Window Usage, Ventilation, and Formaldehyde Concentrations in New California Homes: Summer Field Sessions

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ABSTRACT

Concerns have been raised regarding whether homeowners use windows, doors, exhaust fans and other mechanical ventilation devices often enough to remove indoor air pollutants and excess moisture. In 2006-2007 we conducted a multi-season study of ventilation and IAQ in 108 new single-family, detached homes in California. This paper presents the ventilation and formaldehyde measurements from the Summer field sessions. A total of 10% of the 63 homes did not open their windows/doors at all during the 24-hour test period and 16% opened their windows/doors less than an average of 0.5 ft^2 (0.05 m^2). A total of 50% of the 62 homes with PFT measurements had outdoor air exchanges rates below 0.35 ach. A total 62% of the 61 homes with formaldehyde measurements had indoor concentrations exceeding the California ARB exposure guideline of 33 µg/m^3. We conclude that the new single-family detached homes in California are built relatively tight, and in those homes where the windows/doors are not opened for ventilation (e.g. for security, noise, odor, dust, thermal comfort concerns) the outdoor air exchange rates are typically low (e.g. 0.2 ach) and indoor concentrations of air contaminants with indoor sources such as formaldehyde can be significantly elevated. This study suggests that consideration should be given to installing mechanical outdoor air ventilations systems in new single-family residences to provide a dependable and continuous supply of outdoor air to the residence.

INTRODUCTION

Concerns have been raised regarding whether homeowners use windows, doors, exhