Exposure Level of 140 μg/m^3. Indoor concentrations were higher than outdoor in all cases, with median indoor-to-outdoor ratios of 7.1 and 7.7 in the bedrooms and kitchens, respectively.

	One-Week Acetaldehyde Concentration (μg/m3)							
Location	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum	nd	n
Bedroom	6.3	12.6	16.2	19.0	20.4	50.3	0	24
Kitchen	6.4	10.5	16.1	19.1	22.2	58.0	0	24
Outside	bd	1.1	2.0	2.2	3.0	6.5	1	24

Table 31 One-Week Acetaldehyde Concentrations Summary, Bedroom, Kitchen and Outdoor

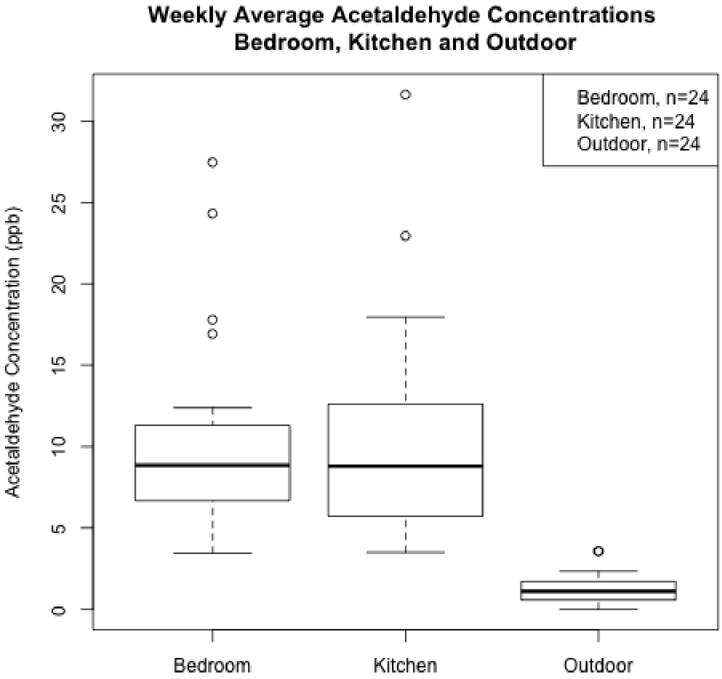

Figure 25 Weekly Average Acetaldehyde Concentrations, Bedroom, Kitchen and Outdoor

Kitchen acetaldehyde concentrations were compared in homes with gas cooktops and electric cooktops (Figure 26). A significant difference between the two groups was not observed (Wilcoxon Ranked Sums, W = 82, p-value = 0.4115).

No correlation was found between measured air exchange rates and acetaldehyde concentrations in kitchens and bedrooms, with r = 0.01 and r = -0.002, respectively (Figure 27).

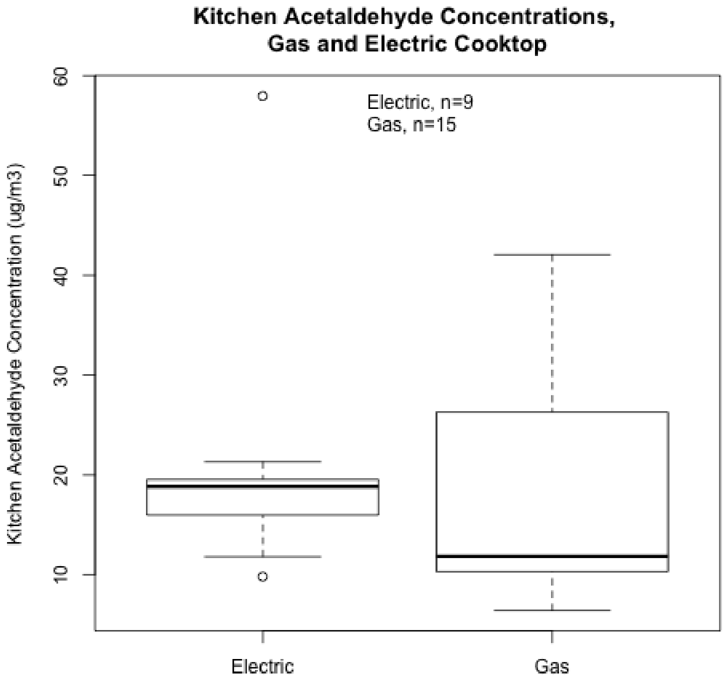

Figure 26 Kitchen Acetaldehyde Concentrations, Gas and Electric Cooktops

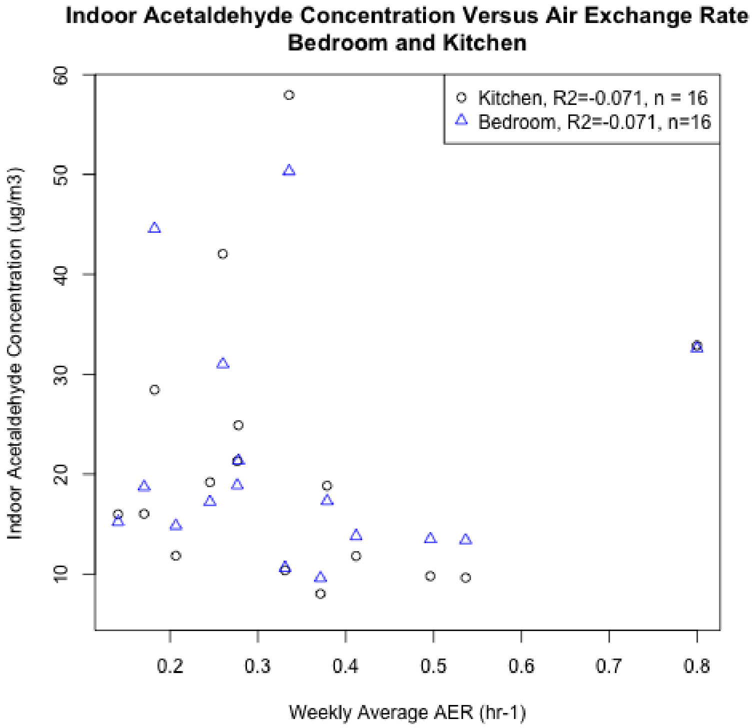

Figure 27 Acetaldehyde Concentrations Versus Air Exchange Rate, Gas and Electric Cooktops

1.16.5 Nitrogen Oxides Measurements

Nitrogen oxides were measured in all 24 project homes in kitchen, bedroom and outdoor locations, providing time-integrated samples for each location. Results are reported in two ways: (1) the absolute concentration in ppb and (2) the indoor-outdoor ratio. The results of the NO_x measurements are summarized in the tables below. The I/O ratio attempts to account for the variance in indoor concentrations caused by outdoor NO_2 levels, which varied substantially from site-to-site.

NO_2 measurements are summarized in Table 32 below (House-by-house data in Table 56 in appendix). The median indoor NO_2 concentration was 9.2 ppb in bedrooms and 8.7 ppb in kitchens, which are both slightly elevated above the median outdoor concentration of 7.6 ppb (Figure 28). These one-week average values are most comparable to the annual reference levels for NO_2 of 30 and 53 ppb, from the California EPA and the U.S. EPA, respectively (green and red lines in Figure 28 below, respectively. Homes 0501 and 1302 exceeded the CalEPA level in the bedroom. Homes 0501 and 0801 both exceeded the CalEPA level in the kitchen, and Project 1302 exceeded the U.S. EPA level in the kitchen. Project 1901 nearly exceeded the CalEPA standard in the kitchen. All four of these homes used gas cooktop appliances. It should be noted that the CalEPA and U.S. EPA reference levels do not apply indoors, and the NO_2 measurements made in this project were not annual average measurements. These reference levels are used for the purposes of comparison only.

It was notable that outdoor NO_2 levels varied significantly, from a minimum of 1.9 ppb to a maximum of 26.9 ppb. This variation likely resulted from a variety of factors including weather variations across sampling weeks, the locations of the homes and their relative proximities to outdoor NO_2 sources, such as major highways. As a result of its high deposition rate, indoor NO_2 concentrations are expected to be less than outdoors in the absence of an indoor source. High outdoor concentrations clearly contributed to the CalEPA and U.S. EPA exceedences mentioned above, with homes 0801 and 0501 having the highest and 3rd highest outdoor NO_2 concentrations, respectively. But homes 1302 and 1901 were notable for their high indoor NO_2 concentrations and lower outdoor levels, of 12 and 9 ppb, respectively.

		One-Week Average Concentrations, NO_2, NO and NO_x (ppb)								
Pollutant	**Location**	**Min**	**1st Quartile**	**Median**	**Mean**	**3rd Quartile**	**Max**	**NA**	**bd**	**n**
NO_2	Bedroom	1.9	6.0	9.2	11.5	11.0	45.7	0	0	24
	Kitchen	2.2	5.4	8.7	13.6	14.7	57.9	0	0	24
	Outdoor	1.9	4.9	7.6	9.8	12.3	26.8	0	0	24
NO	Bedroom	0.8	4.4	9.1	20.7	24.3	93.6	0	0	24
	Kitchen	bd	6.0	8.7	20.1	22.2	122.8	1	1	22
	Outdoor	0.7	2.3	4.8	8.5	10.5	35.2	0	0	24
NO_x	Bedroom	2.7	9.8	18.7	32.2	33.8	126.3	0	0	24
	Kitchen	2.3	10.9	23.5	32.7	36.2	180.7	1	0	23
	Outdoor	3.6	6.2	12.7	18.4	22.5	62.0	0	0	24

Table 32 One-Week NO_2, NO and NO_x Concentrations Summary, Bedroom, Kitchen and Outdoor

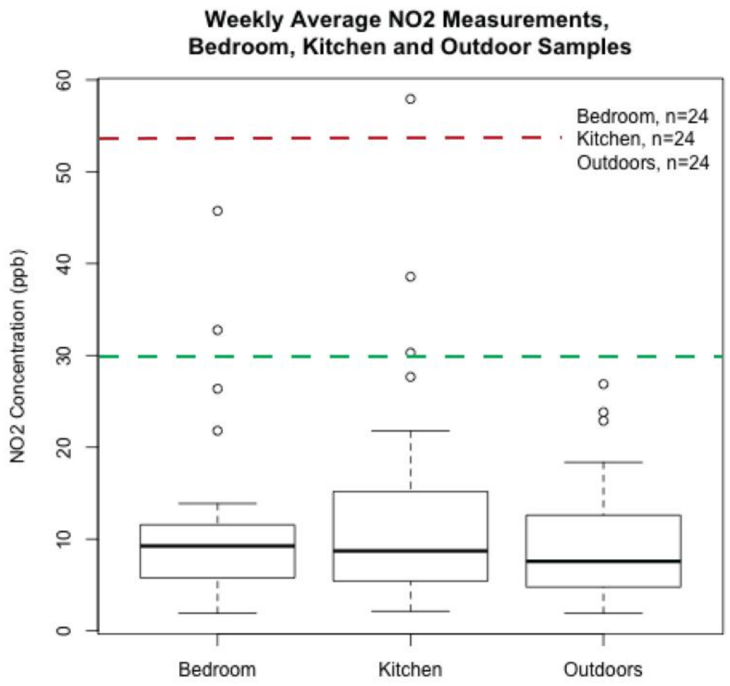

Figure 28 Weekly Average NO_2 Concentrations, Bedroom, Kitchen and Outdoor

A statistically significant difference in indoor NO_2 concentrations was observed between groups of gas cooktop and electric cooktop homes (Wilcoxon Ranked Sums, W = 130, p-value = 0.002381). These groups are summarized in Table 33 and are pictured in Figure 29 below. Not only were median kitchen NO_2 concentrations in gas cooking kitchens higher than in electric cooking kitchens (13.1 vs. 5.4 ppb), but outdoor NO_2 concentrations at gas cooking homes were lower than at electric (medians of 7.3 vs. 10 ppb). Lacking indoor sources, the Gas cooking homes should have had lower indoor NO_2 concentrations, on average. No electric cooking homes exceeded either the CalEPA or U.S. EPA annual standards.

Pollutant	Cooktop Fuel Type	Location	One-Week Average Concentrations, by Location and Cooktop Fuel, NO_2, NO and NO_x (ppb)								n
			Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	NA	bd	
NO_2	Elec	Bedroom	1.9	2.7	6.2	6.5	10.2	10.4	0	0	9
	Elec	Kitchen	2.2	3.6	5.4	6.6	8.3	13.6	0	0	9
	Gas	Bedroom	1.9	7.2	9.4	14.5	17.8	45.7	0	0	15
	Gas	Kitchen	5.3	7.3	13.1	17.9	24.7	57.9	0	0	15
	Elec	Outside	1.9	5.5	10.1	10.5	13.2	23.8	0	0	9
	Gas	Outside	2.3	4.8	7.3	9.4	10.6	26.9	0	0	15
NO	Elec	Bedroom	0.8	1.3	7.1	9.9	15.9	23.8	0	0	9
	Elec	Kitchen	bd	2.1	7.4	10.2	18.0	22.1	0	1	8
	Gas	Bedroom	1.8	5.4	9.8	27.2	28.8	93.6	0	0	15
	Gas	Kitchen	1.9	6.7	13.8	26.5	31.8	122.8	1	0	14
	Elec	Outside	0.7	2.4	6.0	8.9	10.5	26.6	0	0	9
	Gas	Outside	0.9	2.2	3.3	8.3	7.9	35.2	0	0	15
NO_x	Elec	Bedroom	2.7	7.6	10.0	16.3	26.4	33.4	0	0	9
	Elec	Kitchen	2.3	8.1	10.9	16.7	28.8	33.8	0	0	9
	Gas	Bedroom	9.2	14.1	19.2	41.7	43.2	126.3	0	0	15
	Gas	Kitchen	9.7	12.9	29.9	42.9	41.7	180.7	1	0	14
	Elec	Outside	3.6	6.2	16.0	19.4	22.5	46.2	0	0	9
	Gas	Outside	3.9	6.8	10.1	17.8	18.5	62.0	0	0	15

Table 33 One-Week NO_2, NO and NO_x Concentrations Summary, Bedroom, Kitchen and Outdoor, by Gas and Electric Cooktop Type

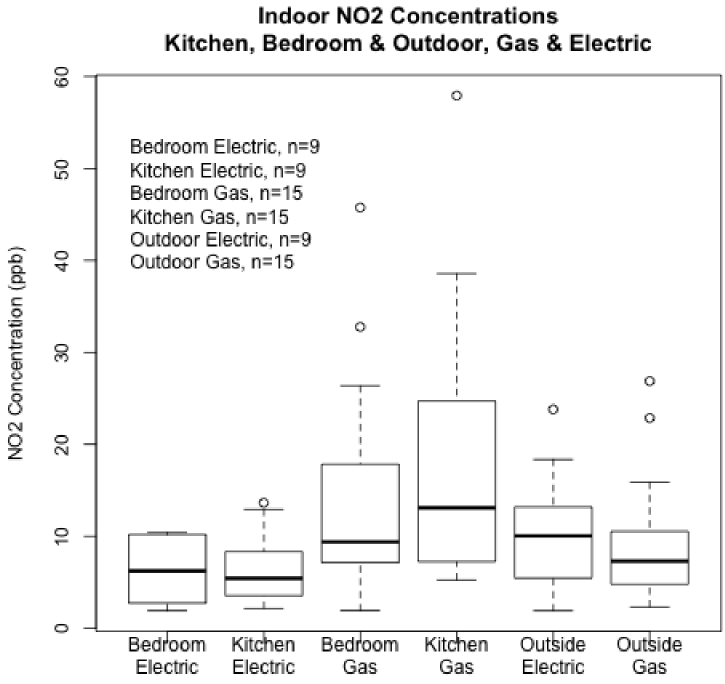

Figure 29 Indoor NO_2 Concentrations, Kitchen, Bedroom and Outdoor by Gas vs. Electric Cooktop

The indoor-outdoor (I/O) ratios provide a simple method for identifying those homes with indoor NO_2 sources. They are pictured in Figure 30 below. The values do not have physical meaning in and of themselves, but they prove useful for comparing between groups of homes, with differing outdoor levels and indoor sources. Once again, a statistically significant difference was observed in gas cooktop and electric cooktop homes (Wilcoxon Ranked Sums, W = 47, p-value = 2.153e-06). The median I/O ratio was twice as high in gas cooking homes as in electric cooking homes. In fact, the maximum value in an electric home was less than the median value in gas cooking homes. Clearly, gas cooking homes had substantial indoor sources of NO_2, which were not being properly controlled through kitchen ventilation measures, such as range hoods.

Pollutant	Cook Top Fuel	Location	One-Week Average Indoor-Outdoor Ratios, by Location and Cooktop Fuel, NO_2, NO and NO_x								n
			Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	NA	bd	
NO_2	Elec	Bedroom	0.29	0.40	0.79	0.73	1.0	1.1	0	0	9
	Elec	Kitchen	0.33	0.51	0.71	0.74	1.0	1.1	0	0	9
	Gas	Bedroom	0.55	1.1	1.4	1.7	1.9	3.3	0	0	15
	Gas	Kitchen	0.74	1.4	1.7	2.1	2.3	4.8	0	0	15
NO	Elec	Bedroom	0.49	0.60	1.1	1.4	1.9	3.6	0	0	9
	Elec	Kitchen	0.06	0.74	1.1	1.6	3.0	3.4	0	1	8
	Gas	Bedroom	0.55	1.8	2.7	5.6	6.7	30	0	0	15
	Gas	Kitchen	0.57	1.4	3.2	8.8	7.9	39	1	0	14
NO_x	Elec	Bedroom	0.44	0.70	0.74	0.92	1.2	1.5	0	0	9
	Elec	Kitchen	0.45	0.66	0.77	0.93	1.3	1.6	0	0	9
	Gas	Bedroom	0.87	1.5	1.7	2.8	4.2	6.7	0	0	15
	Gas	Kitchen	0.78	1.4	2.2	3.4	5.6	8.0	1	0	14

Table 34 One-Week NO_2, NO and NO_x Indoor-Outdoor Ratios Summary, Bedroom and Kitchen, by Gas and Electric Cooktop Type

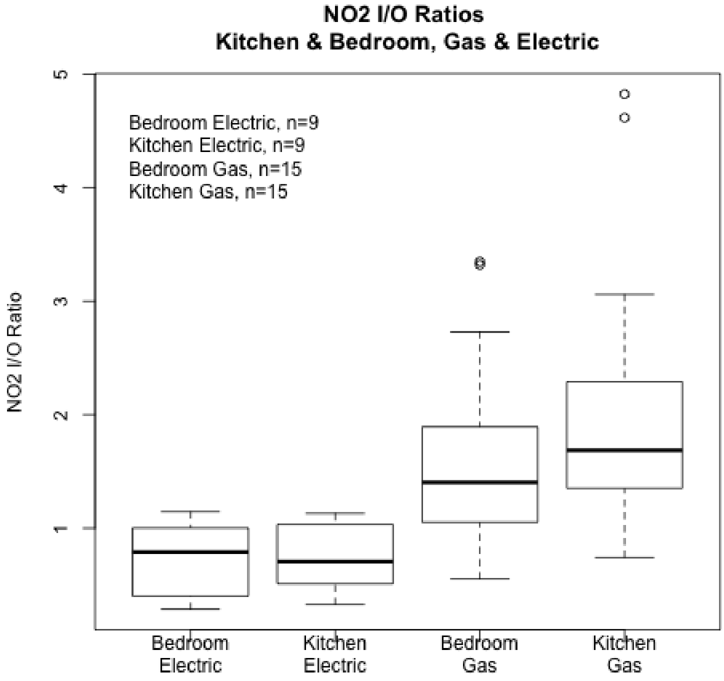

Figure 30 NO_2 Indoor-Outdoor Ratios, by Kitchen and Bedroom, and by Gas and Electric Cooktop

A trend has been noted for homes built in accordance with Passive House design principles to not use traditional kitchen range hoods that exhaust to outside. Instead they provide some combination of recirculating range hood with carbon filtration and continuous general kitchen exhaust by the ERV or HRV. Such a set up was used in three Passive Houses in this research, which also used gas cooking appliances. A fourth Passive House with gas cooking (Project 1601) used a commercial-grade kitchen range hood exhausted to the outside. These four Passive Houses are compared with the other gas cooking homes in Figure 31 below. Statistical significance was not achieved despite elevated concentrations in Passive Houses, due to small sample size (Wilcoxon Ranked Sums, W = 13, p-value = 0.2799). It was notable that two of the Passive Houses, houses 0501 and 1901, either exceeded or very nearly exceeded the CalEPA annual standard of 30 ppb. While one of the Passive Houses, 0502, has quite a low indoor NO_2 concentration (8.6 ppb), its outdoor concentration was also very low (5.1 ppb). In this case, the I/O ratio is quite informative (Figure 32). The I/O in project 0502 was 1.7, which was identical to the I/O value in project 0501, which had the 2nd highest indoor NO_2 concentration of all 24 homes. This suggests that both homes had substantial indoor sources of NO_2; project 0502 was simply blessed by having very low outdoor concentrations and potentially lower indoor sources. Passive House kitchen ventilation may be acceptable in situations with very low outdoor pollutant sources. It was notable that the highest I/O ratios did not occur in Passive Houses, but rather in homes with historic gas ranges, which likely emitted more NO_2 than newer models.

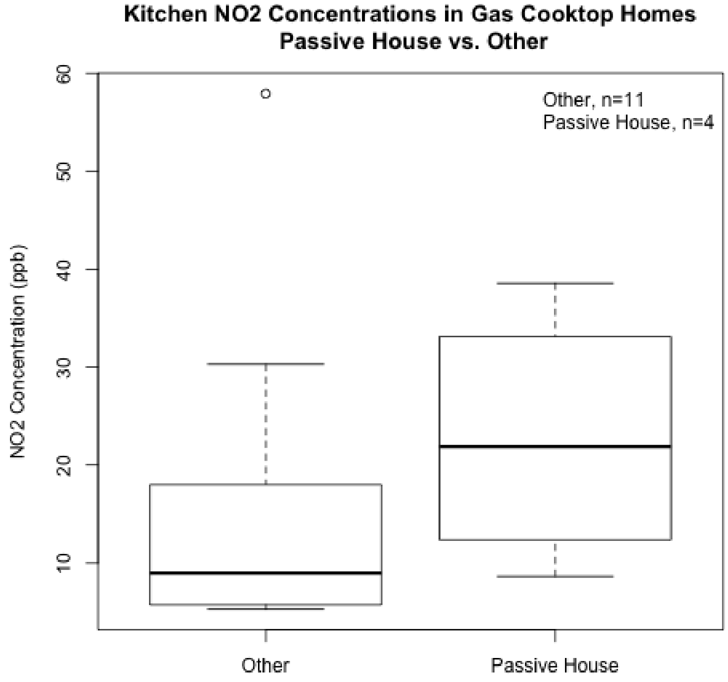

Figure 31 Kitchen NO_2 Concentrations in Gas Cooktop Homes, Passive House vs. Other

Multivariate regression modeling was performed in order to predict the most significant contributors to indoor NO_2 levels in high performance green homes. Kitchen NO_2 data were log-normal (Shapiro-Wilk Test, W = 0.975, p-value = 0.7888), and these transformed data were used in linear modeling. The most successful iteration of the model used three variables—outdoor concentration, air exchange rate, and cooktop fuel type. An adjusted R^2 of 0.8603 was achieved (F-statistic: 31.8 on 3 and 12 DF, p-value: 5.423e-06), with all three independent variables having significance levels of $p<0.001$. Another model was created without the AER, which was only measured in 16 of 24 homes. This incorporated more data points and avoided the use of a difficult to measure variable—AER. This model used four variables—outdoor concentration, cooktop fuel type, reported frequency of cooking during sampling and presence of continuous mechanical ventilation. This model achieved an adjusted R^2 of 0.7873 (F-statistic: 20.44 on 4 and 17 DF, p-value: 2.573e-06). The outdoor concentration, cooktop fuel type and reported cooking frequency were highly significant ($p<0.01$), and the model intercept was significant ($p<0.05$) and the presence of continuous mechanical ventilation was not ($p=0.2203$). Both models explained significant levels of the variance in log-NO_2 concentrations based on relatively few, simple independent variables. It was notable that despite the obvious importance of cooking fuel type, the presence of a kitchen exhaust fan to outside was not significant in any model tested. Status as Passive House was also not significant in the context of these models, again most likely due to the small sample size of four homes.

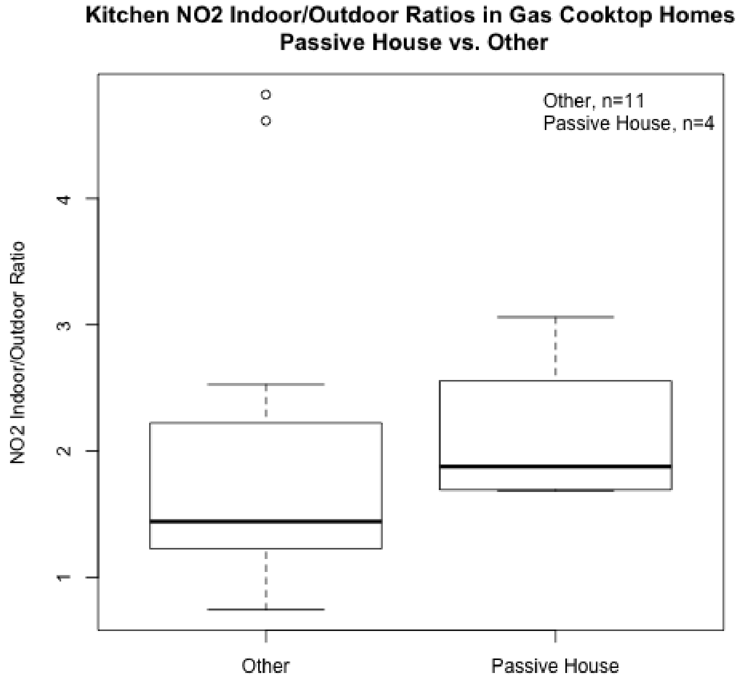

Figure 32 Kitchen NO_2 Indoor-Outdoor Ratios in Gas Cooktop Homes, Passive House vs. Other

1.16.6 Temperature and Relative Humidity Measurements

Temperature and relative humidity measurements were made in the kitchen, bedroom and outside at each home. One-week average values of one-minute time series data are summarized by location in Table 35 below. Summaries by project home are located in Table 57 in appendix. The indoor average temperature across all homes was 20.4 and 20.7

degrees C in the bedroom and kitchen, respectively. Outdoor temperatures averaged 11.3 degrees C. Indoor average relative humidity averaged 46.9% and 46.5% in the bedroom and kitchen, respectively. Outdoor relative humidity averaged 69.7%. No relationship was found between interior temperatures and humidity ratios, as pictured in Figure 33 below. No relationship was found between indoor humidity ratio and air exchange rate, when outdoor humidity ratio was accounted for. Occupant choice of interior temperature had substantial impacts on the indoor relative humidity, which if elevated can lead to issues with dust mites and other allergens that can affect human health. Temperature choice may be just as important as, or more so than, moisture sources and ventilation levels in determining indoor relative humidity.

	One-Week Average Temperature and Relative Humidity, Bedroom, Kitchen and Outside						
	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	NA's
Location	Temperature (Degrees C)						
Bedroom	16.2	19.0	20.8	20.4	21.5	24.1	3
Kitchen	15.9	20.1	20.8	20.7	21.7	23.8	0
Outside	6.8	10.5	11.6	11.3	12.3	14.0	0
	Relative Humidity (%)						
Bedroom	34.7%	40.7%	47.4%	46.9%	53.3%	57.8%	3
Kitchen	32.9%	41.3%	47.2%	46.5%	51.4%	61.5%	0
Outside	51.1%	64.4%	70.9%	69.7%	74.6%	84.1%	0

Table 35 One-Week Average Temperature and Relative Humidity Summaries, Bedroom, Kitchen and Outside

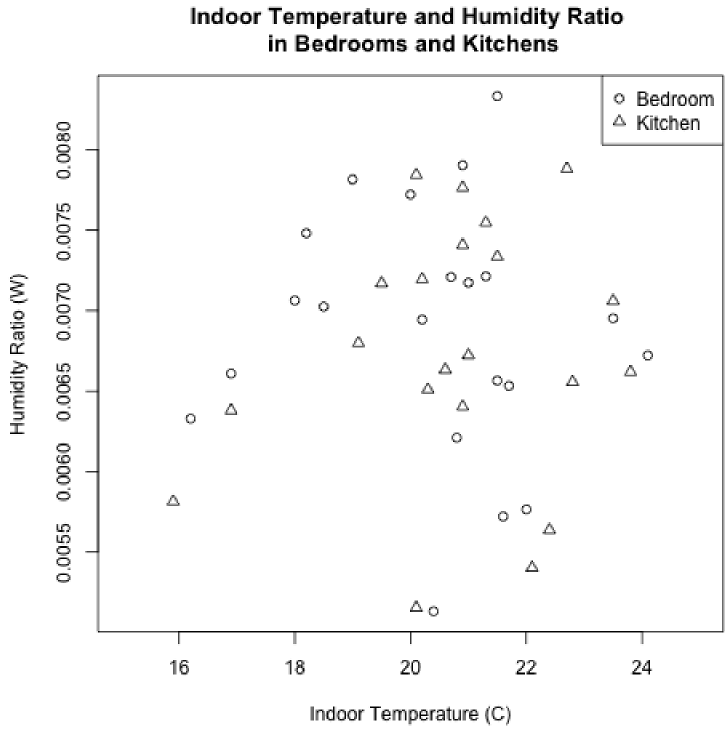

Figure 33 Relation of Indoor Temperature and Humidity Ratio, Kitchen and Bedroom

1.16.7 CO Measurements

Carbon Monoxide measurements were made on a one-minute basis using standalone CO sensors and data loggers located with the kitchen sampling equipment. Logger errors led to data loss in 4 of 24 homes. Maximum one-hour and eight-hour concentrations were calculated for each home, as were counts of one-hour incidences above 20 ppm and eight-hour incidences above nine ppm. These values correspond to the California EPA eight-hour standard of 9 ppm and one-hour standard of 20 ppm. Finally, the fraction of total time with concentrations above five ppm was calculated. These data are presented in Table 36 below.

No homes had dangerous levels of CO at any point during monitoring. No homes had either an one-hour concentration greater than 20 ppm, nor an eight-hour concentration over 9 ppm. Project 0801 had substantially more time above 5 ppm than others, with 4.4% of time above 5 ppm, whereas the next highest home was 0.4%. Project 0801 has an historic gas range, pictured above in Figure 14, and its pilot lights could have contributed to elevated CO levels. Not surprisingly, this same home had the highest one-hour and eight-hour concentrations.

Project ID	Max 1hr (ppm)	Max 8hr (ppm)	Fraction >5 ppm
501	NA	NA	NA
502	NA	NA	NA
601	0.2	0.0	0.00%
602	0.6	0.4	0.00%
801	14.8	5.8	4.40%
802	4.0	1.0	0.10%
902	1.7	1.6	0.00%
1001	3.0	2.3	0.00%
1002	1.1	0.3	0.01%
1201	2.0	1.9	0.00%
1202	0.7	0.0	0.00%
1301	1.6	1.3	0.00%
1302	4.7	4.3	0.02%
1303	0.2	0.1	0.00%
1401	2.8	0.9	0.13%
1402	2.0	1.4	0.02%
1501	NA	NA	NA
1502	NA	NA	NA
1601	0.3	0.0	0.00%
1801	1.4	1.0	0.00%
1802	0.0	0.0	0.00%
1901	2.2	0.4	0.08%
1902	0.1	0.0	0.00%
1911	1.9	0.5	0.05%

Table 36 CO Concentration Summaries

1.16.8 Particulate Matter Measurements

Time resolved, one-minute particle number concentrations were measured in the kitchen of 23 of the 24 homes during the entire sampling period. In 21 homes, counts were made in two size bins—>0.5 micron and >2.5 micron—and in two of the homes, counts were made solely in the >0.5 micron size bins. Particle counts in these size bins are referred to below as 0.5 micron and 2.5 micron particle number concentrations ($PN_{>0.5}$ and $PN_{>2.5}$ concentrations). These values include all particles of the specified size and larger. Summary statistics were calculated for each house's time series and are reported below. Outdoor air quality standards exist for PM_{10} and $PM_{2.5}$, but their units are in μg/m^3. The count data collected in this research cannot be reliably transformed into mass concentrations, yet these data are useful for comparing between groups of homes and assessing particle generation events that occurred during sampling.

The median $PN_{>0.5}$ level across all project homes was 83,780, and was 3,869 for $PN_{>2.5}$. Summary statistics are compared between homes with gas and electric cooktops in Figure 34 and Figure 37. Median particle counts in both groups were similarly distributed. Whereas maximum one-hour and eight-hour particle counts in both size bins appeared to be higher in electric cooktop homes than in gas cooking homes, though the difference was not significant (Median, Wilcoxon Ranked Sums, $PN_{>0.5}$: W = 81, p-value = 0.1901, and $PN_{>2.5}$: W = 72, p-value = 0.1614) (Mean, Wilcoxon Ranked Sums, $PN_{>0.5}$: W = 69.5, p-value = 0.5612, and $PN_{>2.5}$: W = 55.5, p-value = 0.828). Particle emissions during cooking events can be very high, often elevating particle concentrations far above background levels. For this reason, one-hour maximum particle number concentrations may be related to cooking activities, whereas other factors may dominate the median. Of course, as discussed in the literature review, the actual cooking activity or food being prepared can have just as big of an impact on particle emissions as the cooktop fuel source.

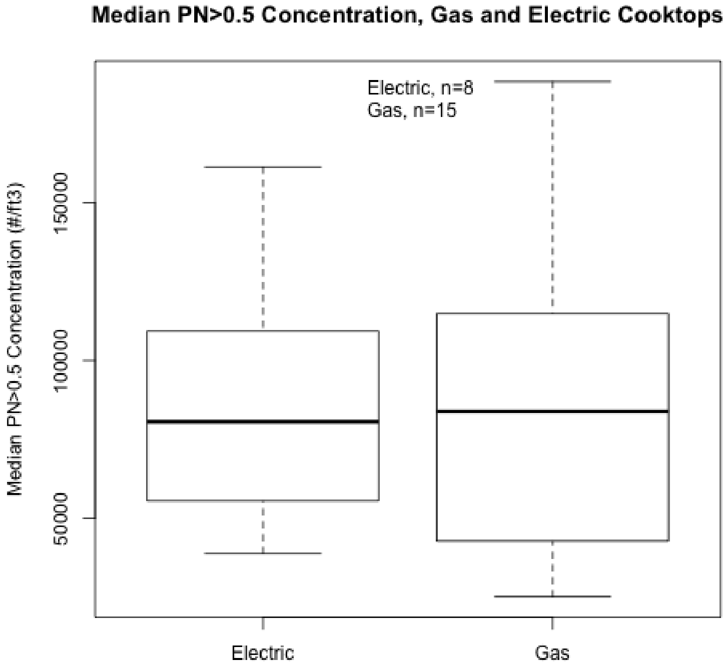

Figure 34 Median $PN_{>0.5}$ Concentrations, Gas and Electric Cooktops

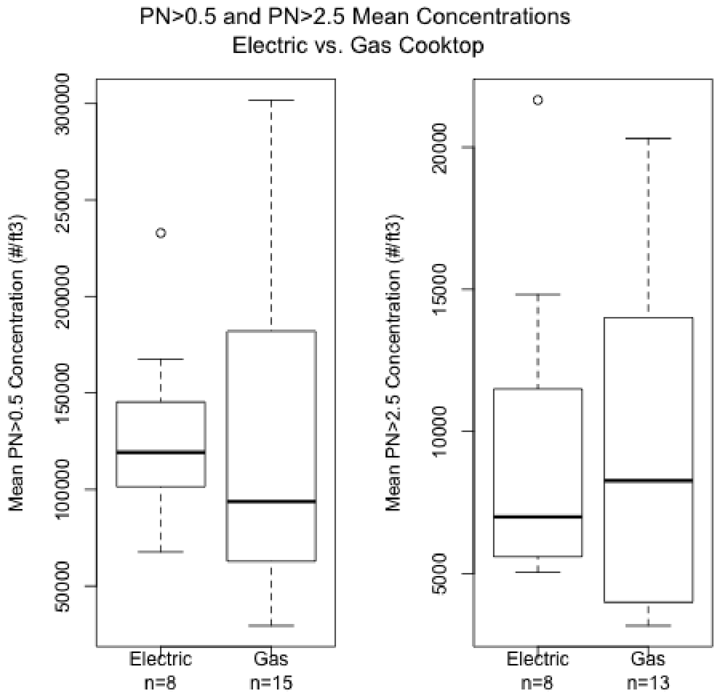

Figure 35 Mean $PN_{>0.5}$ Concentrations, Gas and Electric Cooktops

It was notable that the time-series plots of the particle number concentrations showed significant variability in the frequency of peaks, in addition to median concentrations. This variability between homes is illustrated by two relatively extreme examples in Figure 36 below, representing homes 1302 and 1301. Both homes were measured in the same week, and both had gas-cooking appliances with range hoods exhausted to outside. Home 1302 reported using the range hood 75% or more of the time during cooktop use, and home 1301 reported using the range hood “about half the time”. The notable difference was that the cooking appliance in project 1302 was an historic range, pictured in Figure 16 above, and cooking was done for approximately eight adults each day, as opposed to a family of four with two small children. 13 of 23 homes with $PN_{>0.5}$ data had at least one 5-minute peak particle count greater than 1,000,000 #/ft^3. Home 1302 pictured below had 11 5-minute peak particle count events greater than 1,000,000 #/ft^3.

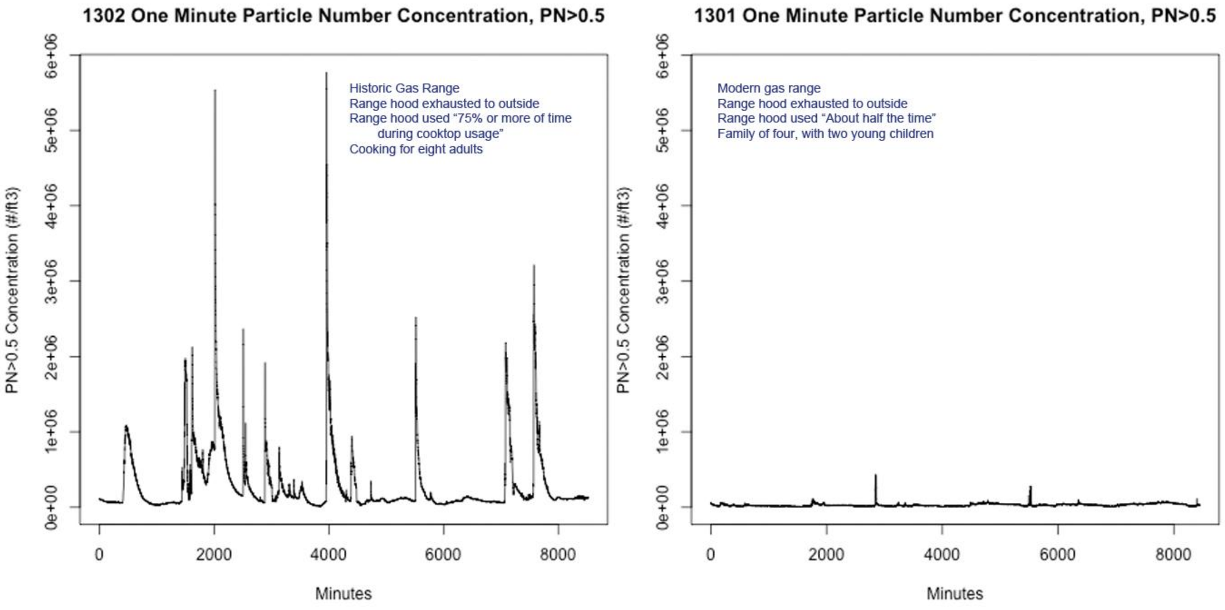

Figure 36 Time Series of One-Minute PN$_{>0.5}$ Concentrations, Homes 1301 and 1302

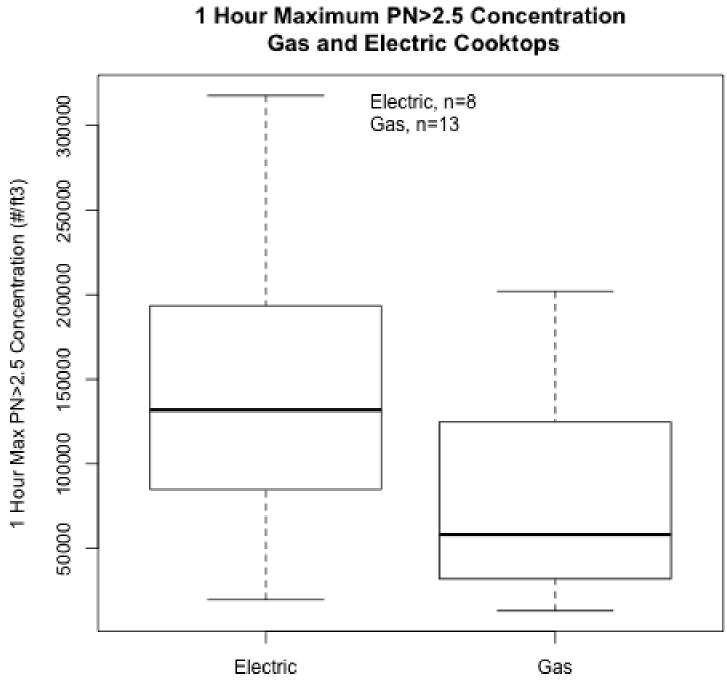

Figure 37 1 Hour Maximum PN$_{>2.5}$ Concentrations, Gas and Electric Cooktops

Particle number concentrations were also compared between groups of homes with characteristics that might contribute to differing particle levels, including cooktop fuel type, air exchange rate, presence of continuous mechanical ventilation and forced air versus radiant heat distribution. While outdoor particulate levels were not measured at each site, an effort was made to identify representative AQMIS monitoring sites with outdoor PM$_{2.5}$

data. Median and mean outdoor $PM_{2.5}$ mass concentrations were calculated for each project home during the time period of sampling. This effort was imperfect, especially due to variability in particle concentrations in a diverse urban environment, but they provide some support for the idea that outdoor particulate was not driving the observed differences highlighted below.

The median indoor particle number concentrations for homes with continuous mechanical ventilation and without are pictured in Figure 38 below. As a group, the homes with continuous mechanical ventilation had significantly lower median $PN_{>0.5}$ levels (Wilcoxon Ranked Sums, W = 111.5, p-value = 0.004324) (mean, Wilcoxon Ranked Sums, W = 93.5, p-value = 0.0824) and nearly significantly lower median $PN_{>2.5}$ levels (W = 80, p-value = 0.08428) (mean, W = 77.5, p-value = 0.1212). Median outdoor $PM_{2.5}$ levels at these homes were similar (None: 6 μg/m^3; Continuous Mechanical Ventilation: 5 μg/m^3). It is notable that 12 of 13 mechanically ventilated homes in this research were either HRV/ERV or CFIS systems, all of which provided some level of purposeful particulate filtration. It may be that the presence of filtration was the important determinant of median particle counts and not mechanical ventilation.

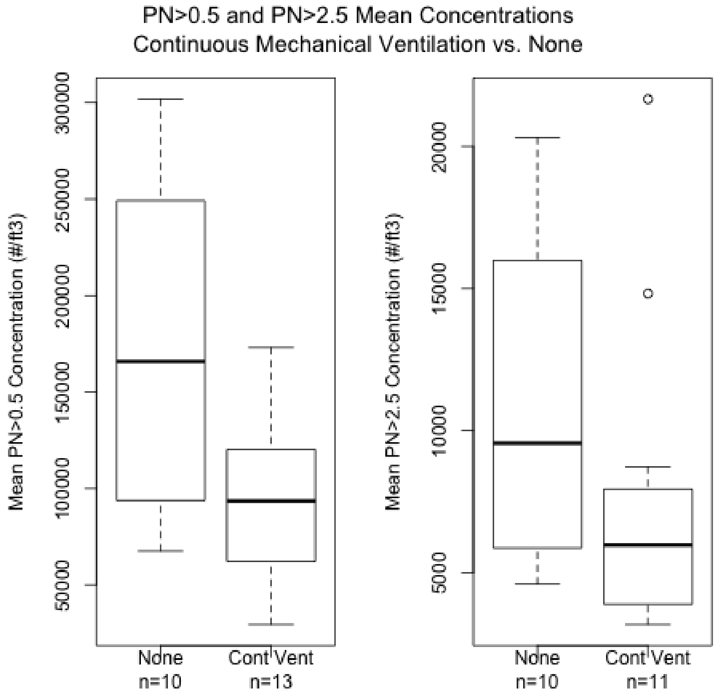

Figure 38 $PN_{>0.5}$ and $PN_{>2.5}$ Mean Concentrations, Continuous Mechanical Ventilation vs. None

A similar comparison was made between homes with and without forced air space conditioning systems (Figure 39), which included homes with and without mechanical ventilation. The homes without forced air conditioning used either hydronic radiant systems or point-source systems, such as gas fireplaces, and some had filtered HRV/ERV. Forced air homes included nine traditional forced air furnaces/heat pumps, as well as two systems that used HRV supply air to distribute heat. Significantly lower particle number concentrations were observed in forced air homes ($PN_{>0.5}$: W = 33, p-value = 0.04537, and $PN_{>2.5}$: W = 26, p-value = 0.05051) (mean, $PN_{>0.5}$: W = 39.5, p-value = 0.1095, and $PN_{>2.5}$: W = 20.5, p-value = 0.01898). In this case, homes with forced air systems had slightly elevated outdoor median $PM_{2.5}$ concentrations (Forced Air: 6 μg/m^3 versus Other: 5 μg/m^3). Once again, the difference between these groups could be due to filtration occurring in forced air cabinets.

An effort was made to further divide these ventilation and forced air systems into three groups—traditional forced air systems, ventilation-only systems and other. These groups are illustrated in Figure 40 below. Given that filtration was the most likely contributor to the reduced particle levels seen above, it would be expected that traditional forced air systems, with their higher airflows and potentially higher MERV ratings, would outperform ventilation only systems, which would in turn outperform systems lacking any filtration. This pattern was observed in the data. Outdoor $PM_{2.5}$ median mass concentrations in these groups were similar but somewhat variable (Full forced air: 5 μg/m^3; Ventilation Only: 5.75 μg/m^3; and None: 7 μg/m^3). Finally, those homes providing any air filtration were grouped and compared with those homes providing no filtration (Figure 41). Once again, filtered homes had significantly lower particle number concentrations, with median reductions in $PN_{>0.5}$ and $PN_{>2.5}$ of 48% and 57%, respectively. Outdoor median concentrations were very similar, with 6 μg/m^3 and 5.5 μg/m^3 in non-filtered and filtered homes.

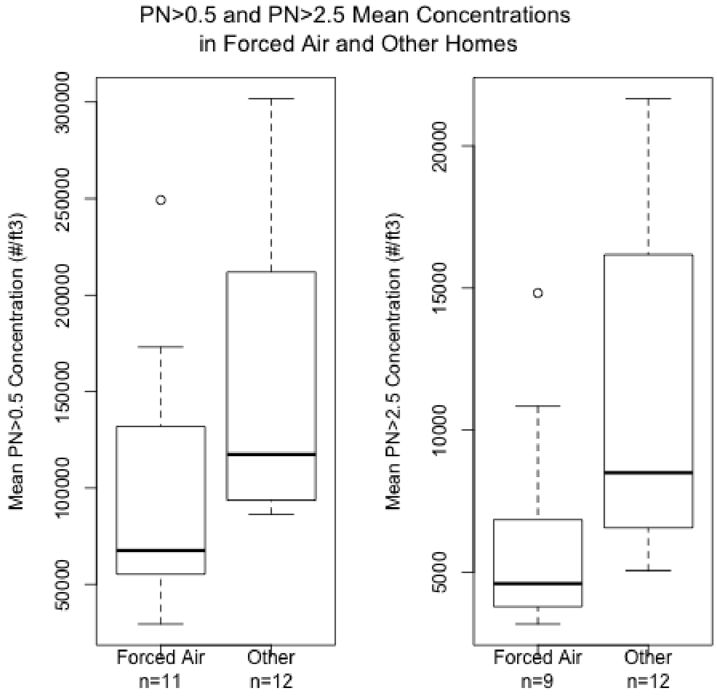

Figure 39 $PN_{>0.5}$ and $PN_{>2.5}$ Mean Concentrations, Forced Air and Other Space Conditioning System Type Homes

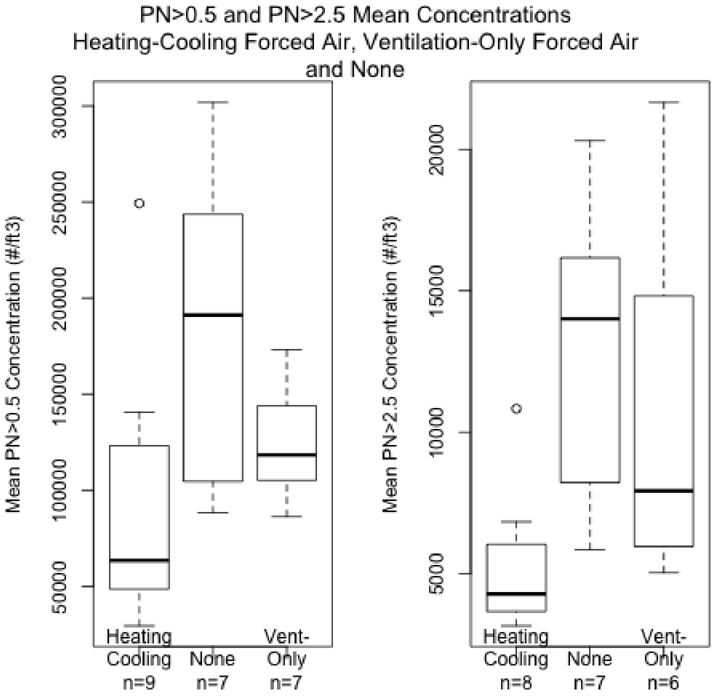

Figure 40 $PN_{>0.5}$ and $PN_{>2.5}$ Mean Concentrations, Traditional Forced Air, Ventilation Only and No Filtration Homes

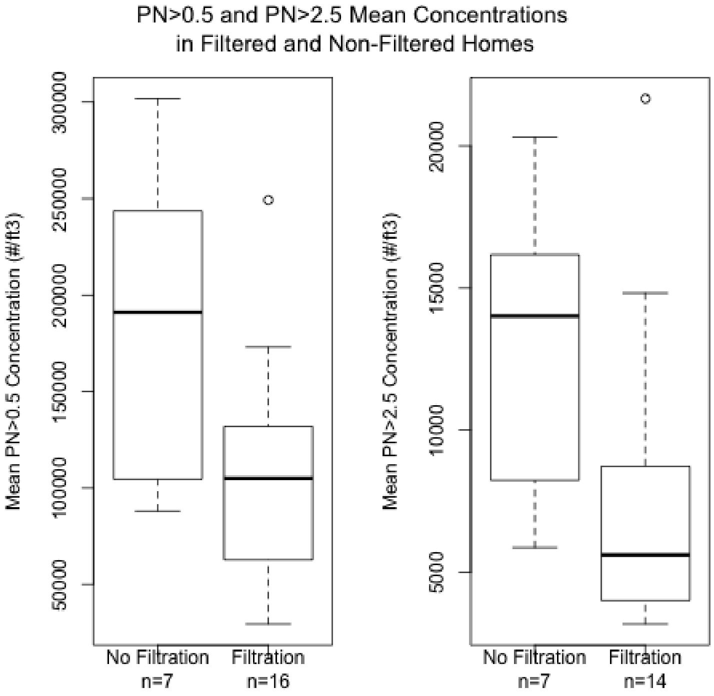

Figure 41 $PN_{>0.5}$ and $PN_{>2.5}$ Mean Concentrations, Filtered and Non-Filtered Homes

Discussion

1.17 Particles

Particle pollution levels in high performance green homes deserve significant consideration, because these homes could be very well suited to providing indoor environments with very low particle pollution, yet a trend was observed to the contrary. $PM_{2.5}$ has been identified as the dominant contributor to DALYs lost in the U.S. from chronic indoor air pollutant exposures (J. M. Logue et al., 2012). So, in terms of health risks, controlling indoor PM is more important than either formaldehyde or nitrogen dioxide, whose annual DALY impacts were estimated to be approximately one and three orders of magnitude less than $PM_{2.5}$, respectively. At the same time, indoor particle levels can be controlled through the use of common engineering technologies—furnace and ventilation filters, as well as kitchen range hoods—and through air exchange rates reduced to meet minimum requirements for other pollutants, such as odor and moisture. This latter element is consistent with energy reduction objectives. Nevertheless, a trend was observed in the 24 homes in this research towards elimination of forced air systems (and their filters), which led to higher average levels of $PN_{>0.5}$ and $PN_{>2.5}$ in unfiltered homes, compared with homes using either furnace filters or filtered ventilation air.

Substantially lower median $PN_{>0.5}$ and $PN_{>2.5}$ levels were documented in the kitchens of those homes that used either forced air heating and cooling or mechanical ventilation systems[26], as opposed to no-filtration homes. As discussed in the literature review, field measurements and simulation efforts have shown that particle filtration can be effective at lowering indoor particle concentrations, with efficacy varying with filter efficiency, airflow rate through the filter and occupant activity levels (Rodes et al., 2001; Janssen, Schwartz, Zanobetti, & Suh, 2002; Burroughs & Kinzer, 1998; Macintosh et al., 2009; Fugler, Bowser, & Kwan, 2000; Fisk, Faulkner, Palonen, & Seppanen, 2002; and Fugler, 2003). Accordingly, in this research, the lowest particle number concentrations were measured in homes with full forced air systems, in which airflows and filter efficiencies were highest. Mechanically vented homes had median levels between the full-forced air and no-filtration homes. Exhaust-only vented homes have been shown to provide particle removal by the building envelope at rates of 0.37 to 0.43, depending on particle size (Fugler, 2003). Presumably naturally vented homes would enjoy the same benefit. Yet, the elevated particle levels measured in no-filtration homes suggest that enhanced filtration beyond the levels cited by Fugler was provided in the full-forced air and mechanically vented homes in this research. Potentially, the majority of air exchange in naturally vented, non-filtered homes occurred through open windows and doors, which would limit any filtration provided by the envelope. Window and door operation would limit the particle filtration benefit in all three scenarios.

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[26] Only one of 13 mechanically vented homes lacked mechanical particle filtration. These homes used either a filter in the HRV/ERV or a furnace filter coupled with a CFIS system. Exhaust-only ventilation systems may also provide some level of filtration by the building envelope, as discussed above.

Despite this support for the value of filtration in the literature, it is not possible to differentiate between particle removal by filtration and particle distribution by mixing in this research, at least for those particles produced by cooking activities. The indoor particle measurements were made in the kitchen, which is not necessarily representative of concentrations elsewhere in the homes, because cooking is potentially a large source of particles[27]. Homes using full-forced air systems will usually have substantially higher rates of internal mixing, which would tend to redistribute particles from their source in the kitchen throughout the rest of the home. This could make particle levels in the kitchen lower, while elevating particle levels everywhere else. Whereas homes with less mixing would maintain higher particle count concentrations in the kitchen, with mixing proceeding much more slowly, and lower levels elsewhere in the home. How this impacts the home occupants depends on where they are in the home; mixing benefits those in the room with the pollutant source and harms those who are elsewhere. These mixing effects are potentially operating alongside filtration effects. Only one project home reported having a kitchen that was a separate room that could be closed off by a door, and three more reported the kitchen being "mostly" open to the rest of the home. The 20 remaining homes were characterized as "very" open. These characteristics would tend to lead to more even mixing, even by natural means, between the kitchen and rest of the home. It is likely that forced air systems are providing particle filtration, even if they are doing so while also providing increased internal mixing; this combination could have led to lower particle levels measured in the kitchen without providing reduced exposure to the occupants elsewhere in the home. Further research is required to isolate the impacts of filtration from enhanced mixing in forced air homes.

It is becoming common in high performance homes to use hydronic/radiant-heating systems without forced air[28]. This trend is clear in this research, with 11 of 24 homes using radiant heat. The reasons for this shift to hydronic radiant systems include the perception in the building industry that: (1) ductwork is a liability that takes up space, leaks energy and make noise, (2) using water to distribute heat requires less energy than air, due to reduced pumping energy, (3) hydronic systems allow for more zoning control, (4) installation of plumbing pipe is less obtrusive than forced air ducting, particularly in retrofit, (5) forced air systems currently on the market are dramatically over-sized for low-load homes, (6) large surface area radiant surfaces (floors, walls, ceilings) can operate at low temperatures, and (7) radiant heating is more compatible with combined heating and hot water systems (Siegenthaler, 2012). Furthermore, eight of the project homes that used hydronic/radiant systems did not include continuous mechanical ventilation, which could have been designed to provide some filtration. Unfortunately, these trends leave such homes without particle filtration.

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[27] If no particles were generated during cooking, then particle levels in the kitchen would be expected to be the same as elsewhere in the home.

[28] A trend was noted in this research towards the use of hydronic/radiant comfort systems in homes that did not provide mechanical ventilation and therefore no designed particle filtration. There is nothing particular about radiant hydronic systems that caused this issue, other than their lack of fans and ducts. The same problems would apply to a home heated by any non-ducted technology, if a filtered ventilation system were not also installed.

Clearly, there are sometimes good energy efficiency and design justifications for the elimination of forced air systems in high performance green homes. Yet, project homes in this research that did so had substantially higher indoor particle levels, which could pose a significant health risk. This risk can be reduced by providing alternative filtration in one of two ways: (1) a filtered supply air ventilation system or (2) a stand-alone room air-filter. Findings reported in section 1.16.8 suggest that the first method can be effective at reducing indoor particle concentrations, though less so than full forced air systems. Those relying upon ventilation supply filtration might consider improved filter efficiencies to target removal of submicron particles (MERV 14 rating requires that filter 75-85% removal of 0.3-1.0 micron particles). The efficacy of stand-alone filters was not assessed in this research, but they have been reported on extensively in the literature. Ward et al. (2005) modeled the efficacy of using a stand-alone HEPA air filter to facilitate "shelter in place" during acts of bioterrorism. Steady-state 0.2 to 2 micron particle concentrations in the modeled residence were reduced 50% using one device and more than 90% with three devices. Particle removal efficiency was highest in homes with low air exchange rates (Ward, Siegel, & Corsi, 2005). Fugler et al. 2000 measured the performance of a single HEPA stand-alone filter, and found that it reduced particle levels of PM_1, PM_4 and PM_{10} by around 50% in its room of operation (Fugler et al., 2000). Another investigation of stand-alone HEPA, electrostatic precipitators and ion generating air cleaners revealed that first two were able to reduce by 40-60% particle levels (>50nanometers) in a 392 m^3 residence. A word of caution is advisable, as some room air cleaners that generate ozone—such as ion generators and electrostatic precipitators—may actually create more indoor air pollution than they remove, as ozone initiates reactions with certain unsaturated organic compounds that produce ultrafine and fine particles, carbonyls, other oxidized products, and free radicals (Waring, Siegel, & Corsi, 2008). Homes without forced air can sufficiently remove particles, if appropriate technologies are employed consistently and are accepted by the homeowners.

It is also notable that heating and cooling loads are designed to be lower in high performance homes, and that in relatively mild climates, mechanical cooling may be eliminated entirely. This combination of no mechanical cooling and reduced heating loads, and therefore furnace operation, may leave forced air homes unfiltered for large portions of the year. This study sampled homes during the coldest months of the year, when forced air systems were likely operating at their maximum frequency and duration, providing the most filtration benefit. If these same measurements were made during shoulder seasons or the summer, it is possible that no distinction would have been revealed between forced air homes and those lacking filtration. When air handlers do no operate, these homes become effectively unfiltered. This same issue presents itself with CFIS ventilation systems, which must be programmed to operate on a schedule, in order to provide fresh air during periods with no furnace operation. All homes using CFIS ventilation systems in this research used timers and controllers to provide minimum periods of ventilation and therefore filtration, but not a single home with traditional forced air (no CFIS) used such an operational schedule. In forced air project homes without CFIS, a particle filtration solution would be to add timed operation, or if a variable speed blower is present, it can be continually operated on very low speed, which would achieve the same end. .

Particle pollution is potentially the most costly non-organic indoor air pollutant in terms of human health, and it can be successfully controlled using technologies already common in high performance homes. Yet, a subset of homes studied in this research were found to have elevated indoor particle levels, relative to their peers. These homes provided no particle filtration, whereas others did so through a filtered forced air system, ventilation system or both. This no-filtration practice should be avoided, in favor of ventilation supply air filtration or stand-alone filtration, if full forced air is not desirable or practical. Those homes that provided filtration by full forced air system without CFIS were well-filtered, but potentially only during the coldest months. Such homes must ensure that filtration is provided during non-load time periods through either timed or low-level continuous operation, as is currently recommended for CFIS systems.

1.18 Formaldehyde

Formaldehyde concentrations measured in these high performance green homes are significantly lower than levels measured in other new Californian homes. A 2009 study of 105 new (1.7-5.5 years) Californian homes found a median 24-hour formaldehyde concentration of 36 $\mu g/m^3$. This is nearly double the bedroom and kitchen median concentrations of 17.5 and 20.1 $\mu g/m^3$ measured in these high performance green homes. In both studies, nearly all homes had formaldehyde levels above the CREL of 9 $\mu g/m^3$, but not a single high performance green home exceeded the acute REL of 55 $\mu g/m^3$, whereas 28% of homes did exceed it in Offermann (2009). The maximum concentration measured in these 24 high performance green homes just barely exceeded the median value reported in Offermann (2009). Only 25% of the homes in the 2009 study used mechanical ventilation, and very little window operation was reported to increase natural air exchange. The summary results of that study are reproduced in Table 37. The most likely explanation for this difference in formaldehyde levels is source control. Designers, builders and occupants of the homes in this research study actively engaged in limiting formaldehyde-emitting materials. 10 of the homes are certified green homes, which receive credits for use of healthy and low-emitting materials, and 22 of 24 owners reported that using healthy building materials was an explicit goal in their home's design and construction. Clearly, source control is working in these homes to reduce the otherwise elevated pollutant levels in standard construction new CA homes[29]. At the same time, the presence of new materials project homes was a statistically significant determinant of formaldehyde levels, along with indoor relative humidity and home age. Notably, this model only explained 34% of the variability in indoor concentrations.

24-Hour Formaldehyde Concentration ($\mu g/m^3$)			n
Minimum	Median	Maximum	
4.8	36	136	105

Table 37 24-Hour Average Formaldehyde Concentrations Summary in New CA Homes, source Offermann 2009, pg.6

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[29] This appears to be the case whether or not it is engaged in as part of a green building certification. Those pursuing source control on their own terms seem to have had reasonable success.

Formaldehyde levels measured in high performance green Californian homes were more similar to those measured in existing residences than to those in new homes. For example, a 1996 study of air pollutants in 126 Southern Californian homes of all ages found a 24-hour median indoor formaldehyde concentration of 10.1 μg/m^3, with an interquartile range of 6.5 to 15.2 μg/m^3 (Avol et al., 1996). In addition to not being new homes, those houses sampled in Avol et al. (1996) likely had much higher air exchange rates than in the present research, which helps to explain the very low median concentration measured.

The median acetaldehyde values in the kitchen and bedrooms of the high performance green project homes (16.1 and 16.2 μg/m^3, respectively) are just slightly less than the median values measured in Offermann (2009) of 20 μg/m^3. Significant maximum concentration outliers existed in both studies, with a maximum of 58.0 μg/m^3 in high performance green homes and 102 μg/m^3 in CA new homes. It appears that levels are similar between these groups.

1.19 Nitrogen Dioxide

Median and average kitchen concentrations of NO_2 in this research were 8.7 and 13.6 ppb, respectively. Outdoor median and average NO_2 concentrations were 7.6and 9.8 ppb, respectively. NO_2 concentrations in high performance green homes with gas and electric appliances are compared with those found elsewhere in the literature in Table 38. Offermann (2009), the most recent study of IAQ in new CA homes, only sampled NO_2 in 29 homes, and 98% of all 105 homes in the study used electric cooking appliances. Levels were similar to those measured in electric appliance high performance CA homes. The other three studies cited all reported higher indoor and outdoor levels of NO_2 than were sampled in high performance homes with either gas or electric cooking appliances. Spengler et al. (1994) reported that gas stoves with pilot lights contributed, on average, 10 ppb to indoor concentrations, while gas stoves without a pilot contributed, on average, 4 ppb. The lower levels sampled in high performance homes are most likely due to a combination of lower outdoor concentrations, reduced air exchange rates, no smoking, newer gas cooking appliances with lower pollutant emission rates and enhanced kitchen ventilation in high performance homes.

Indoor and Outdoor NO_2 Concentrations from the Literature and Present Research						
Source	**n**	**Indoor Mean (ppb)**	**Indoor Median (ppb)**	**Outdoor Mean (ppb)**	**Outdoor Median (ppb)**	**Sample Duration (days)**
Lee et al., 2002	119	28		20		6
Spengler et al., 1994	482	x	25	x	35	2
Wilson, Colome, & Tian, 1993	293	25	x	23	x	X
Offermann, 2009	29		3.3		1.8	1
Gas cooking high performance green homes	15	17.9	13.1	9.4	7.3	6
Electric cooking high performance green homes	9	6.6	5.4	10.5	10.1	6

Table 38 Indoor and Outdoor NO_2 Concentrations (ppb) from the Literature and the Present Research

Within high performance green homes, NO_2 levels were notably higher in gas appliance homes, even when outdoor concentrations were controlled for. Unfortunately, the presence of kitchen range hood exhausts and other kitchen ventilation equipment (exhaust fan in ceiling, for example) did not adequately reduce average NO_2 indoor levels in gas cooking homes to those in electric appliance homes, which were 59% lower[30]. This result is not necessarily surprising, given the performance of installed range hoods that is highlighted in the literature review section on kitchen ventilation. Even more important than questionable exhaust hood performance was the limited use of kitchen range hoods by occupants—11 of 24 occupants reported using their range hood "infrequently". Levels of reported range hood usage were similar in gas and electric homes. Gas cooking appliances appear to remain a liability in terms of NO_2, even in high performance green homes with kitchen exhaust fans, due to infrequent usage and the likelihood that the installed hoods have poor capture efficiencies[31].

Three homes still exceeded the California annual standard, with a fourth one very close to exceeding it. It appears that these cases can be at least partially explained from the data gathered from surveys and home inspections. Two of the homes contained historic gas ranges (0801 and 1302), with potentially higher NO_2 emission rates than newer models, due to pilot lights and burner tuning. In addition to using an historic range, project 1302 reported the highest levels of cooktop and oven usage of all 24 homes (occupant estimated 35 usages). The two other homes were Passive Houses, which elected to not use a kitchen range hood exhausted to outside, despite their gas cooktops. It would appear that when obvious mistakes are not made—use of high-emitting historic appliances or failure to exhaust pollutants—indoor NO_2 levels can be maintained below 20 ppb in high performance green homes.

1.20 Carbon Monoxide

Results of carbon monoxide measurements were encouraging, with generally very low levels throughout the measurement week in all homes. The high performance green homes in this research very rarely used naturally drafted combustion appliances, such as low-efficiency space or water heaters. Only two homes used natural draft technology for either space or water heating (1301 and 1501), and both were outside the conditioned envelope of the building. With these potential sources of CO and other combustion pollutants outside the house, the only remaining indoor source of CO was either gas cooking or candle/incense usage. CO levels from these sources were kept quite low, with 23 of 24 homes having one-hour maximum CO concentrations less than 5 ppm. The one exception (project 0801), has been commented on elsewhere for its historic gas range, which clearly has some emission issues. This home never reached dangerous levels, with a one-hour

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[30] All homes had some form of kitchen exhaust, range hood, ERV/HRV or exhaust fan in ceiling. 15 homes used gas ranges, and their median NO_2 levels were 2.4 higher than in electric homes. I/O ratios were also 2.4 times higher in gas cooking homes. Furthermore, gas homes were the only ones to exceed ambient standards.

[31] The poor capture efficiency of installed range hoods is speculative, as capture efficiency was not measured in this research.

maximum of 14.8 ppm and eight-hour maximum of 5.8 ppm. These values are below the CalEPA eight-hour and one-hour standards of 9 and 20 ppm, respectively. Yet, the fact that concentrations were sampled at 65-75% of the standards suggests the likelihood that the standards are exceeded at some point during the year, during either periods with more cooking or lower air exchange.

1.21 Temperature and Relative Humidity

Human perception of indoor air quality has been shown to be strongly and significantly impacted by temperature and relative humidity levels (Fang, Clausen, & Fanger, 1998). Temperature levels inside project homes were not consistently within the acceptable comfort ranges stipulated in ASHRAE Standard 55-2010[32] (ANSI/ASHRAE, 2010b). Average weekly bedroom and kitchen temperatures were below acceptable levels (less than approximately 21.25 °C) in 13 of 24 homes and 16 of 24 homes, respectively. No homes maintained interior weekly average temperatures above the range specified in Standard 55. Standard 55 does not specify acceptable ranges of indoor relative humidity for thermal comfort reasons, but other sources provide guidance on acceptable ranges of relative humidity, for the purpose of controlling its impacts on IAQ and occupant health. Extensive reviews of indoor relative humidity and its human health effects are provided in Arundel et al. (1986) and Arens and Baughman (1996), and indoor relative humidity is recommended to be maintained between 30 and 60% (Arundel et al., 1986; Baughman & Arens, 1996). This range represents the consensus that there is a sweet spot where most negative effects of low or high indoor relative humidity are limited. The effects are estimated to grow more severe as levels decrease below or increase above the 30 to 60% range. The durability and health issues that this range is intended to avoid include growth of bacteria, fungus, viruses and mites, as well as respiratory infections, allergies, asthma, chemical interactions and ozone production. The indoor RH in the project homes closely mirrored this recommended range, with minimum RH just above 30% and maximum indoor RH just barely above 60%. Average RH was 47% in both bedrooms and kitchens. No homes had indoor RH in ranges expected to negatively impact occupant health or building durability. Yet, during occupant surveys, 2 of 24 homes reported having some musty or moldy odors in the previous year, and 6 of 24 reported some signs of dampness or moisture during the previous year. No such signs or odors were detected during home inspection by the research team. Reported signs of moisture or mold in housing have been associated with a 30-50% increase in a variety of respiratory and asthma-related health outcomes (Fisk, Lei-Gomez, & Mendell, 2007). While lower indoor temperatures were associated with higher indoor RH, none of the weekly average RH reached troubling levels. Temperature was therefore a matter of comfort and personal preference, presumably under direct control of the occupants.

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[32] It is notable that Standard 55 specifies operative temperature ranges, not dry-bulb temperature ranges. The standard allows for use of dry-bulb temperatures in place of operative temperature if certain criteria are met. Simple dry-bulb temperature was used to make the assessments above.

1.22 Air Exchange Rate

While AER measurement issues were encountered in 8 of 24 homes, 16 valid AER were measured using a passive tracer gas technique. Median and mean AER in the 16 homes were 0.3 and 0.34, respectively, with a range of 0.14 to 0.8. These values are compared in Table 39 with other AER measured in CA from the literature. Offermann (2009) reported that 67% percent of homes had an AER below the 2001 California Building Code requirement of 0.35 ACH (California Building Code, 2001). 62.5% of high performance green project homes were also below this minimum level. Murray & Burmaster (1995) have estimated seasonal AER in the winter in CA using tracer gas data from the literature, and their estimate is very similar to values measured by Yamamoto et al. (2010). On average, new CA homes, both conventional and high performance green, are delivering air exchange at approximately half the rate measured in the older, existing housing stock. This is not surprising, due to changes in construction materials and methods, as well as serious efforts to specifically reduce air exchange for increased efficiency.

Comparison of Air Exchange Rates from this Research and the Literature

Source	n	Median AER	Mean AER	Duration (days)
High Performance Green Homes	16	0.3	0.34	6
Offermann (2009)	106	0.26	x	1
Murray & Burmaster (1995) (CA Winter Estimate)	x	x	0.63	X
Yamamoto et al., 2010 (CA Winter Measured)	105	x	0.61	2

Table 39 Comparison of Air Exchange Rates from this Research and the Literature

No statistically significant relationship was found between AER and either formaldehyde or acetaldehyde concentrations in high performance green homes. This is consistent with the arguments of DuPont & Morrill (1989), who suggested that pollutant sources within homes were the primary drivers of indoor concentrations and that AER played only a secondary role. But AER was a significant predictor of indoor NO_2 levels, along with the outdoor concentration and cooktop fuel type. This is likely due to the variability in outdoor NO_2 concentrations, which are quite inconsistent in comparison to outdoor formaldehyde or acetaldehyde, which tend to be low across the board. Notably, no statistically significant relationship was found between the levels of most pollutants[33] and the provision of continuous mechanical ventilation. The reason for this is most likely that naturally and mechanically vented homes had similar AERs, which may be explainable by the fact that naturally vented homes were less airtight.

Given the overall acceptable levels of pollutants measured in this research, it appears that high performance green homes can maintain acceptable IAQ at these levels of whole house air exchange, provided that source control and local exhaust are provided in kitchens and

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[33] The sole exception was particulate, which as discussed above was hypothesized to be lower in mechanically vented homes due to the presence of particle filtration in 12 of 13 homes.

bathrooms. Increased AER in homes can both increase and decrease pollutant levels, because air exchange dilutes indoor generated pollutants, but increases levels of outdoor pollutants. Given this trade-off, it is not straightforward to say that higher AER would automatically be desirable.

Some level of inconsistency in tracer gas concentrations was observed between the four indoor locations in nearly all homes, with min-to-mean relative errors ranging from 1.9 - 33.0%, and mean-to-max relative errors of 1.1 - 50.2%. The precision of these and other single-point air exchange rate measurements by passive tracer gas are called into question by the variability in these results., For example, Yamamoto et al. (2010) used a single, centrally located passive sampler and four passive tracer gas emitters to measure AER. The benefit of only measuring the tracer gas in a single location is that the single value measured is assumed to be correct, whereas it would appear that it might be 14.8% low or 21.5% high (average relative errors min-to-mean and mean-to-max found in this research). Average errors are slightly less when the bedroom samplers are removed from the present research, approximately ±10%. Sherman (1988) provides a theoretical exploration of the uncertainties in tracer gas airflow measurements. He suggests that an integrated tracer gas measurement will have greater uncertainty than a time-resolved measurement. He identifies mixing and the adequacy of a simple zonal air network model as the primary drivers of bias. Using a sample dataset from the literature, he reported an uncertainty of 8% for the passive PFT method; this is slightly less than the ±10% value reported here (M. Sherman, 1988). In their in-depth reporting on the BNL/AIMS passive tracer gas technique, Dietz et al. (1986) report on the uniformity of tracer gas concentrations in a 2-story test home. They concluded that open and spacious zones have good consistency between samplers (±2.6%), whereas more compartmentalized zones have ±10% consistency between samplers. Closed doors were noted as causing further inconsistency (Dietz et al., 1986). Substantial errors are possible in any such study of AER, as homes are not likely to be any more consistently mixed over multiple day periods, unless all homes have operating forced-air systems. The variability between the four tracer gas sampling locations in the project homes is consistent with those reported elsewhere in the literature. This supports the conclusion that the measurements in this research are valid, or at least of comparable accuracy to those reported elsewhere in the literature.

The AER measured in high performance green homes is similar to that measured in new CA homes in 2006, both for mechanically and naturally vented residences. Results from both of these studies suggest that a substantial number of new, high performance homes are not achieving AER consistent with current standards. In the current research, this included homes that provided continuous mechanical ventilation. Mechanical ventilation is intended to create more consistent levels of ventilation, avoiding under-ventilated and over-ventilated homes. The AER of mechanically vented homes in this research varied from approximately 0.15 to 0.5, with median AER statistically indistinguishable from naturally vented homes. This may have resulted from malfunctioning ventilation equipment on the low AER end, and high AER could be explained by window operation. This range of AER may be acceptable in high performance green homes, provided that they pursue source control, use local exhaust in kitchens and bathrooms, and provide particle filtration. When these strategies are all employed and their performance is verified, AER can likely be lowered without adverse consequences, providing some energy benefit.

1.23 Ventilation Provision and Occupant Behavior

The provision of ventilation in high performance green CA homes and occupant ventilation behaviors are explored in the context of two research efforts on new CA homes. First, Price et al. (2007) surveyed 1,515 residents in CA homes built in 2003, asking questions about ventilation in their homes (Price et al., 2007). Second, Offermann (2009) measured air quality through pollutant sampling and occupant surveys in 108 new (1.4 – 4.7 years) CA homes built between 2002 and 2004 (Offermann, 2009).

1.23.1 Whole House Mechanical Ventilation

Mechanical ventilation was provided in 54% of the high performance green Californian homes in this study, whereas Offermann (2009) reports 24% of Californian homes with mechanical ventilation, and Price et al. (2007) report 52% of Californian homes to have whole house mechanical ventilation systems. Price et al. (2007) suggest that homeowners probably did not understand the survey question, as authors believed rates of mechanical ventilation provision to be much lower. In a subset of 67 homes where Price et al. (2007) confirmed presence of mechanical ventilation, only 21% of occupants reported that it operated continuously during winter. Rates were even lower in other seasons. The rate of 54% in high performance green homes in this study is only for those systems that operate continuously year-round, suggesting the mechanical ventilation behavior is more consistent in high performance green homes. It may be that the homeowners in this research are more aware of their ventilation systems and more likely to use them as directed, as a result of their investments in efficient and sustainable housing. Nevertheless, mechanical ventilation saturation was still just barely above half, whereas it was hoped that nearly all high performance green homes would provide continuous mechanical venting. As discussed elsewhere, this is mostly due to the increased airtightness measured in mechanically vented homes.

Offermann (2009) reported substantial performance issues with CFIS systems, due to insufficient outside airflow and lack of provision for scheduled operation. They also reported better performance from HRV/ERV systems, due to their continuous operation. Different ventilation performance issues were noted in this research. All CFIS systems observed in high performance green homes used controllers for regularly scheduled operation. Their airflows could not be determined. HRV/ERV, on the other hand, presented an array of installed performance issues discussed in section 1.14.3.1.1 above, including low airflow, erratic operation, installation faults and equipment failure.

Those ERV/HRV that were used to provide bathroom and kitchen exhaust, in addition to whole house ventilation, were generally designed and installed in a manner that is inconsistent with scientific and engineering knowledge of IAQ and ventilation. The ability of these systems to conserve energy is laudable, yet they provide spot ventilation ineffectively. For those units that are programmed to operate on high speed during high humidity events in a bathroom, the whole house ventilation rate is doubled or tripled, rather than doubling or tripling the rate of just the wet room. This most likely leads to increased space conditioning and ventilation fan energy use. Furthermore, the pollutant removal efficiency is very low compared with an exhaust fan whose entire airflow exhausts from the bathroom. The situation is even worse in the kitchen, where pollutants emitted can be substantially more harmful than water vapor. Unlike bathrooms, which usually have a closed door during a high humidity event (concentrating and limiting dispersion of water vapor and allowing efficient removal by exhaust fan), the kitchens in most of the project homes were entirely open to the rest of the house, without any door available. The effectiveness of the whole house ventilation to remove cooking pollutants is low due to high rates of pollutant dispersal and the low air exchange rates provided (approximately 0.35). In addition, none of the homes observed had a controller in the kitchen that automatically increased the ERV/HRV speed during cooking, as they did during showers.

The fully ducted HRV in project 1601 provides a partial alternative to these system types. It provides whole house and bathroom ventilation, but it is not used to exhaust the kitchen. The home is an exceptionally airtight Passive House ($ACH_{50}<0.6$), yet a fully functional kitchen range hood is provided. Make-up air is required, in order to not overly depressurize the house[34]. This make-up air is provided using a motorized damper in an outside air duct that provides outside air at the toe kick in front of the range. This system passed Passive House airtightness requirements, but it did not sacrifice IAQ in a home with gas range.

The provision of mechanical ventilation in Passive Houses is troubling, because of the kitchen and bathroom ventilation issues noted above, but it also should be noted that these homes go above and beyond ASHRAE 62.2-2010 or Title 24 2008 code requirements in terms of continuous ventilation. If designed using the current Fan Rate Method in Standard 62.2, these homes would be substantially under-ventilated, due to their extreme airtightness and lack of infiltration. The standard assumes a 0.02 cfm per square foot of floor area infiltration credit, but very airtight homes will not have such high levels of infiltration (approximately 0.17 ACH, depending on the floor area-to-volume ratio). Passive House program requirements avoid this pitfall by requiring a continuous 0.3 ACH in mechanical venting, which is commendable. Fortunately, ASHRAE Standard 62.2-2010 Addendum N now includes a new calculation procedure—the Total Ventilation Rate Method—that removes the 0.02 infiltration credit, and instead requires a higher mechanical airflow (approximately double the current requirement), which can be reduced if a home is tested and found to be leakier than assumed[35]. Unfortunately, Addendum N will not automatically be adopted by the organizations that reference Standard 62.2 in their program requirements, such as Title 24, LEED, Indoor airPLUS, etc. So, this protection

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[34] The airflow of the range hood is far greater than the blower door airflow required to achieve a 50 Pascal pressure difference across the envelope (324 cfm in this case).

[35] The current Fan Rate Method allows the mechanical airflow requirement to be reduced if a blower door test demonstrates that the building is leakier than assumed in the Standard. No adjustment exists in the Fan Rate Method that increases the mechanical airflow requirement if a home is tested using a blower door and is found to be much tighter than assumed in the Standard.

against under-ventilation in very airtight homes may not reach practitioners for a long time.

ASHRAE 62.2, as it is currently enforced in CA Title 24, also does not apply to Deep Energy Retrofits that add less than 1,000 ft^2 floor area. This oversight places all responsibility for ventilation provision on the heads of the designer or contractor. Unfortunately, Deep Energy Retrofits were the least likely of any project home classification to provide continuous mechanical ventilation, with only six of twelve providing it. Three of these six were also Passive House style homes, so only three of nine, non-Passive House Deep Retrofits provided continuous mechanical venting. This rate of 33% is far too low, and it reflects the current lack of code application to Deep Retrofits. In contrast, 66% of zero-net energy homes, 100% of Passive House style homes and 60% of green homes provided continuous mechanical venting. While the low rate in Deep Retrofits is particularly troubling, the inconsistency in zero-net energy and green homes also suggests a general lack of knowledge concerning IAQ and ventilation amongst practitioners in the field.

Continuous mechanical ventilation was provided inconsistently in these high performance green homes, particularly in Deep Retrofit homes. Those homes that provided mechanical venting 100% of the time used ventilation system designs that may be less effective than standard practice for removing pollutants from bathrooms and kitchens. This was reflected in the higher NO_2 concentrations in gas cooking Passive House kitchens. Nevertheless, these high performance green homes did provide continuous mechanical venting much more frequently than previously reported in the literature for new CA homes, suggesting that some progress has been made in getting practitioners to accept the necessity of ventilation in low energy homes. Only one project home installed a continuously operating simple exhaust fan, which has previously been reported as the dominant mechanical ventilation system in the US (Sherman, 2008). The performance and reliability of these more complex ventilation systems was troubling, as numerous faults contributing to poor performance were identified during system measurement. This suggests that even in high performance homes, further commissioning and verification efforts are required.

1.23.2 Bathroom Ventilation

Bathroom exhaust fans (stand alone or integrated with HRV/ERV) were provided in 23 of 24 project homes. Only 9% of homes in Price et al. (2007) reported no bathroom exhaust fan. 27% of those surveyed reported always using the exhaust fan during bathing, 16% used it frequently, 19% sometimes and 13% never. Offermann (2009) found lower rates of usage, with 47% of homes showing no usage of bathroom exhaust during the 24-hour test period, and 27% showing no usage in the previous week. In high performance green project homes, 46% of occupants reported always using bathroom exhaust, including those that operated continuously. 17% reported infrequent or no usage. Those reporting no usage are similar between survey samples, but the actual usage rates reported by Offermann (2009) were much lower than the surveys suggested. Appreciably more occupants in high performance green homes always used bathroom exhaust, and it seems that fewer occupants in high performance homes never or rarely used bathroom exhaust.

The rates of no bathroom exhaust fan use reported by Price et al. (2007) were double those reported in the present research. In general, bathroom exhausts were provided and used across the sample of high performance green homes, both new and retrofitted.

1.23.3 Kitchen Ventilation

Price et al. (2007) report only 3% of homes that had either no kitchen exhaust fan or did not know. Rates of range hood installation were 80%, with 13% being recirculating units. It is unclear how occupants were expected to know if their appliance vented to outside, which could call these data into question. The usage of kitchen exhausts was not reported. Klug et al. (2011) report a survey focused on CA homes; the reported rate of kitchen range hood usage was 34% (Klug et al., 2011). Offermann (2009) reports that 78% of homes had 0 hours of actual kitchen exhaust usage during the 24-hour test day, but whether or not cooking actually occurred was not reported. 71% of occupants in high performance green homes reported kitchen ventilation exhausted to outside, and 29% used either recirculating range hoods or no kitchen ventilation. 42% of occupants in high performance green homes reported infrequent usage of kitchen exhaust, but another 38% reported using kitchen exhaust at least half of the time. This is generally consistent with the previous findings that kitchen exhaust is used infrequently, but a substantially larger proportion of occupants in high performance green homes reported using their systems regularly. Despite this improved usage over conventional CA homes, kitchen exhaust usage is still much too low, given the contribution of cooking to indoor pollutants. Due to the human element involved and the apparent resistance to range hood usage, innovations should be considered for these systems that make them quieter and that automate operation, as is being explored in demand-controlled commercial kitchen venting (Bohlig & Fisher, 2004).

1.23.4 Windows

In homes that are not mechanically ventilated, operation of windows by occupants is relied upon to supplement natural infiltration. Prior to the 2008 version of CA Title 24, window operation was allowed to be the primary means of ventilation in Californian homes. This was changed with adoption of ASHRAE 62.2 into Title 24 2008, with the stipulation that windows were not an acceptable means of providing ventilation.

17% of project homes in this research reported no window operation whatsoever during the sampling week, and 54% reported that windows were usually closed all day during the time of year that the survey was administered (November 2011-April 2012). These values are consistent with those reported in the literature for occupants in new CA homes. In Offermann (2009), 32% of 108 homes reported no window usage during the 24-hour test period and 15% reported no window usage during the previous week. Price et al. (2007) present results on a major survey of CA residents in new homes, and 10% - 25% of occupants reported very few or no hours with windows open during any season. The results of Price et al. (2007) should be interpreted with hesitation, because occupants were asked to report on a whole year of window activity at one moment in time, which may not be as reliable as asking about a given week or the current season. Occupants in high performance green CA homes do not appear to use windows any more reliably for ventilation than do occupants in conventional homes, with significant minorities across all three studies that simply do not report any window operation during certain seasons.

1.24 General Discussion

In this sample of high performance green homes, it appears that acceptable IAQ is being provided across a wide variety of metrics and pollutants, including occupant perception, formaldehyde, NO_2, CO and particulate matter. Some pollutants, such as formaldehyde, were much lower than those in otherwise comparable new CA homes, suggesting that source control[36] by occupants or through sustainability rating systems were effective. Fine particulate mater has been noted for its disproportionate health impacts, as well as its potential to be either very well controlled or forgotten about in high performance green homes.

A number of concerning trends have also emerged based on literature review combined with pollutant measurements and observations in the 24 project homes:

1. Ventilation system installation, commissioning and performance seem to be unreliable, which presents a potential liability, particularly in very airtight residences. Only one of thirteen mechanical ventilation systems was a simple exhaust fan. Simple ventilation systems are easy to measure and verify, and it is possible that they are more reliable. Though they could also be plagued by installation issues, such as crimped ducts, long duct runs, bad fan motors, etc.

2. Cooking needs to be recognized for its contribution to indoor pollutant exposures, both in gas and electric homes. Lack of occupant and designer knowledge can be inferred from: (1) low rates of exhaust fan usage, (2) the specification of kitchen range hoods that will likely have low capture efficiencies[37], and (3) the installation of recirculating range hoods and reliance on whole-house ventilation to remove cooking pollutants.

3. A trend towards hydronic radiant and other non-forced air heating systems has been noted. The opportunity for air filtration is being lost in this transition, unless other filtration means are provided through ventilation supply or in-room units.

4. The ventilation requirements of CA Title 24 2008 do not currently apply to deep energy retrofits, unless more than 1,000 ft^2 are added to the living area. This leaves the determination of ventilation provision entirely up to the designer, in a context of

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[36] Source control by occupants can apply to both building materials and ongoing purchases, such as furniture, cleaning supplies, clothing, etc. Source control should target a variety of indoor pollutants, not solely formaldehye.

[37] Installed range hoods were not rated for capture efficiency, but most units lacked design features recognized as superior—hood coverage of front burners, capture hood as opposed to flat bottom, vented to outside as opposed to recirculating, etc.

increased air tightness and newly emitting materials. It is notable that the Building Performance Institute recently adopted ASHRAE Standard 62.2 into its set of formal standards for home energy auditors (Building Performance Institute, Inc., 2012), as has the Weatherization Assistance Program (U.S. DOE, 2011b) and RESNET (Residential Energy Services Network, 2006). This offers hope that the energy retrofit industry will receive more ample training on ventilation requirements and will become more adept at selling these technologies to homeowners.

5. The ASHRAE Standard 62.2 Fan Rate Procedure does not stipulate appropriate outdoor airflow rates for very airtight homes. Mechanical airflows need to be increased due to the extremely low infiltration in very airtight homes, which is much less than assumed in the current 62.2 formula. Following the Addendum N Total Ventilation Rate procedure should address this issue in very airtight homes.

6. A number of new, very airtight homes did not comply with the kitchen and bathroom ventilation requirements of ASHRAE 62.2, which suggests that enforcement of this new code requirement is not consistent. While the need for continuous mechanical ventilation was recognized in these homes, the specific need for and value of supplementary spot ventilation was not understood.

7. Of the 24 high performance green homes studied, only 13 homes used a continuous mechanical ventilation system. This suggests that the energy design and retrofit industry does not sufficiently value or place emphasis on ventilation provision, which is largely an educational and code issue. Though it is worthwhile noting that mechanically vented homes were more airtight, suggesting that designers likely recognized the need to add mechanical ventilation once sufficient air sealing had occurred.

1.25 Recommendations

A variety of pollutants have been measured in homes with varying physical characteristics. The following recommendations were developed through a consideration of the results of this research in the context of the reviewed literature:

- Prioritize reduction of pollutant sources in building and consumer products.
- Use electric cooking appliances, preferably with induction cooktops for their lack of UFP emission.
- Install a kitchen range hood exhausted to outside that fully covers the front burner surfaces with a proper, non-flat capture hood, with a maximum airflow of at least 200 cfm (Delp & Singer, 2012). Range hoods also should be quiet, so that occupants are not discouraged from using them regularly. This is necessary with both gas and electric cooking appliances.
- Consider adding automatic controls to range hood, so that it operates during cooking without occupant intervention.

- Provide high efficiency particle filtration using a forced air system, filtered supply air ventilation or a stand-alone particle filter..
- Provide continuous mechanical ventilation at ASHRAE 62.2 levels using the Total Ventilation Rate procedure in Addendum N, which should ensure adequate mechanical airflow across a variety of levels of airtightness. Filter supply air wherever possible with MERV14 filtration.
- Carefully commission all ventilation equipment. Assume that more complex ventilation systems, such as fully ducted ERV/HRV, will require substantially more effort in order to achieve their desired performance.
- Use only sealed-combustion, direct vented natural gas appliances, and keep their exhausts far away from ventilation supply inlets (Building Science Corporation, 2009a).
- Use optional rating systems and checklists to ensure that all indoor environment issues are sufficiently addressed in design and construction, because the industry does not appear to be sufficiently well versed in the dynamics of IAQ in homes.

1.26 Opportunities for Future Research

Opportunities for further research in this field abound. Numerous ongoing projects were identified in the literature review, which are assessing health outcomes of moving occupants from stressed to green housing. One epidemiological assessment was identified that did not include stressed housing, and this is an obvious realm for further research. All homes studied were located in relatively mild, Northern California. Similar assessments of air pollutants and occupants surveys should be administered in other climate zones, particularly those with differing moisture and temperature regimes, as well as methods of construction. This research was a broad-based, observational effort, not a carefully controlled intervention study. High performance green homes were recruited as a sample of convenience, and they do not necessarily represent broader practice in the industry. The homes were diverse, in that there was a mix of deeply retrofitted homes and brand new homes that pursued a variety of paths to sustainability. The consistent outcomes of the R-2000 program in Canada suggest that having a homogenous sample is beneficial. Unfortunately, the sample in this study is similar to those U.S. studies that were criticized for small sample sizes and inconsistent definitions of high performance. Larger sample sizes should be assessed in the four categories recognized in this research: deep retrofits, zero-net energy, Passive House and green certified homes. The observations noted in this report should not be considered conclusive; rather they point the way to other efforts. Case controls would enhance the conclusions, as would more detailed assessments on issues such as: (1) pollutant response to varied air exchange rates, (2) the effectiveness of high efficiency air filtration at reducing particle pollution levels, both in forced air, ventilation systems and stand-alone appliances, particularly in very airtight homes with little natural air exchange, (3) the effectiveness of high quality kitchen exhaust systems that are quiet, properly sized/shaped, deliver sufficient airflow and operate automatically, without requiring occupant intervention, or provide simple occupant feedback that encourages consistent use (local particle counter with indication light), and (5) the effectiveness of occupant education on issues like exhaust fan usage, healthy/green cleaning, and purchasing of low-emitting furnishing and decoration.

Conclusion

Extensive measurements of indoor air quality have been completed in 24 high performance green California homes. The data included occupant surveys, field assessments and pollutant measurements. A variety of house types, construction techniques, ventilation strategies and fuel types were incorporated, so as to explore the effect of these variables on air pollutants levels.

The goals of this research were to: (1) identify and assess the ventilation, space conditioning and water heating strategies and equipment being used in a selected sample of high performance CA homes, (2) create a sizeable data set of air pollutant measurements and occupant activities in those homes, (3) assess the acceptability of the air quality being provided, and (4) identify successful strategies and important variables to provide design and policy recommendations on ventilation and IAQ in high performance green homes. Outcomes and conclusions are highlighted below.

1. Formaldehyde levels exceeded the OEHHA CREL (9 $\mu g/m^3$) in nearly all homes, but high performance homes had median concentrations half those found in conventional new CA homes.

2. 22 of 24 occupants reported that low-emitting materials were used in construction or renovation of their home, and most reported some ongoing use of healthy cleaning supplies. This source control seems to have contributed to lower formaldehyde levels.

3. Air exchange rates and most pollutant levels were not significantly different in naturally and mechanically ventilated homes. The sole exception was particulate, which was filtered in 12 of 13 mechanically vented homes, leading to lower levels.

4. Only 13 of 24 homes installed continuous mechanical ventilation, which likely has two causes: (1) highly variable airtightness (from <0.6 to >10 ACH_{50}) and (2) the number of deep retrofits (12 of 24 projects). In general, designers installed mechanical ventilation in airtight homes and left leakier homes naturally vented. Deep energy retrofits were identified as falling outside the ventilation requirements of CA Title 24 2008, which leaves them open to insufficient provision of IAQ in a context of greatly increased air tightness, lower AER and newly emitting materials. Deep retrofits were least likely of any group of homes to have installed continuous mechanical ventilation systems.

5. Particle pollution is not being sufficiently controlled in some project homes. Many high performance green homes in CA are moving away from forced air heating and cooling systems, towards hydronic and point-source systems, due to better alignment with heating/cooling loads, solar resource, zoning, etc. This eliminates the opportunity to filter recirculating air at high rates, with high filtration efficiency using the air handler. Furthermore, a majority of these projects are not installing continuous mechanical ventilation, which would be the alternative option for providing particle filtration. While the results of this study suggest that full forced air systems provide lower particle levels than filtered ventilation systems, the latter are still an improvement over entirely unfiltered homes. This trend is particularly troubling given that $PM_{2.5}$ is the most costly indoor air pollutant, in terms of human health.

6. NO_2 levels were controlled to fairly low levels, except in the case of historical gas ranges and in homes using whole house ERV/HRV to dilute cooking pollutants, rather than a range hood. Four such homes had 6-day integrated concentrations that either exceeded or nearly exceeded CalEPA annual ambient air quality standards.

7. Complex ventilation systems were plagued with performance problems, mostly resulting from installation error, not appliance malfunction. Careful and time consuming commissioning efforts were required to avoid problems in all cases.

8. Occupants and designers in high performance green homes do not sufficiently understand the pollutant and health impacts of cooking. Exhaust fan usage rates were low, and occupants demonstrated that they believed everyday cooking (without burning or foul odors) was essentially harmless. Use of bathroom exhaust was quite high, suggesting that the problems of kitchen pollutants and ventilation are solvable with education and better equipment. The code requirement for a kitchen range hood exhausted to outside was shirked in some project homes.

9. Occupants also do not sufficiently understand what elements of their home contribute to either good or bad IAQ. While most occupants demonstrated basic levels of knowledge, many reported that they had avoided forced air systems specifically to enhance IAQ, whereas this work has shown that these efforts led to increased particle levels.

10. Very airtight Passive Houses were able to deliver acceptable indoor air quality, but they were plagued by numerous ventilation system faults that could be attributed to the difficulties of properly designing, installing, commissioning and operating a complex ventilation system. Further improvements could have been achieved through enhanced supply air filtration and kitchen range hoods exhausted to outside. These homes provide the least amount of resiliency in the face of equipment malfunction and occupant misbehavior, due to their extreme airtightness. Passive Houses made up three of four homes that exceeded OEHHA annual ambient NO_2 levels.

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Appendix I: House-by-House Data Tables

Home ID	Location (city)	Year Built	Age (yrs)	Floor Area (ft^2)	Volume (ft^3)	# of Stories	# of Bed-rooms	# of Bath	# of Occu-pants
0501	Albany	2011	1	1,306	12,756	2	2	1.5	2
0502	Larkspur	1973 / 2010	2	2,143	22,151	1.5	4	2	3
0601	Sebastapol	1978 / 2004	8	2,187	17,679	1.5	4	2.5	3
0602	Sebastapol	2004	8	1,734	16,030	1	3	2	1
0801	San Jose	1924 / 1984	28	1,951	16,889	2	3	3	2
0802	Salinas	2006	6	1,690	18,126	2	3	2	2
0902	Palo Alto	2011	1	1,843	17,865	1	4	2	4
1001	Pacifica	1934 / 2009	3	1,639	14,279	1	3	2	2
1002	Pacifica	1947 / 1994 / 2007	5	1,840	16,657	2	4	2.5	3
1201	Oakland	2008	4	1,474	14,724	2	2	2	2
1202	Portola Valley	2011	1	1,731	22,210	1	3	2	2
1301	Folsom	1998 / 2006	6	2,990	30,172	2	4	2.5	4
1302	Davis	2011	1	1,391	11,126	1	3	1	3
1303	Davis	2011	1	1,347	10,774	1	5	1	5
1401	Oakland	2009	3	1,371	10,154	3	2	1.5	3
1402	Petaluma	1940 / 2010	2	2,510	21,904	2	3	1.5	2
1501	Gilroy	2008	4	2,682	25,256	2	4	3	2
1502	Oakland	1880 / 2011	1	3,411	29,325	3	4	4	2
1601	San Jose	2012	0	2,976	30,558	2	4	4	4
1801	Portola Valley	2010	2	5,006	55,305	1.5	3	4	5
1802	Folsom	2008	4	1,831	17,802	1.5	3	2.5	2
1901	Berkeley	2008	4	1,524	14,646	2	3	2	4
1902	Santa Monica	2006	6			2	3	2.5	1
1911	Palo Alto	2011	1	2,378	21,070	2	5	3	5

Table 40 Project Summary Information

Home ID	Net-Zero Energy	Passive House	Deep Energy Retrofit	Green Certified	Living Building Challenge	EPA Indoor Air Plus	Building America	Energy Star	Very High Performance	Green
Total	*6*	*7*	*12*	*10*	*1*	*1*	*1*	*1*	*3*	*2*
0501		X								
0502		X	X							
0601	X		X							
0602									X	X
0801	X		X							
0802	X									
0902		X		X						
1001			X							
1002			X							
1201	X			X						
1202		X	X							
1301			X							
1302			X	X						
1303			X	X						
1401									X	X
1402			X	X						
1501									X	
1502			X	X						
1601		X		X		X	X			
1801	X				X					
1802	X			X						
1901		X	X							
1902				X				X		
1911		X		X						

Table 41 Energy and Sustainability Classifications of Project Homes

Project Code	Airflow at -50 Pascal	Air Changes per Hour at -50 Pascal
0501	85	0.4
0502	226	0.6
0601	2751	9.3
0602	2694	10.1
0801	2888	10.3
0802	674	2.2
0902	NA	~2
1001	1455	6.1
1002	NA	NA
1201	682	2.8
1202	NA	~0.6
1301	1227	2.4
1302	1114	6.0
1303	991	5.5
1401	1279	7.6
1402	1983	5.4
1501	NA	NA
1502	2300	4.7
1601	324	0.6
1801	NA	NA
1802	NA	NA
1901	271	1.1
1902	NA	NA
1911	193	0.5

Table 42 Blower Door Airtightness Test Results of Project Homes

Home ID	Location	Heating Fuel Type			Combisystem	Heating Equipment Type						Method of Distribution								
						Heat Pump									Radiant					
		Natural Gas	Electric	Solar		Air-to-air	Air-to-water	Geothermal	Gas furnace	Gas boiler	Fireplace	Hydronic	Forced air	Point-source	In-Floor	In-Wall	Radiators	Baseboard	Portable space heater	HRV supply duct
Count		*16*	*7*	*9*	*12*	*3*	*1*	*1*	*4*	*9*	*3*	*12*	*10*	*3*	*7*	*1*	*1*	*1*	*1*	*2*
0501	Interior closet	X		X	X					X		X	X							X
0502	Crawlspace	X		X	X					X		X	X							
0601	Basement		X			X							X							
0602	Basement	X		X	X					X		X			X					
0801	Basement	X							X											
0802	Basement			X	X							X				X				
0902	Living space		X																X	
1001	Basement	X		X	X					X		X			X					
1002	Garage closet	X			X					X		X			X		X			
1201	Crawlspace		X			X							X							
1202	Conditioned Attic	X			X					X		X	X							X
1301	Unconditioned Attic	X							X				X							
1302	Living space	X									X			X						
1303	Living space	X									X			X						
1401	Outside closet	X		X	X					X		X			X					
1402	Interior closet	X							X				X							
1501	Unconditioned Attic	X							X				X							
1502	Living space	X									X			X						
1601	Crawlspace		X			X							X							
1801	Outside closet		X	X	X			X				X			X					
1802	Conditioned Attic	X		X	X					X		X	X							
1901	Living space		X															X		
1902	Basement	X		X	X					X		X			X					
1911	Interior closet		X		X		X					X			X					

Table 43 Primary Heating Systems Summary

Home ID	Supplementary Heater Type				
	Woodstove	**Gas Fireplace**	**Electric Space Heater**	**Denatured Alcohol Heater**	**None**
Total	*3*	*3*	*7*	*2*	*9*
0501			X		
0502					X
0601	X				
0602			X		
0801		X			
0802	X				
0902			X		
1001	X				
1002					X
1201					X
1202			X		
1301					X
1302					X
1303					X
1401			X		
1402			X		
1501					X
1502					X
1601			X		
1801				X	
1802		X			
1901					X
1902				X	
1911		X			

Table 44 Supplementary Heating Systems Summary

Home ID	**Electric**	**Air-to-air heat pump**	**Night ventilative cooling**	**Evaporatively cooled condenser**	**None**
Total	*7*	*7*	*3*	*2*	*17*
0501					X
0502					X
0601	X	X			
0602					X
0801	X	X			
0802					X
0902					X
1001					X
1002					X
1201	X	X			
1202					X
1301	X	X	X	X	
1302					X
1303					X
1401					X
1402					X
1501	X	X			
1502					X
1601	X	X	X		
1801					X
1802	X	X	X	X	
1901					X
1902					X
1911					X

Table 45 Cooling Systems Summary

Home ID	Location	Heating Fuel Type			Combisystem	Heating Equipment Type					Combustion Details		
						Heat Pump							
		Gas	Elec	Solar		Air-to-water	Geothermal	Tank	Tankless	Boiler	Power Vent	Direct Vent	Atmospheric Draft
Total		*19*	*5*	*14*	*12*	*4*	*1*	*18*	*6*	*1*	*3*	*11*	*3*
0501	Interior closet	X		X	X			X				X	
0502	Crawlspace / Outside	X		X	X			X	X		X		
0601	Basement		X			X		X					
0602	Basement	X		X	X			X				X	
0801	Basement	X							X		X		
0802	Basement	X		X	X			X				X	
0902	Basement		X	X		X		X					
1001	Basement	X		X	X			X				X	
1002	Garage closet	X			X			X		X		X	
1201	Garage closet		X			X		X					
1202	Conditioned attic	X		X	X			X				X	
1301	Garage	X						X					X
1302	Attic	X		X					X			X	
1303	Attic	X		X					X			X	
1401	Outside closet	X		X	X			X					
1402	Garage	X							X		X		
1501	Garage	X						X					X
1502	Basement	X						X					X
1601	Garage	X		X				X				X	
1801	Outside closet		X	X	X		X	X					
1802	Conditioned attic	X		X	X			X				X	
1901	Unconditioned attic	X							X			X	
1902	Basement	X		X	X						?	?	?
1911	Interior closet		X		X	X		X					

Table 46 Domestic Hot Water Systems Summary

Home ID	HRV	ERV	Exhaust Fan	CFIS	None	Cycle Schedule
Total	*6*	*3*	*1*	*3*	*11*	
0501		X				
0502	X					
0601			X			
0602					X	
0801					X	
0802					X	
0902	X					
1001					X	
1002					X	
1201				X		25%
1202	X					
1301				X		?
1302					X	
1303					X	
1401					X	
1402					X	
1501					X	
1502	X					
1601	X					
1801		X				25%
1802				X		17%
1901		X				
1902					X	
1911	X					

Table 47 Continuous Ventilation Systems Summary

Project ID	**Type of Filtration**					**Filter Description**
	Full forced air	**Supply Ventilation**	**Stand -alone**	**Range hood carbon filter**	**None**	
Total	*9*	*8*	*1*	*4*	*8*	
0501		X				MERV 12 (ERV)
0502	X					Unknown (AHU)
0601	X					MERV14, Honeywell, Duct Mounted Electronic Air Cleaner, F300E (AHU)
0602					X	None
0801	X					Unknown (AHU)
0802					X	None
0902		X		X		MERV 7 (HRV)
1001					X	None
1002					X	None
1201	X					MERV 13, 4" Pleated. (AHU)
1202		X		X		MERV 7 (HRV)
1301	X					MERV8, 2" (AHU)
1302					X	None
1303					X	None
1401					X	None
1402	X					MERV10, 4" (AHU)
1501	X					Unknown
1502		X				MERV 7 (HRV)
1601	X	X				4" Pleated, electrostatic charge (AHU); MERV 7 (HRV,)
1801		X	X			HEPA (ERV)
1802	X					MERV13 (AHU)
1901		X		X		MERV 12 (ERV)
1902					X	None
1911		X		X		Unkonwn (HRV)

Table 48 Detailed Summary of Filtration Techniques

Home ID	Kitchen Ventilation Description				Range Hood Exhaust to Outside?	Number of Fan Settings	Fan Noise on LOW	Fan Noise on HIGH
	HRV / ERV Exhaust	Range Hood	Exhaust fan in wall / ceiling	Microwave Exhaust Fan				
Total	*6*	*18*	*3*	*2*	*17*			
0501	X	X			No	5	2	3
0502	X				No	2	2	2
0601		X			Yes	5	1	2
0602		X			Yes	Variable	1	3
0801		X			Yes	2	2	3
0802			X		Yes	Variable	1	2
0902	X	X			No	4	3	4
1001			X		Yes	1	3	NA
1002			X		Yes	1	3	NA
1201		X			Yes	3	1	3
1202	X	X			No	3	2	3
1301		X			Yes	3	2	2
1302		X			Yes	2	1	2
1303		X			Yes	2	1	2
1401				X	No	2	2	2
1402		X			Yes	Variable	2	3
1501				X	Yes	3	2	3
1502		X			Yes	4	1	2
1601		X			Yes	4	2	3
1801		X			Yes	3	1	3
1802		X			Yes	3	1	3
1901	X	X			No	3	3	4
1902		X			Yes	3	1	2
1911	X	X			No	4	2	3

Table 49 Kitchen Ventilation Equipment Summary

Home ID	# of Bathroom/Laundry Exhausts*
0501	2
0502	2
0601	1
0602	2
0801	3
0802	0
0902	2
1001	2
1002	2
1201	2
1202	2
1301	3
1302	1
1303	1
1401	1
1402	1
1501	3
1502	5
1601	4
1801	Unknown
1802	5
1901	2
1902	2
1911	3

Table 50 Bathroom and Laundry Exhaust Fans Summary

Home ID	Cooktop Type	Oven Type	Combined Appliance?	Burner Ignition	Number of Cooktop Burners	Self-Clean	Age of Appliance (years)	Kitchen Connection to the rest of the Home (1-3)
0501	Gas	Gas	Together	Electronic	5	Yes	0-5	2
0502	Gas	Gas	Together	Electronic	4	I don't know	16+	3
0601	Gas	Electric	Separate	Electronic	6	Yes	6-10	3
0602	Resistance	Electric	Together	NA	4	Yes	6-10	3
0801	Gas	Gas	Together	Pilot	6	No	16+	3
0802	Propane	Propane	Together	Match light	4	No	16+	3
0902	Induction	Electric	Separate	NA	5	Yes	0-5	2
1001	Gas	Electric	Together	Electronic	4	Yes	0-5	3
1002	Gas	Gas	Together	Electronic	4	Yes	6-10	3
1201	Induction	Electric	Separate	NA	4	No	0-5	3
1202	Induction	Electric	Together	NA	4	Yes	0-5	2
1301	Gas	Electric	Separate	Electronic	5	Yes	6-10	2
1302	Gas	Gas	Together	Match light	5	No	16+	3
1303	Resistance	Electric	Together	NA	4	Yes	0-5	3
1401	Gas	Gas	Together	Electronic	5	Yes	0-5	3
1402	Resistance	Electric	Together	NA	4	Yes	0-5	1
1501	Gas	Electric	Separate	Electronic	4	Yes	0-5	3
1502	Resistance	Electric	Together	NA	5	Yes	0-5	3
1601	Gas	Gas	Together	Electronic	6	No	0-5	3
1801	Induction	Electric	Separate	NA	5	No	0-5	3
1802	Gas	Electric	Together	Electronic	5	Yes	0-5	3
1901	Gas	Electric	Separate	Electronic	4	Yes	0-5	3
1902	Gas	Gas	Separate	Electronic	4	Yes	0-5	3
1911	Induction	Electric	Together	NA	4	Yes	0-5	3

Table 51 Stovetop and Oven Equipment Summary

Project ID	Minimum Background Particles (#/ft^3)	Maximum Adjusted Particles (#/ft^3)	Number of Observations	Cooktop Type
0501	51130	151153	20	Gas
0502	846	49950	35	Gas
0601	2737	73514	56	Gas
0602	7166	204570	63	Resistance
0801	5157	381126	35	Gas
0802	5701	181265	50	Gas
0902	4259	42976	30	Induction
1001	7562	145188	39	Gas
1002	9837	226029	29	Gas
1201	7061	5430	25	Induction
1202	3563	2416	34	Induction
1301	894	36401	5	Gas
1302	18340	225876	24	Gas
1303	6584	71516	19	Resistance
1401	1641	136975	26	Gas
1402	955	259061	37	Resistance
1501	2273	223777	26	Gas
1502	13355	258595	45	Resistance
1601	5114	271419	34	Gas
1801	7830	7573	25	Induction
1802	10346	58094	33	Gas
1901	2450	221483	31	Gas
1911	13745	5103	30	Induction

Table 52 Results of Stovetop Testing of Ultrafine Particles

Project ID	0.5 Minimum	0.5 1st Quartile	0.5 Median	0.5 Mean	0.5 3rd Quartile	0.5 Max
501	10220	69780	106000	173000	196400	2429000
502	3890	16150	34400	45510	67150	253300
601	2642	18970	34890	63390	68450	5723000
602	28110	95840	161300	233000	266700	5252000
801	39330	91540	128800	140600	163000	1402000
802	16950	44870	72280	88080	112700	891100
902	17560	50610	70870	118300	113000	2190000
1001	56960	138000	188400	254300	267100	1364000
1002	21290	87450	134900	191100	217700	1924000
1201	26420	54340	90220	123100	155200	819300
1202	28740	64910	104700	120200	138900	2629000
1301	3952	17050	25010	29440	39830	439700
1302	16890	79060	123800	301800	308700	6054000
1303	NA	NA	NA	NA	NA	NA
1401	26010	62180	106000	115300	142200	834600
1402	19470	46780	60080	67610	76910	872000
1501	24110	57360	94150	249200	198900	2559000
1502	10300	24400	38700	116500	74500	5197000
1601	3549	18770	35090	48560	67340	866800
1801	12800	33200	50800	86260	74000	1146000
1802	8991	30860	50360	62170	82960	873400
1901	11510	43660	69200	93500	127100	511000
1902	26740	48760	83780	93790	126200	563800
1911	36900	80050	113900	167600	174800	4159000

Table 53 Summary Statistics of $PN_{>0.5}$ Counts

Project ID	2.5 Minimum	2.5 1st Quartile	2.5 Median	2.5 Mean	2.5 3rd Quartile	2.5 Max
501	NA	NA	NA	NA	NA	NA
502	NA	NA	NA	NA	NA	NA
601	5.4	327.3	971.2	3168	2473	1137000
602	3.6	942.7	2821	8186	7634	1186000
801	1177	4112	6929	10840	13150	245200
802	434.6	6337	12880	20310	26830	336200
902	112.7	1722	3117	5969	7624	490400
1001	756.5	4727	11380	16360	19750	331700
1002	355.8	4699	9864	15980	18200	369400
1201	220	1937	3332	6844	6659	107200
1202	1060	3877	9864	14820	16910	349700
1301	5.4	1293	2581	3566	5156	52590
1302	355.8	3760	7047	14010	13620	1183000
1303	NA	NA	NA	NA	NA	NA
1401	473.2	2938	4112	5864	7047	129500
1402	541.9	2044	3869	5235	7088	49480
1501	541.9	1937	2795	4592	4620	63750
1502	200	1000	1700	5046	3300	371200
1601	5.4	649.2	1830	3780	5800	41750
1801	100	1500	3000	7150	5600	190600
1802	220	1400	2903	3992	5478	92940
1901	649.2	2795	5049	8717	10950	73080
1902	707.9	3877	5990	8269	9893	76540
1911	1700	6000	15200	21660	24500	2578000

Table 54 Summary Statistics of $PN_{>2.5}$ Counts

House ID	Location	Formaldehyde (μg/m^3)	Acetaldehyde (μg/m^3)	Formaldehyde (ppb)	Acetaldehyde (ppb)
0501	Kitchen	21.7	42.0	17.4	22.9
0502	Kitchen	14.2	10.4	11.4	5.7
0601	Kitchen	13.0	11.8	10.4	6.5
0602	Kitchen	25.5	16.5	20.4	9.0
0801	Kitchen	33.2	8.0	26.6	4.4
0802	Kitchen	13.5	11.8	10.8	6.5
0902	Kitchen	27.3	21.3	21.9	11.6
1001	Kitchen	19.9	24.9	15.9	13.6
1002	Kitchen	15.2	9.6	12.1	5.3
1201	Kitchen	20.3	58.0	16.2	31.6
1202	Kitchen	27.2	18.8	21.8	10.3
1301	Kitchen	27.2	16.0	21.8	8.7
1302	Kitchen	19.3	32.9	15.5	17.9
1303	Kitchen	8.1	11.8	6.5	6.4
1401	Kitchen	16.9	10.6	13.5	5.8
1402	Kitchen	21.0	16.0	16.8	8.7
1501	Kitchen	28.1	28.4	22.5	15.5
1502	Kitchen	30.6	9.8	24.5	5.4
1601	Kitchen	11.1	16.2	8.9	8.8
1801	Kitchen	13.9	19.2	11.1	10.5
1802	Kitchen	9.3	6.4	7.4	3.5
1901	Kitchen	23.1	27.7	18.5	15.1
1902	Kitchen	27.6	10.2	22.1	5.6
1911	Kitchen	12.9	19.5	10.3	10.7
0501	Bedroom	20.0	31.0	16.0	16.9
0502	Bedroom	12.5	10.6	10.0	5.8
0601	Bedroom	15.1	11.4	12.0	6.2
0602	Bedroom	29.6	20.1	23.7	11.0
0801	Bedroom	34.6	9.6	27.7	5.2
0802	Bedroom	15.1	14.9	12.1	8.1
0902	Bedroom	21.5	18.9	17.2	10.3
1001	Bedroom	17.9	21.4	14.4	11.7
1002	Bedroom	20.0	13.4	16.0	7.3
1201	Bedroom	16.9	50.3	13.5	27.5
1202	Bedroom	30.2	17.3	24.1	9.4
1301	Bedroom	34.8	18.7	27.8	10.2
1302	Bedroom	15.9	32.6	12.7	17.8
1303	Bedroom	16.1	13.8	12.9	7.5
1401	Bedroom	15.6	10.1	12.5	5.5
1402	Bedroom	16.1	15.2	12.9	8.3
1501	Bedroom	41.0	44.6	32.8	24.3
1502	Bedroom	47.0	13.5	37.6	7.4
1601	Bedroom	12.7	10.6	10.2	5.8
1801	Bedroom	17.1	17.2	13.7	9.4
1802	Bedroom	13.9	6.3	11.1	3.5
1901	Bedroom	23.8	22.7	19.1	12.4
1902	Bedroom	36.5	13.0	29.2	7.1
1911	Bedroom	11.7	19.7	9.3	10.8
0501	Outside	4.6	2.5	3.7	1.3
0502	Outside	3.0	2.0	2.4	1.1
0601	Outside	2.8	bd	2.2	bd
0602	Outside	2.8	bd	2.2	bd

0801	Outside	4.5	1.7	3.6	0.9
0802	Outside	2.9	0.5	2.3	0.3
0902	Outside	4.0	0.2	3.2	0.1
1001	Outside	2.9	1.1	2.3	0.6
1002	Outside	5.1	2.2	4.0	1.2
1201	Outside	4.3	2.2	3.4	1.2
1202	Outside	2.2	0.6	1.8	0.3
1301	Outside	4.2	3.5	3.4	1.9
1302	Outside	13.2	6.5	10.6	3.6
1303	Outside	13.2	6.5	10.6	3.6
1401	Outside	4.0	1.4	3.2	0.8
1402	Outside	4.5	2.6	3.6	1.4
1501	Outside	3.0	1.5	2.4	0.8
1502	Outside	5.1	1.6	4.1	0.9
1601	Outside	4.1	2.1	3.3	1.1
1801	Outside	6.0	3.3	4.8	1.8
1802	Outside	4.0	2.9	3.2	1.6
1901	Outside	1.6	3.3	1.3	1.8
1902	Outside	0.5	1.0	0.4	0.6
1911	Outside	2.6	4.3	2.0	2.3

Table 55 One-Week Formaldehyde and Acetaldehyde Concentrations, Bedroom, Kitchen and Outside

House ID	Location	NO_2 (ppb)	NO (ppb)	NO_x (ppb)	NO_2 (I/O)	NO (I/O)	NO_x (I/O)
501	Bedroom	45.7	78.3	124.0	2.0	2.4	2.2
502	Bedroom	9.1	25.7	34.8	1.8	30.0	5.9
601	Bedroom	9.4	9.8	19.2	1.0	1.8	1.3
602	Bedroom	10.3	14.1	24.4	1.0	2.4	1.5
801	Bedroom	26.4	82.6	108.9	1.0	2.3	1.8
802	Bedroom	7.8	8.5	16.3	3.3	5.3	4.2
902	Bedroom	10.2	19.5	29.7	0.6	0.7	0.7
1001	Bedroom	6.8	26.7	33.5	1.5	8.0	4.2
1002	Bedroom	10.2	30.9	41.1	3.3	10.2	6.7
1201	Bedroom	9.6	23.8	33.4	0.4	1.1	0.7
1202	Bedroom	2.7	0.8	2.7	0.9	0.6	0.7
1301	Bedroom	5.3	6.5	11.8	1.1	2.7	1.6
1302	Bedroom	32.8	93.6	126.3	2.7	8.9	5.6
1303	Bedroom	4.8	5.2	10.0	0.4	0.5	0.4
1401	Bedroom	21.8	23.5	45.3	1.4	1.7	1.5
1402	Bedroom	2.0	7.1	9.1	0.3	1.2	0.7
1501	Bedroom	1.9	7.3	9.2	0.6	3.7	1.7
1502	Bedroom	10.4	15.9	26.4	0.8	3.6	1.5
1601	Bedroom	13.9	4.4	18.2	1.8	0.9	1.4
1801	Bedroom	1.9	1.3	3.2	1.0	0.5	0.7
1802	Bedroom	7.5	1.8	9.3	1.1	0.6	0.9
1901	Bedroom	12.7	4.3	17.0	1.4	4.4	1.7
1902	Bedroom	6.6	4.2	10.8	0.9	0.8	0.9
1911	Bedroom	6.2	1.3	7.6	1.1	1.9	1.2
501	Kitchen	38.6	NA	NA	1.7	NA	NA
502	Kitchen	8.6	33.4	42.0	1.7	39.0	7.1
601	Kitchen	13.1	6.7	19.8	1.4	1.3	1.4
602	Kitchen	5.4	18.0	23.5	0.5	3.0	1.5
801	Kitchen	30.3	67.5	97.8	1.1	1.9	1.6
802	Kitchen	5.9	6.6	12.5	2.5	4.2	3.2
902	Kitchen	12.9	20.8	33.8	0.7	0.8	0.8
1001	Kitchen	8.8	27.1	35.9	1.9	8.1	4.5
1002	Kitchen	14.2	22.3	36.6	4.6	7.3	6.0
1201	Kitchen	8.3	22.1	30.4	0.4	1.0	0.7
1202	Kitchen	3.0	NA	2.8	1.0	NA	0.8
1301	Kitchen	5.6	5.7	11.3	1.1	2.3	1.5
1302	Kitchen	57.9	122.8	180.7	4.8	11.7	8.0
1303	Kitchen	3.9	6.2	10.2	0.3	0.6	0.5
1401	Kitchen	21.8	18.9	40.7	1.4	1.4	1.4
1402	Kitchen	3.6	7.4	10.9	0.5	1.2	0.8
1501	Kitchen	5.3	8.7	13.9	1.5	4.5	2.6
1502	Kitchen	13.6	15.1	28.8	1.0	3.4	1.6
1601	Kitchen	16.1	7.9	24.0	2.1	1.5	1.9
1801	Kitchen	2.2	0.1	2.3	1.1	0.1	0.5
1802	Kitchen	9.0	1.9	10.9	1.3	0.6	1.1
1901	Kitchen	27.7	37.3	65.0	3.1	38.0	6.5
1902	Kitchen	5.4	4.3	9.7	0.7	0.8	0.8
1911	Kitchen	6.0	2.1	8.1	1.1	2.9	1.3
501	Outside	22.9	32.9	55.8	NA	NA	NA
502	Outside	5.1	0.9	5.9	NA	NA	NA
601	Outside	9.1	5.3	14.4	NA	NA	NA
602	Outside	10.0	6.0	16.0	NA	NA	NA

801	Outside	26.9	35.2	62.0	NA	NA	NA
802	Outside	2.3	1.6	3.9	NA	NA	NA
902	Outside	18.4	26.6	44.9	NA	NA	NA
1001	Outside	4.6	3.3	7.9	NA	NA	NA
1002	Outside	3.1	3.0	6.1	NA	NA	NA
1201	Outside	23.8	22.4	46.2	NA	NA	NA
1202	Outside	2.9	0.7	3.6	NA	NA	NA
1301	Outside	5.0	2.4	7.4	NA	NA	NA
1302	Outside	12.0	10.5	22.5	NA	NA	NA
1303	Outside	12.0	10.5	22.5	NA	NA	NA
1401	Outside	15.9	13.5	29.4	NA	NA	NA
1402	Outside	7.0	6.1	13.0	NA	NA	NA
1501	Outside	3.5	1.9	5.4	NA	NA	NA
1502	Outside	13.2	4.4	17.6	NA	NA	NA
1601	Outside	7.8	5.1	13.0	NA	NA	NA
1801	Outside	1.9	2.4	4.3	NA	NA	NA
1802	Outside	6.8	3.3	10.1	NA	NA	NA
1901	Outside	9.0	1.0	10.0	NA	NA	NA
1902	Outside	7.3	5.1	12.5	NA	NA	NA
1911	Outside	5.5	0.7	6.2	NA	NA	NA

Table 56 One-Week Nitrogen Oxides Concentrations and I/O Ratios, Bedroom, Kitchen and Outside

Project ID	Average Temperature (°C)			Average Relative Humidity (%)		
	Bedroom	Kitchen	Outside	Bedroom	Kitchen	Outside
501	19.0	20.9	11.4	57.4%	50.7%	67.7%
502	18.5	19.5	9.5	53.3%	51.1%	72.8%
601	22.0	22.1	6.8	35.3%	32.9%	70.9%
602	20.8	20.9	6.8	40.9%	41.9%	70.9%
801	20.9	21.3	11.1	51.6%	48.1%	74.6%
802	21.7	20.3	12.0	40.7%	44.2%	64.0%
902	18.2	20.2	11.7	57.8%	49.1%	72.9%
1001	NA	20.4	11.7	NA	61.5%	84.1%
1002	NA	20.1	12.2	NA	53.8%	81.6%
1201	70.3	22.7	12.4	46.0%	46.1%	62.9%
1202	69.7	20.9	10.5	46.6%	48.4%	65.4%
1301	NA	21.0	10.0	NA	43.7%	70.8%
1302	20.2	20.6	13.7	47.4%	44.2%	57.7%
1303	16.2	15.9	13.7	55.6%	52.1%	57.7%
1401	21.6	22.4	10.5	35.9%	33.7%	66.1%
1402	18.0	19.1	10.0	55.3%	49.7%	64.5%
1501	16.9	16.9	11.5	55.5%	53.6%	81.7%
1502	23.5	23.5	11.6	38.8%	39.4%	79.9%
1601	21.5	22.8	11.2	41.4%	38.2%	73.5%
1801	24.1	23.8	10.3	36.2%	36.3%	57.2%
1802	20.4	20.1	13.4	34.7%	35.5%	51.1%
1901	20.0	20.7	12.2	53.3%	56.4%	74.6%
1902	21.5	19.7	14.0	52.4%	59.9%	79.6%
1911	20.7	21.5	12.5	47.7%	46.2%	71.6%

Table 57 One-Week Temperature and Relative Humidity Data, Bedroom, Kitchen and Outside

Method Detection Limit (MDL) calculation for Ozone and NOx Analysis

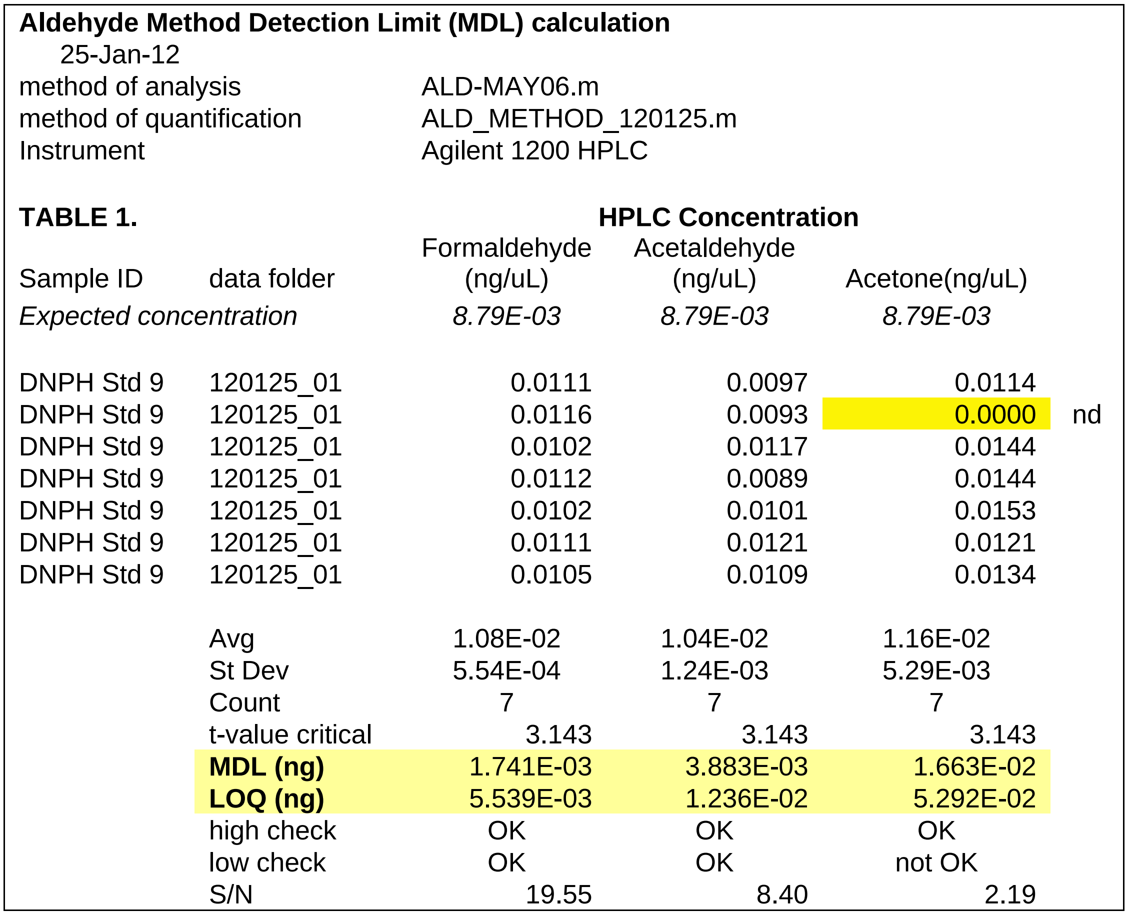
16-Feb-12

method of analysis	111006_NOx_O3.pgm
method of quantification	NO2 and NO3 Quant 111011.qnt
Instrument	Dionex 2000 Ion Chromatography System

TABLE 1. Method detection limit.

Sample ID	data folder	Nitrite (ug/mL)	Nitrate (ug/mL)
Expected concentration		*1.00E-01*	*1.00E-01*
NO2NO3 Std 1	120215_01.s	0.082	0.083
NO2NO3 Std 1	120215_01.s	0.083	0.089
NO2NO3 Std 1	120215_01.s	0.082	0.086
NO2NO3 Std 1	120215_01.s	0.084	0.089
NO2NO3 Std 1	120215_01.s	0.087	0.087
NO2NO3 Std 1	120215_01.s	0.086	0.100
NO2NO3 Std 1	120215_01.s	0.088	0.091
	Avg	8.45E-02	8.91E-02
	St Dev	2.50E-03	5.26E-03
	Count	7	7
	t-value critical	3.143	3.143
	MDL (ng)	7.855E-03	1.655E-02
	LOQ (ng)	2.499E-02	5.264E-02
	high check	not OK	OK
	low check	OK	OK
	S/N	33.82	16.93

Table 58 Method Detection Limit Analysis, Ozone and NOx



Aldehyde Method Detection Limit (MDL) calculation

25-Jan-12

method of analysis	ALD-MAY06.m
method of quantification	ALD_METHOD_120125.m
Instrument	Agilent 1200 HPLC

TABLE 1.

		HPLC Concentration			
Sample ID	data folder	Formaldehyde (ng/uL)	Acetaldehyde (ng/uL)	Acetone(ng/uL)	
Expected concentration		*8.79E-03*	*8.79E-03*	*8.79E-03*	
DNPH Std 9	120125_01	0.0111	0.0097	0.0114	
DNPH Std 9	120125_01	0.0116	0.0093	0.0000	nd
DNPH Std 9	120125_01	0.0102	0.0117	0.0144	
DNPH Std 9	120125_01	0.0112	0.0089	0.0144	
DNPH Std 9	120125_01	0.0102	0.0101	0.0153	
DNPH Std 9	120125_01	0.0111	0.0121	0.0121	
DNPH Std 9	120125_01	0.0105	0.0109	0.0134	
	Avg	1.08E-02	1.04E-02	1.16E-02	
	St Dev	5.54E-04	1.24E-03	5.29E-03	
	Count	7	7	7	
	t-value critical	3.143	3.143	3.143	
	MDL (ng)	1.741E-03	3.883E-03	1.663E-02	
	LOQ (ng)	5.539E-03	1.236E-02	5.292E-02	
	high check	OK	OK	OK	
	low check	OK	OK	not OK	
	S/N	19.55	8.40	2.19	

Table 59 Method Detection Limit Analysis, Aldehydes

Appendix II: Site Visit Protocols

VISIT 1: Sampler Deployment and Residence Characterization

Conditions for Visit

Adult host. Either the study participant or a surrogate adult prearranged by the participant must be present. The surrogate should be aware that the visit is related to an indoor air quality study. The visit may proceed with a non-pre-arranged, on-site adult if the participant can be reached by phone to confirm this arrangement. Otherwise, the visit should be rescheduled.

Researcher Safety. If at any time the researchers feel that their personal safety may be at risk, they should stop work and exit the premises as directly as the hazard demands. Example conditions include belligerent host, physical or extreme verbal abusiveness between residents, occupants brandishing or displaying weapons or engaging in any other activity that the researchers feel present an unusual hazard. If the situation allows, the researchers should engage the host in a discussion of the perceived threat / hazard to assess whether the situation can be resolved. If researchers need to exit for safety, they should remove with them all equipment and sampling materials as feasible. This is a worker safety issue and is entirely at the discretion of the field researchers. Follow up steps will be coordinated with the principal investigator.

Summary of Visit Elements

1. Orientation and Approval to Enter Home
2. Residence and Appliance Characterization
3. Sampler Deployment
4. Final Check-In

Each of these items is described in more detail below.

1. Orientation and Approval to Enter Home

a. Overview of visit. Briefly describe to the host what the researchers will do during visit:
   i. Initial walk-through to locate appliances and other relevant features, including any sampler deployment locations discussed by phone.
   ii. Collect information about gas appliances and other relevant features:
      1. Taking pictures of appliances and features (avoiding personally identifiable information or personal items such as photographs).
      2. Clearing paths as needed to access appliances to obtain information and to install monitoring devices. Potentially removing then reinstalling the cover of appliances with concealed information plates.
      3. Operating some appliances for 5-10 minutes to characterize performance either through measurements or visual assessment.
      4. Sketching floor plan to show locations of appliances and features.
   iii. Set up air quality samplers and sensors and taking photos of sampler placement.
   iv. Final check-in and exit

b. Host involvement and approval.
   i. Inform the host that the visit will take roughly 1.5 hours. Confirm that they will be at the home for at least the next 1.5 h and available to meet briefly at the end of the visit.
   ii. Ask that the host accompany you on the initial walk through or obtain verbal agreement that you can proceed through the home unaccompanied. The host is welcome but not required to accompany the researchers through the visit.
   iii. Ask if there are any rooms that the host would *not* like researchers to enter?
   iv. If two researchers are present, note that our standard approach is to conduct simultaneous activities at different locations as this allows U.S. to finish faster. Ask for clear verbal approval for this approach. If this is not acceptable and the host wants to accompany the researchers at all times, adjust the procedures to accommodate.
   v. Researchers should exclude any activities planned for the visit to which the resident expresses concerns or objections.

c. Inform the host that this *is **NOT*** a gas safety inspection. If the host has any concerns about gas safety in their home, they should contact PG&E. Provide paper with contact information.

d. Researcher safety.
   i. Known hazards. Review with host any hazards mentioned in previous call and ask if there are others, e.g. dogs, alarms, electrical hazards?

2. Residence and Appliance Characterization (Provided below)

2. Sampler deployment:

a. *Sampler deployment criteria:* Indoor samplers will be deployed at least 3 feet from combustion source plume (approximate plume spread based on 30º angle), out of the flow path of incoming air from doors and/or windows, 3 feet from the floor and 1 foot from ceiling. Outdoor samplers will be deployed in a location that provides maximum protection from the elements and from potential theft.

b. Deploy main sampler assembly in kitchen or in larger room that includes kitchen. Photograph location (if acceptable to participant) and/or indicate on sketch of home where it is located. Note height from floor, orientation and distance from any windows, doors and appliances.

c. Place secondary indoor sampler assembly in a second room with the following preferred priority order: (1) bedroom of youngest child, (2) bedroom of another child aged 12 or under, (3) bedroom of oldest resident, (4) bedroom of head of household, (5) home office, (6) other room that is disconnected from kitchen. Place time-resolved CO_2 instrument in close vicinity. Photograph location (if acceptable to participant) and/or indicate on sketch of home where it is located. Note height from floor, orientation and distance from any windows, doors and appliances.

d. Deploy outdoor sampler assembly in a location that is convenient and secure.

e. Deploy temperature sensors/thermocouples to monitor the use of the gas heating appliance(s), gas water heater(s), and gas cooking appliance(s).

f. In homes where air-exchange rate measurements will be made, the following criteria will be used for PFT vial placement (excerpted from approved HSC protocol): “[PFT] Vials will be placed in several (usually 2 to 4) locations in the home in consultation with the participating resident. The vials are always placed out of the reach of children and in locations that are unobtrusive.”

4. Departure and Final Briefing

a. Sampler placement. Inform host of placement of all sampling and monitoring equipment.
    a. If samplers are to be mailed back by participant, provide return mailers and instructions to host. If host is participant, review instructions for repackaging and mailing back samplers. (Otherwise, ask host to pass materials along to participant and follow up with participant by phone).
    b. If samplers are to be retrieved on return visit, leave paper with planned date and time of return and follow up to confirm with participant.

b. Remind the host that the intent of the study is to measure indoor air quality during a normal week of activities; therefore they should carry out their activities as usual.

c. Remind host that samplers should NOT be touched or handled during the week as this could interfere with the measurement.

d. Remind the host that they can call you, if any questions arise. Provide contact information.

e. Inform host that the visit has been completed and say “Thank you”.

Residence Characterization Form

To be used for data collection in visit 1. Estimated total time: 60 minutes.

Note: If researchers assess that any of gas appliances are malfunctioning in a manner that represents a clear and present danger, inform the host of the problem and advise that they contact PG&E immediately at the number we have provided to them. Assist with the call if requested by the host. At the discretion of the field researcher, the visit and sampling may or may not proceed depending on the nature of the problem and the stated plan of the host to resolve the issue. (For example, work may proceed if the problem is with a wall furnace that provides supplemental heat.) Follow-up with participant to document resolution of issue during sampling or to reschedule work.

Suggested schedule for two-researcher visit:

Elapsed time (min)	Researcher 1	Researcher 2
0-10	Orient resident	Orient resident
10-20	Walk through	Walk through
20-30	Floor plan sketch	Inspect oven and cooktop. Close up kitchen and turn on oven and 2 cooktop burners
30-40	Floor plan sketch	Turn off kitchen burners. Keep kitchen closed for next 15 minutes. Inspect furnace
40-50	“Other pollutant sources” & “Basic information”	Inspect water heater
50-60	Other gas appliances (dryer, fireplace, other)	Inspect range hood

Equipment

1. Home characterization form
2. Combustion analyzer
3. Sampling packages:
    a. Kitchen (CO logger, TRH logger, HCHO sampler, NO_2/NO_X sampler)
    b. Bedroom (CO_2 logger, HCHO sampler, NO_2/NO_X sampler)
    c. Outside (TRH logger, HCHO sampler, NO_2/NO_X sampler)
    d. T logger for appliance monitoring: Furnace, water heater, range hood.
4. Particle monitor (TSI P-Trak)

1. **Walk through** home and confirm locations of appliances, exhaust fans, moisture damage, and windows that are open during time of visit. Only identify objects/issues present in the living space or a space connected to the living space (e.g. attached garage or attic). Also provide notes regarding general observations; detailed notes will be included later in inspection. (Prefill tables with information provided by participant in initial questionnaire.)

Gas Appliance Type	**Location in the home**	**Notes**
1.a.1 (e.g. gas wall furnace)	(e.g. living room)	(e.g. in use upon arrival)
1.a.2		
1.a.3		
1.a.4		
1.a.5		
1.a.6		
1.a.7		
1.a.8		

Ventilation system type	**Location in the home**	**Notes**
1.b.1 (e.g. ceiling exhaust fan)	(e.g. bathroom)	(e.g. very noisy)
1.b.2		
1.b.3		
1.b.4		
1.b.5		

Location of open window(s), by wall*	**Approx. area of window opening, by wall***
1.c.1 (e.g. master bedroom, south wall)	(e.g. 10 cm x 60 cm)
1.c.2	
1.c.3	
1.c.4	
1.c.5	
1.c.6	
1.c.7	
1.c.8	
1.c.9	
1.c.10	

*If two or more windows are open on same wall, record combined area (effect of two or more window openings on same wall is same as one larger opening).

2. **Sketch the floor plan** of the home, making note of the following:
    a. Basic orientation of rooms, including garage if adjacent to living space.
    b. Type of flooring in each room (carpet, wood, vinyl, rugs, etc.).
    c. Assessment of general furnishings, couches, cabinetry, pressed wood products, etc.
    d. Location of each gas appliance.
    e. Location of each exhaust fan (including estimated height from ground).
    f. Locations of air quality samplers and sensors.
    g. Orientation of home within building (for apartment or attached home) or proximity of nearby buildings to detached home. Note direction and distance to any obvious local outdoor pollutant sources, e.g. bus stops.
    h. (Locations of "Other Pollutant Sources" will be added in Section 13)

3. Confirm / correct information collected in initial questionnaire:

a. Housing structure type (apartment, single-detaches etc.)
b. Number of stories
c. Presence and location of garage
d. Location of home within the building (for apartments)
e. Location of kitchen within the home.

4. Gas cooktop and oven

a. **Measurements**

Set up small package of pollutant monitors at location 2-4 m from cooktop and oven. Note distance and orientation on sketch of kitchen.

- i. Start analyzers.
- ii. Prepare pots of water.
- iii. Take a picture of entire cooktop and of oven compartment, with no burners on.
- iv. Light the 4 burners on the outer corners one at a time. Start with the right-front burner and go clockwise. Note information in Tables d and e below.
- v. Take a picture of all four burners.
- vi. Turn off all burners. Put pots on right-front and left-rear burners and relight. Take photos of these burners with pots on. Leave on for 5 min.
    - a. Note time cooktop burners were turned on:
- vii. Light oven burner at 350 ºF. Note information in Tables e and d. Take a photo of oven burner if feasible. Leave on for 5 min.
    - a. Note time oven burner was turned on:
- viii. After 5 min of first 2 cooktop burners on, turn burners off and move pots to other two burners (Right-rear, Left-front) and light these burners. Note information in Tables e and d. Take photos of these burners with pots on. Leave on for 5 min.
    - a. Note time cooktop burners were turned on:
- ix. After 5 min of oven burner being on, turn it off. Repeat procedure for broiler burner if there is one: light burner, and note information in Tables e and d. Take photo. Leave on for 5 min.
    - a. Note time broiler burners were turned on:

Pictures:

b. Take pictures of the following for the *cooktop*:
- i. Close-up of each burner with flame ignited and no pot
- ii. Close-up of each burner with flame ignited and with pot
- iii. The entire cooktop surface with no flames
- iv. The location of the cooktop in the kitchen.

c. Take pictures of the following for the *oven and broiler*:
- i. Picture of oven compartment from outside door with burner on
- ii. Picture of broiler compartment from outside door; burner on
- iii. Picture of problematic areas in oven compartment (e.g. blocked vents).
- iv. The location of the oven in the kitchen (*if* location is different from cooktop).

Flame visual inspection (Turn on each burner, and inspect the following):

d. Identify if any of the burner(s) are affected by the following issues (CT=cooktop):
   i. Doesn't start (Code-DS)
   ii. Slow to start; i.e. delay of more than 2 seconds (Code- SS)
   iii. Light by match (Code- M)

Burner:	Issue Codes	Comments
4.d.1. CT Front-right		
4.d.2. CT Front-left		
4.d.3. CT Rear-right		
4.d.4. CT Rear-left		
4.d.5. Front-Central		
4.d.6. Rear-Central		
4.d.6. Only-Central		
4.d.7 Oven burner		
4.d.8 Broiler burner		

e. Identify if burner(s) are affected by any of the following issues: (Burners should burn blue, be unwavering and at most emit a quiet hiss. Burners should *not* burn yellow or sound like a blowtorch; otherwise flames may be over-fired or under-fired.).
   i. Burner wavers like a candle (W)
   ii. Burner has 50% or more orange like a candle (O)
   iii. Burner sounds like a blow torch (BT)

Burner:	Issue Codes	Comments
4.e.1. CT Front-right		
4.e.2. CT Front-left		
4.e.3. CT Rear-right		
4.e.4. CT Rear-left		
4.e.5. CT Front-Central		
4.e.6. CT Rear-Central		
4.e.6. CT Only-Central		
4.e.6. Oven		
4.e.6. Broiler		

General information (*Only complete if easily identifiable*):

f. Information from the rating plate(s) of range or oven and cooktop if separate:
   i. Manufacturer:
   ii. Model number:
   iii. Serial number:

g. Nominal firing rate of *cooktop* burners (all that apply)
   i. Front right:
   ii. Front left:
   iii. Rear right:
   iv. Rear left:
   v. Front middle:
   vi. Rear middle:

    vii. Only middle:

h. Nominal firing rate of *oven* burners (all that apply):
    i. Bottom:
    ii. Top:

i. Are the *cooktop* burners sealed or open?

j. Do the *cooktop* burners have pilot light or electronic ignition or light by match?

k. Does the *oven* burner have pilot light, electronic ignition or light by match?

l. Are the *broiler* burner controls separate from the rest of the oven?

5. Kitchen exhaust

General Information:

a. Which types of kitchen exhaust fans are present?
    ____Range hood above the cooktop
    ____Microwave and exhaust fan combination above the cooktop
    ____Downdraft exhaust at the back or middle of the cooktop
    ____Exhaust fan in ceiling or wall above (within 30º of) cooktop
    ____Exhaust fan in ceiling or through wall not within 30º of cooktop.
    ____Other. Describe:
    ____No exhaust system in the kitchen

b. If a range hood is present (and it is possible to assess from interior or ground):
    i. Does it exhaust outside?
        ____Yes
        ____No
    ii. If exhausts outside, where does it exhaust?
        ____Through roof
        ____Through wall
    iii. Estimate the vertical and horizontal distance of hood inlet and exhaust point.
        1. Vertical:
        2. Horizontal:

c. Provide the following information from the rating plate, if locatable:
    i. Manufacturer:
    ii. Model number:
    iii. Serial number:

d. What is the approximate distance between the center of the cooktop surface and the center of exhaust fan opening?
    i. Vertical distance:
    ii. Horizontal distance:

e. How many settings does the exhaust fan have?

f. How much of front burner is covered by range hood (0, 25, 50, 75 or 100%)?

Visual inspection (range hood):

g. If range hood is present, rate amount of grease on screen:

____No grease- recently cleaned or unused
____Modest grease deposits but minimal dust accumulated
____Significant grease and dust build up

Measurements:

h. Ensure room is quiet, then measure background sound level at a locations 15 cm from front of cooktop and 150 cm from floor.

		Sound level
5.h.1	Background sound (start)	
5.h.2	Lowest Setting (1)	
5.h.3	Intermediate Setting (2)	
5.h.4	Intermediate Setting (3)	
5.h.5	Highest Setting (4)	
5.h.6	Background sound (end)	

i. If feasible, measure exhaust fan flow rates at all or most used settings:

		Flow rate
5.i.1	Lowest Setting (1)	
5.i.2	Intermediate Setting (2)	
5.i.3	Intermediate Setting (3)	
5.i.4	Highest Setting (4)	

Pictures:

i. Take a pictures from the following perspectives, as feasible:
   i. Side view to show coverage
   ii. Front view
   iii. Looking up with grease screens in place
   iv. Looking up with grease screens removed.

6. Gas forced-air furnace

General Information:

a. Does the furnace have pilot light, electronic ignition or light by match?

_____ Pilot light
_____ Electronic ignition

b. Please provide the following information from the rating plate:

   i. Manufacturer:
   ii. Model number:
   iii. Serial number:
   iv. Burner rating:

c. Please indicate which of the following technologies apply to this furnace:

   i. Atmospheric draft
   ii. Assisted draft
   iii. Sealed combustion
   iv. Other:

Visual inspection:

d. If visible, what percentage of the flame is yellow?

Measurements:

e. If possible, use combustion analyzer to measure CO in flue at draft diverter.

   i. CO:
   ii. CO2 (calculated):

Pictures:

f. Take a picture of each of the following:

   i. Entire wall furnace, showing placement in the room
   ii. Close up of black deposits on the wall above the furnace, if present
   iii. Close up of the wall furnace interior (with panel removed)
   iv. Close up of areas of rusting or cracking
   v. Thermostat showing current settings

7. Gas wall furnace

General Information:

a. Does the wall furnace have pilot light, electronic ignition or light by match?
    _____ Pilot light
    _____ Electronic ignition

b. Is the furnace controlled by a thermostat?
    _____Yes
    _____No

c. Please provide the following information from the rating plate:
    i. Manufacturer:
    ii. Model number:
    iii. Serial number:
    iv. Burner rating:

Visual inspection:

d. Which best describes the burner flame?
    i. Sharp blue flame; possibly with some orange at tip.
    ii. Significant blue at center, but flame is long and yellow at tip (possibly due to impingement)
    iii. Wobbly yellow flame with little or no blue.

e. Is there any indication of a crack in the heat exchanger?
    i. If yes, what is the approximate size of the crack?

Measurements:

f. Use combustion analyzer to measure CO in flue at draft diverter.
    i. CO:
    ii. CO2 (calculated):

Pictures:

g. Take a picture of each of the following:
    i. Entire wall furnace, showing placement in the room
    ii. Close up of black deposits on the wall above the furnace, if present
    iii. Close up of the wall furnace interior (with panel removed)
    iv. Close up of areas of rusting or cracking
    v. Thermostat showing current settings (if furnace connected to thermostat)

8. Floor furnace

General Information:

a. Does the floor furnace have pilot light, electronic ignition or light by match?

_____ Pilot light
_____ Electronic ignition

b. Please provide the following information from the rating plate, if locatable:

   i. Manufacturer:
   ii. Model number:
   iii. Serial number:
   iv. Burner rating:

Visual Inspection:

c. Is the burner flame visible when looking into the furnace from above?

_____Yes
_____No

   i. If yes, describe color and sharpness of flame:

Pictures

d. Floor furnace close up from above, with floor furnace powered on
e. Floor furnace from further away, showing placement in the room
f. Any problematic areas (e.g. leaks in vent system, cracks on heat exchanger)
g. Thermostat showing current settings (if furnace connected to thermostat)

9. Gas water heater

General Information:

a. Indicate the technology of the water heater (check all that apply)
   - i. Flammable Vapor Ignition Resistant (FVIR)
   - ii. Sealed combustion
   - iii. Power vent
   - iv. Natural vent
   - v. Solar
   - vi. Heat Pump
   - vii. Electric
   - viii. Other:

b. Please provide the following information from the rating plate:
   - i. Manufacturer:
   - ii. Model number:
   - iii. Serial number:
   - iv. Burner rating:

Visual Inspection:

c. Are inspection doors present on the burner compartments?

_____Yes
_____No

d. Provide the following information regarding the exhaust duct/flue, if possible:
   - i. Is the flue vent in line with the draft diverter?

     _____Yes
     _____No

   - ii. Is the exhaust combined with that of any other appliances?

     _____Yes
     _____No

   - iii. Are there visible gaps in vent connections?

     _____Yes. Please describe:
     _____No

e. Are there visual indications of back drafting (check all that apply)?
   - i. Staining on top of the water heater
   - ii. Corrosion on the diverter side of nipples
   - iii. Melted pipe insulation next to diverter
   - iv. Carbon deposits outside of burner chamber

Measurements:

f. Place combustion analyzer probe inside of flue below cone. Open faucet for hot water to ignite water heater burner. Log for 3 minutes.
   - i. Start/stop time of measurement:

Pictures:

g. Entire water heater, showing placement in the room
h. Close up of exhaust cone and duct
i. Full visible part of exhaust duct, including connections to furnace if relevant.
j. Close up of items e (i-iv) listed above, if identified
k. Air inlet
l. Temperature setting knob
m. Name plate (with firing information and model number etc.)
n. Any problematic areas (e.g. leaks in vent system, cracks on heat exchanger)

10. Gas clothes dryer

(Note: If time is constrained, only answer "general information" question for dryer.)

General Information:

a. Please provide the following information from the rating plate:
    i. Manufacturer:
    ii. Model number:
    iii. Serial number:

b. Where does the dryer vent?
    ____Indoors
    ____Outdoors
    ____Attic
    ____Crawl space

Visual Inspection:

c. If dryer vents outdoors, provide the following information if possible:
    i. Is the dryer to vent connection intact?
    ____Yes
    ____No (take picture)

    ii. Is the vent to wall connection intact?
    ____Yes
    ____No (take picture)

    iii. How long is the vent duct?

    iv. Is the vent exhaust obstructed on the outside of the house (only check for single-family homes)?

d. Is there excessive lint in the screens?
    ____Yes. Describe:
    ____No

Pictures:

e. The entire dryer, showing placement in the room.
f. The vent connection at the dryer and wall, if vented.

11. Gas fireplace

General Information:

a. Please provide the following information from the rating plate:
   1. Manufacturer:
   2. Model number:
   3. Serial number:
   4. Burner rating:

b. Is it controlled by a thermostat?

_____Yes
_____No

c. Does it sit into the wall or separate from the wall, entirely in the room?

_____Entirely in wall
_____Partially in wall, partially in room
_____Entirely in room, separate from wall

d. Is it vented?

_____Yes
_____No

e. What is the source of combustion air for the fireplace?
   1. Air ducted from outside
   2. Air from the room?

Pictures:

f. The entire fireplace, showing placement in the room
g. The inside of the fireplace
h. Problematic areas (e.g. leaks in vent connections)

12. Other unvented gas appliances

General Information:

a. Provide the following information (if locatable) for all unvented gas appliances not already inspected:
   1. Manufacturer:
   2. Model number:
   3. Serial number:
   4. Burner rating:

b. In what room(s) is/are the appliance(s) located at the time of inspection?

Pictures:

c. Take a picture of any unvented gas appliances present in the home.

13. Other possible pollutant sources:

a. Please indicate on the floor plan the location of each of the following “other” pollutant sources, using the codes provided:

Source	**Code**
Wood fireplace or stove- clean (contains no ash or char)	W-c
Wood fireplace or stove- dirty (contains ash or char)	W-d
Candles at least partly burnt	C
Burned or burning incense	In
Wood surfaces smelling of lacquer	W-laq
Surfaces smelling of paint	Pt
Plug-in air fresheners- strong smell	AF-3
Plug-in air fresheners- moderate smell	AF-2
Plug-in air fresheners- faint smell	AF-1
Air freshener spray can	AF-s
Perfume or cologne bottles	Perf
Cigarette smell (indicate if most strong in certain rooms)	Cig
Musty smell (indicate if most strong in certain rooms	Must
Open fish tank	FT
Humidifier	H

b. Does the entire home smell of cigarette smoke?
_____Yes.
_____No

c. Does the entire home smell musty?
_____Yes.
_____No

d. If air fresheners are present in the home, which scents are observed?
_____Pine
_____Lemon
_____Citrus
_____Floral
_____Other:

14. Other notes about the home:

Appendix III: Occupant Surveys

HEALTHY HOMES PARTICIPANT QUESTIONNAIRE

OVERVIEW:
Information about the homes in which monitoring occurs will be collected from participants via two interviews. The first part of the survey features questions about the home and appliances as well as activities and occupancy patterns. This will be administered to all participants by telephone roughly 1-2 weeks prior to sampling and was designed to take 20-30 minutes to complete. The second will be administered at the end of the sampling week. It will be administered by telephone for homes with mail-out samplers or in person for homes that are visited to collect samplers. The second questionnaire was designed to take about 10-20 minutes to complete.

The questionnaires will be administered to a consenting adult in each study household. In the initial phase of the Year 1 study, it will be conducted by our core project staff, and available only in English. In later phases of Year 1 or starting in Year 2, other project staff may administer the questionnaire. If resources allow, we may hire research assistants to translate and administer the questionnaires in other languages; starting with Spanish then either Mandarin or Cantonese.

The questionnaires includes subsections for appliances that won't be applicable to all homes. For example, most respondents will have to answer only one set of questions about a furnace.

These questionnaires were designed by Brett Singer and Nasim Mullen with a focus on data that is relevant to the current project. In June 2011, these questionnaires were piloted with coworkers and acquaintences. The first questionnaire was piloted with 7 different individuals and took an average time of 21 minutes to complete (standard deviation of 5 minutes). The second questionnare was piloted with 4 different individuals and took an average time of 10 minutes to complete (standard deviation of 2 minutes). The responses to the questions provided by this small sample of individuals were not saved or documented, and were intended only for the purpose of gauging the time needed to complete the survey and the clarity of the questions as phrased. Some questions were added, removed or rephrased as a result of this pilot. Additional changes were made subsequently.

Notes to researcher conducting the interview are in italics.

{INITIAL GREETING}
Hello, is (*insert name of resident contact*) home?
Hi (*insert name of resident*), this is (*insert name of researcher*) from Lawrence Berkeley National Lab. Is now a good time to do the 20-30 minute phone interview we had scheduled to do today?

Yes→Great! Then let's begin.
No→Okay… *schedule another time, ideally on the same day, to call back.*

A. GENERAL HOME CHARACTERISTICS

{INTRODUCTION}
I am going to ask you questions about your household, about the physical characteristics of your home, about the appliances in your home, and about how you use appliances, exhaust fans and windows. These questions will help U.S. analyze the measurements we make in your home to better understand the air quality in other homes and households with similar characteristics. You are welcome to say that you don't know or that you decline to answer in response to any of the questions that you are asked.

A.1 Do you rent or own your home? ☐Own ☐Rent

A.2 How many years have you lived in this home? ☐

A.3 In what kind of building do you live?
☐Single, detached house
☐Townhouse or Side-by-Side Duplex
☐Apartment building with 2 to 4 units
☐Apartment building with 5 or more units
☐Mobile home
☐ Other (Please describe): ☐

A.4 In what year was this building constructed? ☐
{Record exact year if known or ask about these ranges.}
If you don't know the exact year, was it…
☐ Before 1950
☐ 1950 to 1979
☐ 1980 to 1995
☐ 1996 to 2005
☐ 2006 or newer
☐ Don't know

A.5 *If the home is a house, townhouse or side-by-side duplex…*

☐ Not Applicable

A.5.1 How many stories are there in your home?

☐ 1 story
☐ 1 ½ story split level
☐ 2 stories
☐ 2 ½ story split level
☐ 3 stories
☐ more than 3 stories

A.5.2 Does the home have a garage, and if so, where is it located?

☐ Attached at side with interior door
☐ Under part of house with interior door
☐ Under part of house with no interior door
☐ Garage not attached, or attached at side without interior door
☐ No garage

A.5.3 *If there is an attached garage…*
Is the garage used regularly for vehicle parking?
☐ Yes ☐ No

A.6 *If home is in a building with multiple units…*

☐ Not Applicable

A.6.1 On what story of the building is your home located? ☐

A.6.2 How many stories in the building? ☐

A.6.3 How many sides of your apartment are on outside walls? ☐

A.6.4 Is there a garage in the building? ☐
(removed question A.6.4.1)

A.7 What is the floor area of your home, in square feet? If you are unsure, please feel free to estimate and note that you are unsure.

Exact if known: ☐
- ☐ Less than 500
- ☐ 500 – 750
- ☐ 751 – 1000
- ☐ 1001 – 1250
- ☐ 1251 – 1500
- ☐ 1501 – 2000
- ☐ 2001 – 2500
- ☐ 2501 – 3000
- ☐ More than 3000
- ☐ Unsure
- ☐ No idea

A.8 How many bedrooms are in the home?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ >5

A.9 How many bathrooms are in the home? *[Toilet only is ½ bath]*

☐ 1 ☐ 1.5 ☐ 2 ☐ 2.5 ☐ 3 ☐ >3

A.10 How many bathroom exhaust fans in the home, including those that don't work?

☐ None present ☐ 1 ☐ 2 ☐ 3 ☐ >3

A.11 Do you have any bathroom fans that don't work well or don't work at all?
- ☐ Don't work well. How many? ☐
- ☐ Don't work at all. How many? ☐
- ☐ All present work well
- ☐ Not applicable; no fans present

A.12 Which *best* describes how the kitchen is connected to other parts of the home?
- ☐ The kitchen is very open: At least one side of the kitchen is open to a large area of the home.
- ☐ The kitchen is mostly open: There is a large doorway or pass-through open to large areas of the home.
- ☐ The kitchen is a separate room with doors that can be closed.

A.12.1 If a separate room, are doors to the kitchen usually kept closed or open?

☐ Open ☐ Closed

A.13 To your knowledge, has the home or building been renovated within the past 5 years to reduce air leakage, for example, is there new caulking or weatherstripping, was their specific air sealing done to the walls, attic, basement or ducts?

☐ Yes ☐ No ☐ Don't know

A.13.1 *If yes*, was a contractor involved in the renovations?

☐ Yes ☐ No ☐ Don't know

A.13.2 *If yes*, was it done through a government sponsored Weatherization program?

☐ Yes ☐ No ☐ Don't know

A.14 Does your home use propane as a fuel for your furnace, hot water heater or another appliance?

☐ No propane
☐ All combustion appliances use propane
☐ Some combustion appliances use propane
☐ Don't know

A.15 Does your home have air-conditioning?

☐ Yes ☐ No

A.15.1 *If yes*, how often do you use it in the middle of the summer?

☐ Every day ☐ Few times per week ☐ Other (explain)

A.16 Do you have a service contract with a heating and air-conditioning company?

☐ Yes
☐ No
☐ I don't know

A.17 Have any of the following changes been made to your home in the last year?

A.17.1 New vinyl flooring: ☐ Yes ☐ No
A.17.2 New carpet: ☐ Yes ☐ No
A.17.3 New furniture: ☐ Yes ☐ No
A.17.4 New cabinets: ☐ Yes ☐ No
A.17.5 New paint: ☐ Yes ☐ No

Removed question A.17.6 regarding presence of water damage.

Only ask questions A.18- A.20 for "High Performance" homes (determined from screening survey).

A.18 Have you achieved or pursued any building certifications for your home? If so, which of the following apply?

- ☐ LEED for Homes
- ☐ Green Point Rated New Home
- ☐ Green Point Rated Existing Home
- ☐ Certified Green Home - NAHB National Green Building Program
- ☐ Environments for Living by MASCO
- ☐ Earth Advantage certified home
- ☐ EPA Indoor Air Plus
- ☐ Living Building Challenge
- ☐ Passive House
- ☐ EarthCraft
- ☐ Energy Star for Homes
- ☐ Deep Energy Retrofit
- ☐ ACI Thousand Home Challenge
- ☐ Other; Please Describe:
- ☐ No building certifications achieved or pursued

A.19 Were healthy building material goals incorporated into your home's design and construction, possibly as part of a green home certification?

☐ Yes ☐ No ☐ I don't know

A.19.1 If yes, which of the following is the most appropriate designation?

- ☐ Living Building Challenge Red List chemical/material avoidance
- ☐ EPA Indoor Air Quality Plus certification
- ☐ U.S. Green Building Council's LEED or other green building rating system's healthy materials credits
- ☐ Tried to avoid VOC's and toxins in paints and other materials
- ☐ Not sure

A.20 Was your home tested for air tightness using a blower door test? This may have been done by your contractor, energy auditor, or HVAC technician as part of a green building, Energy Star or Passive House program.

☐ Yes ☐ No ☐ I don't know

A.20.1 If yes, do you know the result of the blower door test?

- ☐ Yes, it is:
- ☐ I do not know the result, but you may contact my contractor/builder for this information at:
- ☐ I do not know, and please do not contact my building/contractor.

A.21 Were you given a guide by your builder or contractor describing how to operate your home, including equipment and warranty information?

☐ Yes ☐ No ☐ I don't know

B. GENERAL INDOOR AIR QUALITY

The next few questions are about your general indoor air quality and respiratory health.

B.1 How often do you smell cooking or smoking fumes from neighboring homes?

☐ Never
☐ Rarely (once per month or less)
☐ Somewhat often (a few times per month)
☐ Very often (several times per week or more)

B.2 Is there anything outside of your home that you think might affect your indoor air quality, such as a bus stop, busy road or factory?

☐ No
☐ Yes. Please describe: ☐

B.3 Does anyone in your household have asthma or another medical condition that affects breathing?

☐ Yes ☐ No

The next few questions address features of your home and actions that you take to manage indoor air quality.

B.4 Which features of your home most contribute to good indoor air quality? List up to five.

B.5 Are there any features of your home that contribute to bad indoor air quality? If so, list up to five.

B.6 What actions do you take to improve or manage indoor air quality in your home? List up to five.

(3 questions removed regarding perceived "stuffiness" in home or presence of lingering odors)

The next two questions ask about dampness and mold in your home environment. Dampness or mold may result from leaks, flooding, or condensation on windows or walls.

B.7 Signs of dampness or moisture may include water stains, peeling paint, or rotten wood. In the past 12 months, have there been any signs of continual or repeated dampness or moisture in your home?

☐ Yes ☐ No ☐ Don't know

B.7.1 *If yes*, in what parts of your home?

- ☐ Main bathroom
- ☐ Second bathroom
- ☐ Basement or garage
- ☐ Bedroom
- ☐ Other location: ☐
- ☐ Decline to state

B.8 In the past 12 months, has anyone SEEN mold or SMELLED moldy or musty odors inside your home? Do not include mold on food [*small amount of mold in shower (such as on tile grout, shower curtain or shower doors) counts as "No"].*

☐ Yes ☐ No ☐ Don't know

B.8.1 *If yes*, in what parts of your home?

- ☐ Main bathroom
- ☐ Second bathroom
- ☐ Basement or garage
- ☐ Bedroom
- ☐ Other location: ☐
- ☐ Decline to state

C. HEATING CHARACTERISTICS

The next set of questions is about how you heat your home.

C.1 Which of the following types of heater is used as the main source of heat in your home? In the questions that follow, this will be referred to as your primary heater.

Heating System	Primary
Forced-air furnace (Blows warm air from several locations) – § D	☐
Wall furnace – § E	☐
Floor furnace – § F	☐
Oven or stove – § G	☐
Gas fireplace (gas fireplace does not burn wood) – § H	☐
Vent-free blue flame wall heater – § I	☐
Portable space heater – § J	☐
Heat Pump	☐
Baseboard electric	☐
Hot water radiator	☐
Wood fireplace or wood stove	☐
Other. Please describe: ☐	☐

C.2 Do you use any other heaters in addition to your primary heater? Please indicate which of the following are used, in order of the frequency that they are used. These will be referred to as supplemental heaters.

Heating System	Supplemental
Forced-air furnace (Blows warm air from several locations) – § D	☐
Wall furnace – § E	☐
Floor furnace – § F	☐
Oven or stove – § G	☐
Gas fireplace (gas fireplace does not burn wood) – § H	☐
Vent-free blue flame wall heater – § I	☐
Portable space heater – § J	☐
Heat Pump	☐
Baseboard electric	☐
Hot water radiator	☐
Wood fireplace or wood stove	☐
Other. Please describe:________________________________	☐

If primary heater was marked with a § for follow-up….

C.1.1 How often is your primary heater used during the middle of winter?

☐ Every day ☐ Few times per week ☐ Other (explain)

C.2.1 *If relevant*…how often is your first supplemental heater used during the middle of winter?
☐ Every day ☐ Few times per week ☐ Other (explain)

C.2.2 *If relevant*…how often is your second supplemental heater used during the middle of winter?
☐ Every day ☐ Few times per week ☐ Other (explain)

C.2.3 *If relevant*…how often is your third supplemental heater used during the middle of winter?
☐ Every day ☐ Few times per week ☐ Other (explain)

D. CENTRAL FORCED AIR FURNACE (*Repeat for each forced air furnace.)*

D.1 *Interviewer indicates here if this is primary or supplemental heater:*

☐ *Primary* ☐ *Supplemental*

D.2 Is this furnace powered by natural gas, electricity or propane?

☐ Gas ☐ Electricity ☐ Propane ☐ Don't know

If not sure, provide the following guidance:

If you are not sure, one way to tell is if your gas bill goes up a lot in the winter compared to the summer. If the gas bill goes up a lot, the furance is probably gas.

[If powered by electricity, skip to next section]

D.3 Where is this furnace located?

☐ Attic or roof
☐ Crawl space, basement, or garage under living space
☐ Side-attached garage
☐ Closet in main living area
☐ Don't know

D.4 Approximately how many years old is this furnace? If you are unsure, please feel free to estimate and note that you are unsure.

☐ 0-5
☐ 6-10
☐ 11-15
☐ 16+
☐ Unsure
☐ Don't know

D.5 If you don't know, has it been replaced since you moved in?

☐ Yes ☐ No ☐ Don't recall

D.6 Has this furnace been checked or serviced by a professional in the past 3 years?

☐ Yes ☐ No ☐ Not sure about 3; but not during the past ☐ years

D.7 How often do you change your furnace filter?

☐ Every 1-3 months
☐ Every 3-6 months
☐ Every 6-12 months
☐ Less than once a year
☐ Never

☐ I don't know

E. WALL FURNACE

Repeat for each wall furnace.

E.1 *Interviewer indicates here if this is primary or supplemental heater:*
☐ *Primary* ☐ *Supplemental*

E.2 Is this furnace powered by natural gas, electricity or propane?
☐ Gas ☐ Electricity ☐ Propane ☐ Don't know

E.3 *If single family home or townhouse with more than one story…*
On which story is this furnace located?
☐ 1st floor ☐ 2nd floor ☐ 3rd floor ☐ Not applicable

E.4 Is this a tall furnace set into the wall or a short, wide furnace that sits next to the wall?
☐ Tall – set into wall ☐ Short, wide – next to wall

E.5 In which room is the furnace located? ☐

E.6 Approximately how many years old is this furnace? If you are unsure, please feel free to estimate and note that you are unsure.

☐ 0-5
☐ 6-10
☐ 11-15
☐ 16+
☐ Unsure
☐ No idea

E.6.1 If you can't estimate, has it been replaced since you moved in?
☐ Yes ☐ No ☐ Don't recall

E.7 Has this furnace been checked or serviced by a professional in the past 3 years?
☐ Yes ☐ No ☐ Not sure about 3; but not during the past ☐ years

E.8 *If wall furnace is gas or propane…*
Does this furnace have a pilot burner? A pilot burner is a small flame that always burns and is used to light the main burner when the furnace turns on.
☐ Yes ☐ No ☐ Don't know ☐ Not applicable

E.9 Are there now or have there been in the past, any black deposits on the wall just above the furnace?
☐ Yes ☐ No ☐ Don't know

E.10 In the past 3 years, have there been any periods when your furnace has not operated properly?

☐ Yes ☐ No ☐ Not sure

E.10.1 *If yes…b*riefly describe the problem: ☐.

F. FLOOR FURNACE

Repeat for each floor furnace.

F.1 *Interviewer indicates here if this is primary or supplemental heater:*
☐ *Primary* ☐ *Supplemental*

F.2 Approximately how many years old is this furnace? If you are unsure, please feel free to estimate and note that you are unsure.

☐ 0-5
☐ 6-10
☐ 11-15
☐ 16+
☐ Unsure
☐ No idea

F.2.1 If you can't estimate, has it been replaced since you moved in?
☐ Yes ☐ No ☐ Don't recall

F.3 Has this furnace been checked or serviced by a professional in the past 3 years?
☐ Yes ☐ No ☐ Not sure about 3; but not during the past ☐ years

F.4 In which room is the furnace located? ☐

F.4.1 *[If single family home or townhouse with more than one story]* On which story is this furnace located? ☐ 1st floor ☐ 2nd floor ☐ 3rd floor ☐ Not applicable

F.5 In the past 3 years, have there been any periods when your furnace has not operated properly?
☐ Yes ☐ No ☐ Not sure

F.5.1 *If yes...b*riefly describe the problem: ☐.

G. OVEN AND STOVE USED FOR HEATING

G.1 *Interviewer indicates here if this is primary or supplemental heater:*

☐ *Primary* ☐ *Supplemental*

G.2 Which of your cooking appliances do you use most often for heat?

☐ Stovetop
☐ Oven
☐ Both

G.3 Why do you use your stove and/or oven for heat?

☐ Other heater broken
☐ Other heater doesn't provide enough heat
☐ Just to heat the kitchen
☐ Other, explain: ☐

H. GAS FIREPLACE

Repeat for each gas fireplace.

H.1 *Interviewer indicates here if this is primary or supplemental heater:*
☐ *Primary* ☐ *Supplemental*

H.2 Is this gas fireplace powered by natural gas or propane?
☐ Gas ☐ Propane ☐ Don't know

H.3 Is this gas fireplace controlled by a thermostat?
☐ Yes ☐ No

H.4 If you live in a house or townhouse with more than one story, on which story is this gas fireplace located? ☐ 1st floor ☐ 2nd floor ☐ 3rd floor

H.5 In which room is the fireplace located?

H.6 Is this gas fireplace set into the wall or does it sit in the room?
☐ Inside wall ☐ Out in room

H.7 Approximately how many years old is this gas fireplace? If you are unsure, please feel free to estimate and note that you are unsure.

☐ 0-5
☐ 6-10
☐ 11-15
☐ 16+
☐ Unsure
☐ No idea

H.8 Has this furnace been checked or serviced by a professional in the past 3 years?
☐ Yes ☐ No ☐ Not sure about 3; but not during the past ______ years

H.9 Is this fireplace vented or vent-free?
☐ Vent-free ☐ Vented

H.10 Did you buy this furnace? If so, do you recall how and where you bought it?

☐ Not applicable; did not buy it
☐ Internet from retailer
☐ Internet from private seller
☐ Store outside of California

☐ Store inside of California

H.11 In the past 3 years, have there been any periods when your furnace has not operated properly?

☐ Yes ☐ No ☐ Not sure

H.11.1 *If yes…b*riefly describe the problem: ☐.

I. VENT-FREE BLUE FLAME WALL HEATER

Repeat for each wall heater. (These are uncommon in CA.)

I.1 *Interviewer indicates here if this is primary or supplemental heater:*

☐ *Primary* ☐ *Supplemental*

I.2 If you live in a house or townhouse with more than one story, on which story is this gas fireplace located? ☐ 1st floor ☐ 2nd floor ☐ 3rd floor

I.3 In which room is the furnace located? ☐

I.4 Approximately how many years old is this wall heater? If you are unsure, please feel free to estimate and note that you are unsure.

☐ 0-5
☐ 6-10
☐ 11-15
☐ 16+
☐ Unsure
☐ No idea

I.5 Has this wall heater been checked or serviced by a professional in the past 3 years?

☐ Yes ☐ No ☐ Not sure about 3; but not during the past ☐ years

I.6 Did you buy this furnace? If so, do you recall how and where you bought it?

☐ Not applicable; did not buy it
☐ Internet, from retailer
☐ From private seller outside of California
☐ From private seller inside of California
☐ Store outside of California
☐ Store inside of California

I.7 In the past 3 years, have there been any periods when your furnace has not operated properly?

☐ Yes ☐ No ☐ Not sure

I.7.1 *If yes…*briefly describe the problem: ☐

.

J. PORTABLE SPACE HEATER

Repeat for each space heater.

J.1 *Interviewer indicates here if this is primary or supplemental heater:*

☐ *Primary* ☐ *Supplemental*

J.2 Is this PORTABLE heating appliance powered by natural gas, propane or kerosene?

- ☐ Electricity
- ☐ Propane
- ☐ Kerosene
- ☐ Don't know
- ☐ Other

J.3 Approximately how many years old is this portable heater? If you are unsure, please feel free to estimate and note that you are unsure.

- ☐ 0-5
- ☐ 6-10
- ☐ 11-15
- ☐ 16+
- ☐ Unsure
- ☐ No idea

J.4 If this is used for supplementary heat, why do you use it?

- ☐ Other heater broken
- ☐ Other heater doesn't provide enough heat
- ☐ Other, explain: ☐

J.5 [*If heater is propane or kerosene*] Did you buy this heater? If so, do you recall how and where you bought it?

- ☐ Not applicable; did not buy it
- ☐ Internet, from retailer
- ☐ From private seller outside of California
- ☐ From private seller inside of California
- ☐ Store outside of California
- ☐ Store inside of California

J.6 In the past 3 years, have there been any periods when your furnace has not operated properly?

☐ Yes ☐ No ☐ Not sure

J.6.1 *If yes…b*riefly describe the problem: ☐

.

K. WATER HEATER CHARACTERISTICS

K.1 Please note all of the following types of water heaters that you use in your home. A storage water heater is the most common type; it has a large tank that stores heated water. On-demand or "tankless" water heaters heat water as needed.

☐ Storage water heater
☐ On-demand water heater that serves much or all of the home→ *Skip to §L*
☐ Solar water heating system (may be combined with storage water heater)
☐ Other (describe)

K.2 Is this water heater powered by natural gas, electricity or propane?
[If not sure, can ask if there is a large exhuast duct atop the water heater]

☐ Natural gas
☐ Propane
☐ Electric→ *Skip to §L*

K.3 Do you have more than one storage water heater?

☐ Yes ☐ No *[If yes, repeat all of the following questions for each.]*

K.4 Does this water heater provide most of the hot water for your home?

☐ Yes (primary) ☐ No (supplemental)

K.5 Where is this water heater located?

☐ Outside
☐ Basement or garage under living space
☐ Side-attached garage
☐ Closet in main living area
☐ Laundry room
☐ Other location in main living area

K.6 Approximately how old is this water heater? If you are unsure, please feel free to estimate and note that you are unsure.

☐ 0-5
☐ 6-10
☐ 11-15
☐ 16+
☐ Unsure
☐ No idea

K.6.1 If you can't estimate, has it been replaced since you moved in? ☐ Yes ☐ No

K.7 Has this WATER HEATER been checked or serviced by a professional in the past 3 years?

☐ Yes ☐ No ☐ Not sure about 3; but not during the past ☐ years

K.8 Is this water heater a "power vent" water heater? One way to tell is that a power vent water heater has a noisy fan or blower on top.

☐ power vent water heater ☐ *not* power vented

L. CLOTHES DRYER CHARACTERISTICS

L.1 Do you have a clothes dryer in your residence?

☐ Yes ☐ No

L.2 If yes, is this dryer powered by natural gas, electricity or propane?

☐ Gas ☐ Electricity ☐ Propane ☐ Don't know

[If dryer is electric, skip to §M]

L.3 Approximately how old is this dryer? If you are unsure, please feel free to estimate and note that you are unsure.

☐ 0-5
☐ 6-10
☐ 11-15
☐ 16+
☐ Unsure
☐ No idea

L.4 Where is this dryer located?

☐ Basement or garage under living space
☐ Side-attached garage
☐ Closet or laundry room in main living area

Is the door to this room typically open, or does the door have louvered openings?

☐ Typically open or lovered openings ☐ Not open

☐ Other location in main living area

L.5 Is this dryer vented to the outdoors? In other words, is there an exhaust duct that directs air from the dryer to the outside of the house?

☐ Yes ☐ No ☐ Don't know

M. KITCHEN APPLIANCE CHARACTERISTICS

The next few questions are about appliances in your kitchen. The questions may be easier to answer if you are in the kitchen, looking at the appliances.

M.1 Are your COOKTOP and OVEN part of the same appliance – a cooking range – or separate?

☐ Together ☐ Separate

M.2 Is the COOKTOP powered by natural gas, electricity or propane?

☐ Natural Gas ☐ Electricity ☐ Propane

If the cooktop is natural gas or propane, please ask questions M.2.1-M.2.3 below.

M.2.1 Do the cooktop burners have a pilot light, electronic ignition or light by match? Electronic ignition uses a small spark to light the flame. If the COOKTOP makes a clicking sound when you turn the knob to start the flame, it is electronic ignition.

☐ Electronic ☐ Pilot ☐ Match light

M.2.2 Are the burners sealed or open? Open burners have openings around the burner, such that food can fall through.

☐ Sealed ☐ Open

M.2.3 How many burners are on the cooktop? (Central griddle or grill counts as 1 burner)

☐ 1 ☐ 2 ☐ 4 ☐ 5 ☐ 6

M.3 Approximately how old is the cooktop? If you are unsure, please feel free to estimate and note that you are unsure.

☐ 0-5
☐ 6-10
☐ 11-15
☐ 16+
☐ Unsure
☐ No idea

M.3.1 If you can't estimate, has it been replaced since you moved in? ☐ Yes ☐ No

M.4 When cooking, do you more often use the front or back burners, or do you use all the burners equally?

☐ Front burners ☐ Back burners ☐ Use both equally ☐ I don't know

M.5 If separate from the cooktop, is the OVEN powered by natural gas, electricity or propane?

☐ Natural Gas ☐ Electricity ☐ Propane

If the oven is natural gas or propane, please ask questions M.4.1 and M.4.2 below.

M.5.1 Does the oven burner have a pilot light, electronic ignition or do you light it by match?

☐ Electronic ☐ Pilot ☐ Match light

M.5.2 Does the oven have a broiler with controls that are separate from the rest of the oven?

☐ Yes ☐ No ☐ Don't know

M.6 Does the oven have a self-clean setting? ☐ Yes ☐ No ☐ Don't know

M.7 Do you cook using your stove or oven more often in the winter compared to other seasons?

☐ Yes ☐ No

M.8 Do you have any of the following types of KITCHEN EXHAUST fans in the home? Please indicate all that apply.

☐ Range hood above the cooktop
☐ Microwave and exhaust fan combination above the cooktop
☐ Downdraft exhaust at the back of the cooktop
☐ Downdraft exhaust in the middle of the cookop
☐ Exhaust fan in ceiling or wall above cooktop
☐ Exhasut fan in ceiling or wall not above the cooktop
☐ Other. Please describe:
☐ There is no exhaust system in the kitchen

M.9 If you have a range hood or microwave exhaust fan above the cooktop, does it exhaust to the outdoors or does it have grills or holes in the front where it blows air back into the kitchen?

☐ Exhaust to the outdoors
☐ Blows air back to the kitchen
☐ Doesn't work
☐ Don't know
☐ No hood

If uncertain, provide this guidance. If you can feel air being blown back out from the device through a grill or set of holes at the top, it probably does not exhaust. If you can see a duct going from the top of the hood up toward the roof or back into the wall, it exhausts. This duct may be inside a cabinet above the range hood.

M.10 How many fan settings does your range hood or microwave have?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ Continuously variable control knob

M.11 How noisy is the <u>lowest</u> fan setting on your range hood?

☐ Quiet, barely noticeable
☐ Noticeable but does not interfere with conversation
☐ Interferes with conversation or radio or TV but can talk over it
☐ Loud; can't have conversation or hear radio or TV

M.12 How noisy is the <u>highest</u> fan setting on your range hood?

☐ Quiet, barely noticeable
☐ Noticeable but does not interfere with conversation
☐ Interferes with conversation or radio or TV but can talk over it
☐ Loud; can't have conversation or hear radio or TV

N. OTHER EXHAUST SYSTEMS CHARACTERISTICS

The next few questions are about OTHER EXHAUST SYSTEMS in your home.

N.1 To your knowledge, does your home have a ventilation fan that operates continuously or on a set schedule? These devices are most commonly found in very new houses, in homes that have been “air sealed” for energy efficiency and in some apartment buildings.

☐ Yes ☐ No ☐ I don’t know

N.1.1 *[If yes]*, please describe: ☐

Can give these options:

☐ Continuous exhaust fan
☐ Heat or energy recovery ventilator
☐ “Fresh Vent” that directs outdoor air into the heating and cooling system

N1.2 *[If yes]* Have you ever disabled or turned off your ventilation system?

☐ Yes ☐ No ☐ I don’t know

N1.2 *[If yes]* Why did you disable or turn off the ventilation system?

☐ Not needed
☐ Too noisy
☐ Wastes energy
☐ Doesn’t work well
☐ Open window instead
☐ Causes a cold draft in winter
☐ Other (explain)

N1.3 *[If answer to N.1 is “yes”, and home is a “High Performance Home”*] Does your home’s continuous ventilation system have any of the following?

☐ Thermostat
☐ Humidity controller (in the bathroom for example)
☐ Speed control (for changing from low to high speed for example)
☐ Motion sensor
☐ CO_2 sensor
☐ No controls that I know of
☐ I don’t know

N1.4 *[If answer to N.1 is “yes”, and home is a “High Performance Home”*] Do you or a service technician perform maintanance on your home’s continuous ventilation system?

☐ Yes ☐ No ☐ I don't know

N1.4.1 *[If yes]* which of the following do you perform?

- ☐ Changing filters
- ☐ Cleaning filters
- ☐ Replacing heat exchanger elements (the "core") of the ERV/HRV
- ☐ I don't know
- ☐ Other. Please describe:

N.2 In the most used full bathroom, how is the exhaust fan used? *Mark all that apply*.

- ☐ Fan operates continuously
- ☐ Always when showering or bathing
- ☐ As needed to remove steam when showering or bathing
- ☐ Used by some but not everyone when showering or bathing
- ☐ As needed to remove odors
- ☐ Not very often or never
- ☐ Fan doesn't work
- ☐ No fan in this bathroom

N.3 If your main bathroom exhaust fan is not used routinely, why not? Check all that apply.

- ☐ Don't think about it
- ☐ Not needed
- ☐ Too noisy
- ☐ Wastes energy
- ☐ Broken
- ☐ Doesn't work well
- ☐ Open window instead
- ☐ Other (explain)

(Deleted the question: "In the second most used full bathroom, how is the exhaust fan used?")

O. HOUSEHOLD OCCUPANY, ACTIVITY, and DEMOGRAPHICS

The next few questions ask about activities that could impact air quality in your home.

0.1 During a typical week, on how many days does anyone in your household use the cooktop or oven for meals or at other times? Please include using the cooktop to boil water.

	All (7)	Most (4-6)	Some (1-3)	Rarely or never (<1)
BREAKFAST	☐	☐	☐	☐
LUNCH	☐	☐	☐	☐
DINNER	☐	☐	☐	☐
Any other time	☐	☐	☐	☐

0.2 How often do you cook with these other appliances inside your home?

	1+ times per day	Few times per week	<1 time per week	Never
Microwave	☐	☐	☐	☐
Toaster oven	☐	☐	☐	☐
Toaster	☐	☐	☐	☐
Electric wok	☐	☐	☐	☐
Electric grill	☐	☐	☐	☐
Propane grill	☐	☐	☐	☐
Rice Cooker	☐	☐	☐	☐
Electric Crokpot	☐	☐	☐	☐
Other (specify)	☐	☐	☐	☐

0.3 Do you ever cook indoors with charcoal briquettes? ☐ Yes ☐ No

0.4 Do you ever use a power generator indoors that burns fuel? ☐ Yes ☐ No

The next few questions ask about window opening in your home.

0.5 How often do you have windows open in your house during this time of year?

☐ More than half the time
☐ Several hours per day
☐ Less than an hour each day
☐ Usually closed all day

O.6 Which windows are opened most often (indicate all that apply)?

☐ Bedroom
☐ Bathroom
☐ Kitchen
☐ Common room (living room, entryway, etc.)
☐ Other

We will end with a few questions about your <u>household</u>. This information will help U.S. relate what we measure in your home to other homes across California.

O.7 How many people live in your home at this time?

O.8 How many people in your home are in each age group?

0-5 years: ☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
6-17 years: ☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
18-30 years: ☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
31-64 years: ☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
65+ years: ☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

O.9 What is the highest education level of anyone in the household?

☐ Grade school
☐ Some high school
☐ Completed high school
☐ Some college or trade school
☐ Associates degree or trade school completion
☐ College degree
☐ Graduate degree

O.10 Please indicate all races and/or ethnicities of people living in your household.

☐ American Indian, Alaska Native
☐ Asian or Pacific Islander
☐ Black, African American
☐ Hispanic / Latino
☐ White, Caucasian
☐ Other; please list if you wish: .
☐ Prefer not to answer

0.11 What is the total income for all members of your household combined?

- ☐ Less than $25,000
- ☐ $25,000 - $49,999
- ☐ $50,000 - $74,999
- ☐ $75,000 - $99,999
- ☐ $100,000 - $150,000
- ☐ >$150,000
- ☐ Prefer not to answer

[If home is owned by residensts]
0.12 If your furnace were to break, and required $200 worth of repairs, how soon would you be able to afford these repairs?
☐ Right away ☐ Within a week ☐ Within a month ☐ Not sure

0.13 If your furnace were to break beyond repair, and cost $1000 to replace or repair, how soon would you be able to afford to afford to do this?
☐ Right away ☐ Within a week ☐ Within a month ☐ Not sure

[If home is rented by residents]
0.14 How reliable is your landlord at making repairs to appliances when needed?

☐ HARDLY or NOT reliable:

The landlord is generally unresponsive when we request that an appliance in the home be inspected or repaired.

☐ SOMEWHAT reliable:

The landlord responds eventually to requests to have appliances repaired, but not always right away.

☐ VERY reliable:

The landlord can be counted on to make repairs to appliances in a timely manner when needed.

0.13 *Note the gender of the resident responding to the survey:*
☐ *Male* ☐ *Female* ☐ *Unclear from voice*

0.14 Is there anything more you would like to say about your house related to this study?

☐

0.15 This study will continue for another year after this one, and we may make some changes to this survey. Are there any changes that you recommend we make to this survey to make the questions easier to understand or to make taking the survey more convenient?

If yes, describe:

Thank you very much for your time and help.

EXIT INTERVIEW: QUESTIONS ABOUT WEEK OF SAMPLING

1. During the past week (WEEKDAYS), was anyone in the home during the following periods? Please count anyone in the home even if they don't live there. Answer "usually" if 3 or more days; "sometimes" if 1-2 days.

After breakfast and before lunch	☐ Usually	☐ Sometimes	☐ Rarely
During lunch	☐ Usually	☐ Sometimes	☐ Rarely
After lunch until dinner	☐ Usually	☐ Sometimes	☐ Rarely
During dinner	☐ Usually	☐ Sometimes	☐ Rarely
After dinner until bedtime	☐ Usually	☐ Sometimes	☐ Rarely

(removed two time categories)

2. During the past WEEKEND, was anyone in the home during the following periods? Please count anyone in the home even if they don't live there.

After breakfast and before lunch	☐ Saturday	☐ Sunday
During lunch	☐ Saturday	☐ Sunday
After lunch until dinner	☐ Saturday	☐ Sunday
During dinner	☐ Saturday	☐ Sunday
After dinner until bedtime	☐ Saturday	☐ Sunday

(Changed options from "usually" "sometimes" and "rarely" to "Saturday" and "Sunday." Also, removed two time categories)

3. During the past week, were any of the following used to heat your home? Check all that apply.

- ☐ Central forced-air furnace
- ☐ Wall furnace
- ☐ Floor furnace
- ☐ Gas oven or stove
- ☐ Electric oven or stove
- ☐ Gas fireplace
- ☐ Wood fireplace
- ☐ Wood stove
- ☐ Heat Pump
- ☐ Baseboard electric
- ☐ Portable electric space heater
- ☐ Portable space heater that burns fuel
- ☐ Other. Please describe:

Please can you tell me a bit more about how you used these heating devices?

4. MOST used heater: ☐

4.a How often was it used? ☐ Every day ☐ 4-6 days ☐ 1-3 days

4.b When was it used? *Check all that apply.*
☐ Weekday morning ☐ Weekday afternoon ☐ Weekday evening
☐ Weekend morning ☐ Weekend afternoon ☐ Weekend evening
☐ Overnight

5. SECOND most used heater: ☐

5.a How often was it used? ☐ Every day ☐ 4-6 days ☐ 1-3 days

5.b When was it used? *Check all that apply.*
☐ Weekday morning ☐ Weekday afternoon ☐ Weekday evening
☐ Weekend morning ☐ Weekend afternoon ☐ Weekend evening
☐ Overnight

6. THIRD most used heater: ☐

6.a How often was it used? ☐ Every day ☐ 4-6 days ☐ 1-3 day

6.b When was it used? *Check all that apply.*
☐ Weekday morning ☐ Weekday afternoon ☐ Weekday evening
☐ Weekend morning ☐ Weekend afternoon ☐ Weekend evening
☐ Overnight

The next few questions ask how often you opened your windows over the past week.

7. On how many nights did you leave any windows open OVERNIGHT?
☐ All ☐ Most (4-6) ☐ Some (1-3) ☐ None
7.a Typically how many windows were open? ☐

8. On how many days did you open any windows in the MORNING?
☐ All ☐ Most (4-6) ☐ Some (1-3) ☐ None
8.a Typically how many windows were open? ☐

9. On how many days did you leave any windows open during the DAY?

☐ All ☐ Most (4-6) ☐ Some (1-3) ☐ None

9.a Typically how many windows were open? ☐

10. On how many days did you have any windows open during the EVENING?

☐ All ☐ Most (4-6) ☐ Some (1-3) ☐ None

10.a Typically how many windows were open? ☐

(deleted question: "During the past week, what was the weather during the middle of the DAY/Night?")

11. During the past week, on how many days did anyone in the household use the COOKTOP to cook during the following times:

BREAKFAST	☐ 7	☐ 5-6	☐ 3- 4	☐ 1-2	☐ <1
LUNCH	☐ 7	☐ 5-6	☐ 3- 4	☐ 1-2	☐ <1
DINNER	☐ 7	☐ 5-6	☐ 3- 4	☐ 1-2	☐ <1
Any other time	☐ 7	☐ 5-6	☐ 3- 4	☐ 1-2	☐ <1

12. During the past week, on how many days did anyone in household use the OVEN to cook during the following times:

BREAKFAST	☐ 7	☐ 5-6	☐ 3- 4	☐ 1-2	☐ <1
LUNCH	☐ 7	☐ 5-6	☐ 3- 4	☐ 1-2	☐ <1
DINNER	☐ 7	☐ 5-6	☐ 3- 4	☐ 1-2	☐ <1
Any other time	☐ 7	☐ 5-6	☐ 3- 4	☐ 1-2	☐ <1

13. Did you use the self-cleaning cycle of your oven during the past week? ☐ Yes ☐ No

13.a *(If yes)* Do you remember when? ☐

14. During the past week, how often did any smoking, candle or incense use occur in the home?

☐ More than 3 times per DAY
☐ 1 to 3 times per DAY
☐ 3 to 6 times over the course of the WEEK
☐ 1 to 2 times over the WEEK

☐ None

15. How many loads of laundry did you dry in your dryer during the past week?
☐ >10 ☐ 6-10 ☐ 1-5 ☐ None

16. Did anyone in your home use the cooktop or oven to cook in the past 24 h? ☐ Yes ☐ No

16.1 *[If yes]* How many times?

17. Please tell me about the <u>FIRST</u> cooking event. Approximately what time did it occur?

☐ Before 9:00 am
☐ 9:00 am – 11:00 am
☐ 11:00 am – 2:00 pm
☐ 2:00 pm – 5:00 pm
☐ 5:00 pm – 8:00 pm
☐ After 8:00 pm
☐ Not applicable

17.a Was the oven used? ☐ Yes ☐ No

17.b *If oven used…*What was the oven temperature setting?

☐ Not used
☐ <300 °F
☐ 300-400 °F
☐ >400 °F

17.c *If oven used…*How many minutes was the oven used?
☐ <30 ☐ 30-60 ☐ 60-90 ☐ >90

17.d How many cooktop burners were used?
☐ 1 ☐ 2 ☐ 3 ☐ 4

17.e *If relevant…*How many minutes was the first burner used?
☐ <10 ☐ 10-30 ☐ 30-60 ☐ >60

17.f *If relevant…*How many minutes was the second burner used?
☐ <10 ☐ 10-30 ☐ 30-60 ☐ >60

17.g *If relevant…*How many minutes was the third burner used?
☐ <10 ☐ 10-30 ☐ 30-60 ☐ >60

17.h *If relevant…*How many minutes was the fourth burner used?

☐ <10 ☐ 10-30 ☐ 30-60 ☐ >60

17.i Did you use the exhaust fan during cooking?

☐ For entire time ☐ Part of time ☐ Not at all

17.j Did you open any windows specifically to remove cooking fumes, smoke or odors?

☐ For entire time ☐ Part of time ☐ Not at all

18. Please tell me about the <u>SECOND</u> cooking event. Approximately what time did it occur?

☐ Before 9:00 am
☐ 9:00 am – 11:00 am
☐ 11:00 am – 2:00 pm
☐ 2:00 pm – 5:00 pm
☐ 5:00 pm – 8:00 pm
☐ After 8:00 pm
☐ Not applicable

18.a Was the oven used? ☐ Yes ☐ No

18.b *If oven used...*What was the oven temperature setting?

☐ Not used
☐ <300 °F
☐ 300-400 °F
☐ >400 °F

18.c *If oven used...*How many minutes was the oven used?

☐ <30 ☐ 30-60 ☐ 60-90 ☐ >90

18.d How many cooktop burners were used?

☐ 1 ☐ 2 ☐ 3 ☐ 4

18.e *If relevant...*How many minutes was the first burner used?

☐ <10 ☐ 10-30 ☐ 30-60 ☐ >60

18.f *If relevant...*How many minutes was the second burner used?

☐ <10 ☐ 10-30 ☐ 30-60 ☐ >60

18.g *If relevant...*How many minutes was the third burner used?

☐ <10 ☐ 10-30 ☐ 30-60 ☐ >60

18.h *If relevant...*How many minutes was the fourth burner used?

☐ <10 ☐ 10-30 ☐ 30-60 ☐ >60

18.i Did you use the exhaust fan during cooking?

☐ For entire time ☐ Part of time ☐ Not at all

18.j Did you open any windows specifically to remove cooking fumes, smoke or odors?

☐ For entire time ☐ Part of time ☐ Not at all

19. Please tell me about the <u>THIRD</u> cooking event. Approximately what time did it occur?

- ☐ Before 9:00 am
- ☐ 9:00 am – 11:00 am
- ☐ 11:00 am – 2:00 pm
- ☐ 2:00 pm – 5:00 pm
- ☐ 5:00 pm – 8:00 pm
- ☐ After 8:00 pm
- ☐ Not applicable

19.a Was the oven used? ☐ Yes ☐ No

19.b *If oven used*...What was the oven temperature setting?

- ☐ Not used
- ☐ <300 °F
- ☐ 300-400 °F
- ☐ >400 °F

19.c *If oven used*...How many minutes was the oven used?

☐ <30 ☐ 30-60 ☐ 60-90 ☐ >90

19.d How many cooktop burners were used?

☐ 1 ☐ 2 ☐ 3 ☐ 4

19.e *If relevant*...How many minutes was the first burner used?

☐ <10 ☐ 10-30 ☐ 30-60 ☐ >60

19.f *If relevant*...How many minutes was the second burner used?

☐ <10 ☐ 10-30 ☐ 30-60 ☐ >60

19.g *If relevant*...How many minutes was the third burner used?

☐ <10 ☐ 10-30 ☐ 30-60 ☐ >60

19.h *If relevant*...How many minutes was the fourth burner used?

☐ <10 ☐ 10-30 ☐ 30-60 ☐ >60

19.i Did you use the exhaust fan during cooking?

☐ For entire time ☐ Part of time ☐ Not at all

19.j Did you open any windows specifically to remove cooking fumes, smoke or odors?

☐ For entire time ☐ Part of time ☐ Not at all

20. Please tell me about the FOURTH cooking event. Approximately what time did it occur?

- ☐ Before 9:00 am
- ☐ 9:00 am – 11:00 am
- ☐ 11:00 am – 2:00 pm
- ☐ 2:00 pm – 5:00 pm
- ☐ 5:00 pm – 8:00 pm
- ☐ After 8:00 pm
- ☐ Not applicable

20.a Was the oven used? ☐ Yes ☐ No

20.b *If oven used*...What was the oven temperature setting?

- ☐ Not used
- ☐ <300 °F
- ☐ 300-400 °F
- ☐ >400 °F

20.c *If oven used*...How many minutes was the oven used?

☐ <30 ☐ 30-60 ☐ 60-90 ☐ >90

20.d How many cooktop burners were used?

☐ 1 ☐ 2 ☐ 3 ☐ 4

20.e *If relevant*...How many minutes was the first burner used?

☐ <10 ☐ 10-30 ☐ 30-60 ☐ >60

20.f *If relevant*...How many minutes was the second burner used?

☐ <10 ☐ 10-30 ☐ 30-60 ☐ >60

20.g *If relevant*...How many minutes was the third burner used?

☐ <10 ☐ 10-30 ☐ 30-60 ☐ >60

20.h *If relevant*...How many minutes was the fourth burner used?

☐ <10 ☐ 10-30 ☐ 30-60 ☐ >60

20.i Did you use the exhaust fan during cooking?

☐ For entire time ☐ Part of time ☐ Not at all

20.j Did you open any windows specifically to remove cooking fumes, smoke or odors?

☐ For entire time ☐ Part of time ☐ Not at all

21. If you have a kitchen exhaust fan or range hood, how often is it used?

- ☐ Most times (*75% or more*) when cooktop or oven is used
- ☐ Most times when cooktop is used but not when oven is used
- ☐ About half the time
- ☐ Infrequently; only when needed
- ☐ Never

22. When the range hood is used, which fan speed is most commonly selected?

- ☐ Lowest setting
- ☐ Medium setting
- ☐ Highest setting
- ☐ Only one speed available
- ☐ Varies or changes depending on what is being cooked
- ☐ Don't know or prefer not to say

23. If you use your range hood sometimes or only when needed, do you use it for any of the following reasons? Check all that apply.

- ☐ Remove smoke
- ☐ Remove heat
- ☐ Remove odors
- ☐ Remove steam / moisture
- ☐ During oven cleaning
- ☐ Other (explain)

24. If your range hood is not used routinely, why not? Check all that apply.

- ☐ Don't think about it
- ☐ Not needed
- ☐ Too noisy
- ☐ Wastes energy
- ☐ Broken
- ☐ Doesn't work well
- ☐ Open window instead
- ☐ Other (explain)

25. How often do you clean the grease screens?

- ☐ Each week
- ☐ Each month
- ☐ As needed
- ☐ Never
- ☐ No grease screens

26. Does your kitchen exhaust fan have a carbon/charcoal filter?
☐ Yes ☐ No ☐ I don't know

26.a *[If yes]* Does this filter need to be periodically replaced?
☐ Yes ☐ No ☐ I don't know

Have you ever had any of the following problem with any of the cooktop burners?

27. Burners slow to ignite or won't ignite? ☐ Yes ☐ No
27.a *If yes*, How many burners? ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 4+

28. Burners can't be turned down from the highest setting? ☐ Yes ☐ No
28.a *If yes*, How many burners? ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 4+

29. Other. Please describe: ☐.

30. *If yes to any of the questions above*, How was this issue resolved?

- ☐ Hasn't been resolved
- ☐ Was serviced by a professional
- ☐ Was serviced by a resident
- ☐ Appliance was replaced
- ☐ Issue resolved iteself

Have you ever had any of the following problem with the oven or broiler burners?

31. Burners slow to ignite or won't ignite? ☐ Yes ☐ No
32. Thermostat doesn't work properly? ☐ Yes ☐ No
33. Use is accompanied with a burning smell? ☐ Yes ☐ No
34. Other. Please describe: ☐.

35. *If yes to any of the questions above*, How was this issue resolved?

☐ Hasn’t been resolved
☐ Was serviced by a professional
☐ Was serviced by a resident (including cleaning)
☐ Appliance was replaced
☐ Issue resolved iteself

Please describe the quality of each cooktop flame; check all that apply:

How does the flame look *without* a pot?

36. Left Front: ☐ Mostly blue OR ☐ Lots of orange; ☐ Steady OR ☐ Wobbly
37. Left Rear: ☐ Mostly blue OR ☐ Lots of orange; ☐ Steady OR ☐ Wobbly
38. Right Front: ☐ Mostly blue OR ☐ Lots of orange; ☐ Steady OR ☐ Wobbly
39. Right Rear: ☐ Mostly blue OR ☐ Lots of orange; ☐ Steady OR ☐ Wobbly

40. How would you rate the air quality in your home over the past week?
- ☐ Very good
- ☐ Acceptable
- ☐ Barely acceptable
- ☐ Not acceptable

41. Over the past week, how often did you smell cigarette smoke from other nearby homes or apartments, or from the hallways?
- ☐ Never
- ☐ A few days
- ☐ Every day
- ☐ Don't know [Don't read]

42. Over the past week, how much of the time did you smell other odors (for example, cooking) nearby homes or apartments, or from the hallways?
- ☐ Never
- ☐ A few times
- ☐ Every day
- ☐ Don't know [Don't read]

43. Were there any pollution events that occurred outdoors over the last week that may have affected the air quality inside of your home (for example, outdoor fires, fireworks or construction etc.)
- ☐ No
- ☐ Yes. Please describe:

44. Is there anything more you would like to say about your house related to this study?

45. Do you have any questions?

46. This study will continue for another year after this one, and we may make some changes to this survey. Are there any changes that you recommend we make to this survey to make the questions easier to understand or to make taking the survey more convenient?

If yes, describe: ☐

Thank you very much for your time and help. After we receive the samplers back in our lab, we will begin processing the $75 payment. You should receive it within 1 month. If you do not receive it, please get in touch with U.S.

PICTURES
If possible, please take photographs of the appliances that we talked about and sending them to U.S. by email. Here is a list of what we would like pictures of, if possible:

- Cooktop
- Range hood (looking up, sitting on chair in front of cooktop)
- Stove and range hood in same picture (farther back)
- Forced air furnace showing ductwork
- Storage water heater, top area
- Storage water heater, bottom area
- Any other heaters or fireplaces

Appendix IV: QA/QC Procedures

Sample Handling and Quality Assurance (QA) Procedures

Sample handling

A regular schedule for sampler preparation, deployment and processing was maintained throughout the sampling period. Prior to deployment, aldehyde cartridges were stored in a refrigerator until the morning of shipment. The NO_X/NO_2 samplers were generally built on the preceding Friday, and stored at room temperature in airtight bags. Packages were mailed to participants on Monday morning, and were usually received by Tuesday and rarely later than Wednesday. Participants were asked to set-up the samplers as soon as possible, ideally within 24 hours, and to then repackage them six days later. Thus, participants who set-up the samplers on Tuesday evening, which was most often the case, were asked to repackage them on the following Monday evening and mail them back Tuesday morning. The majority of returned packages were received at the lab on Wednesday or Thursday, though it was not uncommon to receive one or two packages on Friday. Within 24 hours of their arrival, packages were opened and their contents inventoried. Besides ensuring that all the sampling materials had been returned, the inventory also included checking that all of the airtight bags were well sealed and that the correct sensor IDs had been recorded for each home.

Following the inventory, aldehyde cartridges were stored in a freezer at -20ºC and NO_X/NO_2 samplers in a laboratory at room temperature to await analysis. Data loggers were downloaded within a few days of their arrival, and were launched for deployment at the next set of sites. NO_X/NO_2 and aldehyde samplers were extracted within 1 week of their arrival, and were chromatographically analyzed within 1 week of extraction. According to information published by the manufacturers, exposed NO_X/NO_2 samples can be stored for 2-3 weeks and extracted samples can be stored for 90 days.[38] Exposed aldehyde samplers can be stored for 2 weeks and extracted samples are stable for up to 2 months.[39] Aldehyde sample extracts were analyzed in a high-performance liquid chromatography (HPLC) system and NO_X/NO_2 extracts were analyzed in an ion chromatography (IC) system, per procedures provided by Waters Inc. and Ogawa & Co. Inc., respectively. Formaldehyde and acetaldehyde mass values output by the HPLC were converted to concentrations using the duration of deployment and the passive sampling rates determined in validation experiments described later in this report. NO_2 and NO mass values output by the IC were converted to concentrations based on the algorithm described by Ogawa & Co. Inc., using the measured T and RH and the noted sampling duration. The Ogawa NO_X samplers have been validated by Singer et al. (2004). At homes where T and RH data were not available for the kitchen or bedroom (<10%), a value was approximated based on the measurement made in the other location at that home. In cases where there was no outdoor T and RH data, a value was acquired using centrally monitored weather data.

Quality assurance

The following procedures were used to calculate the Minimum Detection Limits (MDL) and Limits of Quantification (LOQ) for formaldehyde, acetaldehyde, NO_2 and $NO_{x,}$ based on analytical methods. The MDL was calculated by taking the standard deviation of 7 samples of the same certified standard, and multiplying it by the students' t-value corresponding to a 99% confidence level and a standard deviation estimate with n-1 degrees of freedom, according to US EPA procedure (Title 40 Code of Federal Regulations Part 136, Appendix B, revision 1.11). The LOQ was calculated as 10 times the standard deviation of the 7 analyzed standard samples. Certified standards of 100 μg/L nitrite and nitrate, and of $8.79x10^{-3}$ μg/L formaldehyde and acetaldehyde were use for the analysis. This analysis was performed mid-way through the data collection period. Excluding field blanks, one formaldehyde sample (outdoor) and one NO_2 sample (bedroom) were below the LOQ. The results for these samples were replaced with a value of 0.5 LOQ.

The following procedures were used to minimize and assess the frequency of contamination of the time-integrated samples. Prior to deployment, all parts of the Ogawa NO_X samplers were cleaned with deionized water and air-dried in a laboratory free of combustion sources; they were assembled and placed into sealable envelopes on the Friday before shipping out to participants. The aldehyde samplers required no assembly. They were transported to the participating homes in the individual airtight bags in which they were sent by the manufacturer. The seal on each airtight bag was checked upon receiving the returned samplers from the participants. The end caps on the aldehyde samplers provided a second level of protection from contamination in both directions. Contamination in the field was assessed by deploying duplicate and blank NO_X/NO_2 and

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[38] www.ogawausa.com/pdfs/prono-noxno2so206.pdfz

[39] www.waters.com/webassets/cms/support/docs/wat047204.pdf

aldehyde samplers at 1 to 3 homes every week, for a total of 30 duplicates and 35 blanks for each type of sampler. Homes that received duplicate or blank samplers received one for each type of pollutant (i.e. NO_X/NO_2 and formaldehyde/ acetaldehyde); however, no home received a set of both blank and duplicate samplers. Residents were instructed to deploy duplicate samplers in the bedroom and to keep field blanks in their airtight bags for the duration of the sampling period. Prior to mailing back the sampling package, they were instructed to open the bags of the field blanks, and remove the sampler for 10 seconds before replacing and resealing. This last step was intended to asses how commonly substantial contamination occurred in transit, due to an improperly sealed bag. The average concentration measured by the blank NO_X and NO_2 samplers was 11% greater than the LOQ. The averages measured by the blank formaldehyde and acetaldehyde samplers were 18% and 64% greater, respectively, than the corresponding LOQ. The average relative deviations for all pairs of NO_X, NO_2, formaldehyde and acetaldehyde duplicate samples were 4.1%, 6.3%, 5.2% and 5.5%, respectively.

The following procedures were used to assure quality in the analysis of time-integrated samples. Analytical blanks were included with every batch of samples run through the ion chromatography (IC) or high-performance liquid chromatography (HPLC) systems. For the IC analysis, a blank was included after every 5 samples to ensure that there was no carry-over contamination. Certified standards were purchased for each instrument. Target analytes were identified and measured by comparison to these standards. For the IC, a full calibration series was included with each set of samples analyzed. For the HPLC, one continuing calibration standard was included with each set of samples analyzed. A multipoint calibration series was run every 6 months on the HPLC system. Sample extracts were saved and rerun on occasion, either to confirm unusual results or to test the error introduced by a delay in the analysis of extracts.

The following procedures were used to assure quality of data from continuous monitors. During the data collection phase, CO sensors were calibrated roughly every 2 weeks, and the CO_2 sensors were calibrated roughly every month. The CO calibration involved exposing 6 to 10 sensors to concentrations of roughly 0, 25 and 50 ppm in a 3.8 L chamber. The CO_2 calibration involved exposing 6 to 7 sensors to concentrations of roughly 500, 1250, and 2500 ppm in an 18.9 L chamber. The calibration spans were achieved by titrating CO and CO_2 concentrations of 0.1% and 10%, respectively, with ultra zero air using a Dynacalibrator (Valco Instruments Co. Inc., Model 760). The precise span level was calculated by measuring the flow rate of each gas at the beginning and end of the exposure period. For the CO loggers, an intercept adjustment was calculated based on the loggers response at zero and a slope was calculated from a best-fit linear regression of the logger's response to the 3 tested spans. For the CO_2 loggers, both the slope and intercept were calculated from a best-fit linear regression. In November 2011, prior to the start of data collection, the CO data loggers exhibited a mean ± one standard deviation slope and intercept (calculated across loggers) of 1.09 ± 0.02 and -0.02 ± 0.05 ppm, respectively, and the CO_2 loggers exhibited a mean slope and intercept (calculated across loggers) of 1.34 ± 0.01 and -99 ± 12 ppm, respectively. In April 2012, at the completion of data collection, the CO data loggers exhibited a mean slope and intercept of 1.12 ± 0.05 and -0.19 ± 0.39 ppm, respectively, and the CO_2 loggers exhibited a mean slope and intercept of 1.24±0.03 and -148±59 ppm, respectively. Data collected at each home were adjusted using an average of the slope and intercept calculated from the calibration experiment that took place immediately before and after the sampling period at that home. For the one home where CO readings were high but highly irregular, the participant was offered and accepted the opportunity to do a second week of CO monitoring. Results from the second CO logger indicated that the first logger had been malfunctioning.

The following procedure was used to confirm that samples and monitors from different locations within the homes were accurately tracked. NO_X/NO_2 holders were labeled, and upon return, were checked to ensure that residents had put samples into the bag correctly labeled for its location of deployment. The same was not done for the aldehyde samplers, due to the sampler configuration. However, the NO_X/NO_2 holders were found switched at only 1 of the 127 homes to which samplers were mailed; therefore, the switching of samplers between the bedroom and kitchen is not suspected to have been a significant source of error. The ID numbers of data loggers intended for deployment at each location in homes were recorded prior to departing the lab. At homes to which samplers were mailed, returned packages were inventoried and the records were checked to confirm that the correct ID numbers had been recorded. At homes that were visited, the ID numbers on loggers deployed at each location were recoded during the first visit, after deployment, and confirmed during the second visit, prior to packaging.

We intended to test the accuracy of participant responses to interview questions by comparing information provided by participants in the initial interview with observations made by researchers at the homes that were visited. The data collected in the first year of the study were not suitable for this validation check for two reasons. First, the majority of visited homes in the first year were "high performance" homes. Study participants living in these homes generally were more interested and knowledgeable than the typical homeowner about appliances and building mechanical systems in their home than was characteristic of the residents of conventional homes. Consequently, a test of the accuracy of participant responses from this group could not be accurately extended to the rest of the sample. Second, in practice, differences between initial interview responses and observations made in the home were not systematically documented. Thus, a comparison of participant responses with researcher observation was not possible from the year one data set, nor would it have been very helpful. We did, however, conduct a comparison of responses to questions included in both the screening survey and initial survey. This comparison indicated that roughly a third of respondents could not accurately respond to detailed questions about their appliances and building mechanical systems without the help of a researcher over the phone, reinforcing the decision to conduct the initial and final interviews only over the phone, rather than making the questions available for completion online.

The following procedure was used to characterize potential bias of NO_X and NO_2 measurements made within the outdoor enclosure tin. Tests were performed on four occasions throughout the sampling period, by collocating multiple samplers outside a home in two different enclosure configurations for 6-day periods. One configuration was a relatively open dome-shaped enclosure that had been validated in past experiments (Singer et al., 2004). The second was a more closed box-shaped enclosure with ~1 cm diameter holes drilled on several sides of the box and fitted with grommets. A picture of both types of outdoor enclosures is shown in Figure 2.3. In this study, the open dome enclosure was used at the homes that were visited, while the closed box-shaped enclosure was used at the homes to which samplers were mailed, due primarily to its lighter weight and smaller size.

Figure 2.3. Two enclosure configurations for NO_2 / NO_X sampling: Configuration on the left was used at homes that were visited and has been validated in past studies. Configuration on the right was used at homes to which samplers were mailed.

The first outdoor validation experiment took place on 22 November 2011, simultaneous with pollutant sampling in the first set of homes in this study. The first experiment involved collocating a pair of samplers, each in a different type of enclosure, at the front of a single family home, and deploying a third sampler in a dome enclosure at the back of the home. The results of this experiment indicated that the true NO_2 and NO_X concentrations were, respectively, 31% and 34% higher than the concentration measured by samplers in the closed box. Consequently, the number of holes in the box surface was increased from 4 to 6, which was the largest number of holes deemed possible without overly exposing the samplers to outdoor elements. This slightly modified design was used at homes sampled from Week 3 through Week 19. The subsequent 3 outdoor validation experiments were initiated on 29 November 2011, 7 February 2012 and 11 April 2012, and involved collocating 3 pairs of samplers in each enclosure type for 6 day periods outside of a single home, now with the box enclosure having 2 additional holes. For the first 2 experiments, the 3 pairs were deployed in different locations along the exterior of the home, while in the 3rd experiment the 3 pairs were located together. Results from all 4 experiments are show in Table 2.4. Results from the last 3 experiments were analyzed by linearly regressing the average NO_2 and NO_X concentrations measured by samplers in the metal box enclosures against the average of concentrations simultaneously measured by samplers in the domes, with the intercept of the regression forced through zero (Figure 2.4). The resulting slopes of 1.23 and 1.09 for NO_2 and NO_X, respectively, were used to adjust the data measured by samplers deployed in the box-enclosures at homes sampled in Weeks 3-19. The ratio of concentrations measured by samplers deployed in the box and dome enclosures in the first experiment (22 November 2011) were used to adjust the outdoor data collected at homes in Weeks 1 and 2.

Table 2.4. Results from outdoor validation experiments. Each row corresponds to collocated samplers.

Start Date	Box NO_2 (ppb)	Dome NO_2 (ppb)	Box NO_X (ppb)	Dome NO_X (ppb)
11/22/11	12.3	16.0	30.7	39.9
11/22/11		16.1		42.6
Mean (RSD)	12.3	16.1 (0.4%)	30.7	41.3 (4.6%)
11/29/11	13.3	15.8	28.8	31.2
11/29/11	14.8	17.3	31.5	33. 3
11/29/11	12.2	15.8	27.9	29.2
Mean (RSD)	13.4 (9.7%)	16.3 (5.3%)	29.4 (6.4%)	31.2 (6.6%)
2/7/12	13.9	18.7	29.6	33.4
2/7/12	18.2	18.8	29.5	31.8
2/7/12	15.1	21.7	34.1	38.4
Mean (RSD)	15.7 (14.1%)	19.7 (8.6%)	31.1 (8.5%)	34.5 (10.0%)
4/11/12	5.1	5.7	6.0	7.4
4/11/12	4.6	6.0	7.0	8.1
4/11/12	4.9	5.5	4.7	6.9
Mean (RSD)	4.9 (5.2%)	5.7 (4.4%)	5.9 (19.5%)	7.5 (8.1%)

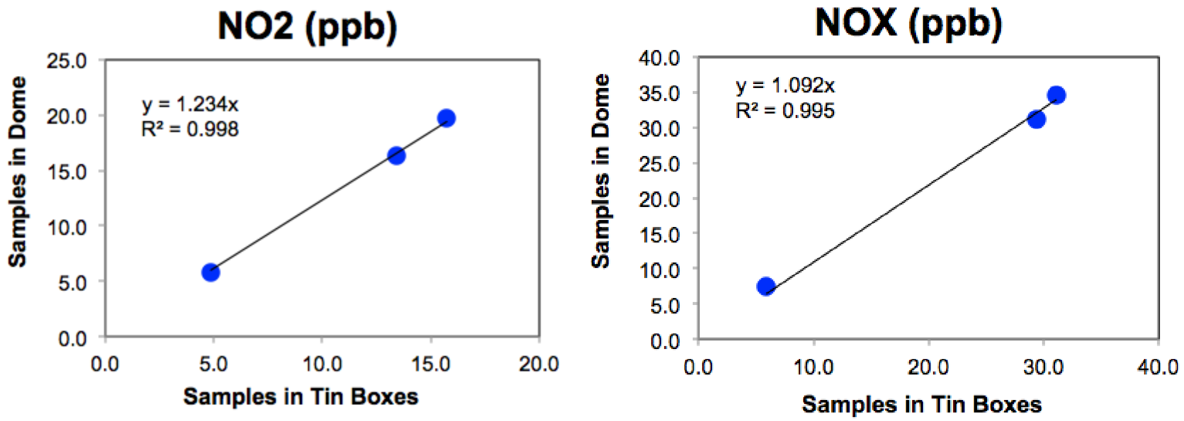

Figure 2.4. Linear regression of NO_2 and NO_x concentrations measured by samplers in two outdoor enclosure types. Each data point represents the average of 3 pairs of samplers deployed for a 6-day period.

The following procedure was used to confirm the sampling rate of the Waters Inc. aldehyde samplers. These samplers are intended by the manufacturer to be used actively, not passively, as used in this study. However, a study conducted by Shinohara et al. (2004) reported that these aldehyde samplers could be used passively, and reported passive sampling rates of 1.48 and 1.23 mL/min for formaldehyde and acetaldehyde, respectively. In 2010, a laboratory experiment was conducted at LBNL to confirm these sampling rates. The experiment involved suspending 9 unmodified Waters aldehyde samplers in a 70 L chamber for 98 hours, during which an aqueous mixture of formaldehyde and acetaldehyde was injected into the chamber using a syringe pump and a GERSTEL Tube Spiking

Apparatus. A Waters sampler connected to a peristaltic pump was used to collect a 40 to 50 L active sample at seven points during the experiment, in order determine the syringe delivery rate of the aldehyde solution, and to monitor the aldehyde concentration in the chamber during passive sampling. The passive sampling rates calculated from the results of this experiment were 1.25 and 0.97 mL/min for formaldehyde and acetaldehyde, respectively. Between April and July 2012, six further validation experiments were conducted by Lawrence Berkeley National Lab to ascertain the passive sampling rate of the Waters DNPH cartridges in residential settings. All six experiments were conducted in homes, one over a 10-day period and five over 6-day periods. The 10-day experiment was conducted as follows: On day one, 14 aldehyde samplers were deployed with two connected to pumps for active sampling and 12 deployed for passive sampling. Every 2 days, the 2 active samplers were removed and sealed in airtight bags and replaced with 2 new samplers. This step was repeated every 2 days of the 10-day sampling period, until 10 active samplers had been used, each deployed for 2 days. On day four, 3 of the passive aldehyde samplers were removed and packaged in airtight bags, but were *not* replaced. Every 2 days following day four, eight and ten, 3 more of the passive samplers were removed, until the final triplicate was removed on day ten. A sample schedule of the 10-day experiment is shown in Table 2.5. Results from this 10-day experiment were used to calculate a passive sampling rate and to investigate whether the sampling rate was stable over a 10-day period. The 6-day field experiments involved deploying 5 aldehyde samplers, 2 connected to pumps to sample actively and 3 sampling passively. At the end of the six days, all 5 samplers were packaged and subsequently analyzed. Thus, 1 data point for comparison was acquired from the 6-day field experiments, while 4 points were acquired from the 10-day field experiment. Results from the experiments are presented in Table 2.6. Using only the Day 6 results from Site 1 where a 10-day experiment occurred, the average ± standard deviation of sampling rates for formaldehyde and acetaldehyde for 6 days of sampling were 1.10 ± 0.09 and 0.86 ± 0.13 mL/min, respectively. These sampling rates were used to calculate formaldehyde and acetaldehyde concentrations measured in homes. Results from the 10-day experiment at Site 1 suggest that the sampling rate for aldehyde species may increase with time, but additional experiments would be required to determine whether the jump in calculated sampling rate between the 6-day and 8-day experiment is repeatable or just variability between deployments.

Table 2.5. Sample schedule for 10-day aldehyde passive sampling rate validation experiment.

	Sample Name [a]	Day									
		1	2	3	4	5	6	7	8	9	10
Active Samples	ACT12-x	▨	▨								
	ACT34-x			▨	▨						
	ACT56-x					▨	▨				
	ACT78-x							▨	▨		
	ACT910-x									▨	▨
Passive Samples	PASS4-x	🟧	🟧	🟧	🟧						
	PASS6-x	🟧	🟧	🟧	🟧	🟧	🟧				
	PASS8-x	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧		
	PASS10-x	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧

[a] The "x" at the end of sample names is intended to identify duplicates (active samples) and triplicates (passive samplers). Results of the this experiment are shown in Table 2.4.

Table 2.6. Results from aldehyde passive sampling rate validation experiments.

Experiment ID	Sampling duration (days)	Pump flow rate (mL/min)	Formaldehyde concentration (ppb) [b]	Acetaldehyde concentration (ppb) [b]	Formaldehyde sampling rate (mL/min, RSD)	Acetaldehyde sampling rate (mL/min, RSD)
Site 1-4d[a]	4.1	10.4	11	5	1.01 (10%)	0.65 (16%)
Site 1-6d	6.0	10.2	10	5	0.99 (4%)	0.68 (6%)
Site 1-8d	8.0	10.2	10	5	1.02 (3%)	0.89 (11%)
Site 1-10d	10.0	10.2	10	5	1.08 (7%)	0.86 (10%)
Site 2	6.1	10.3	12	6	1.03 (8%)	1.04 (1%)
Site 3	5.9	12.8	41	10	1.16 (6%)	0.96 (7%)
Site 4	6.0	11.2	30	11	1.09 (11%)	0.90 (8%)
Site 5	5.6	10.6	123	7	1.09 (6%)	0.79 (8%)
Site 6	5.9	13.6	12	5	1.23 (16%)	0.81 (16%)

[a] A 10-day experiment occurred at site 1. At the remaining sites, a 6-day experiment occurred.

[b] Concentrations determined from active sampling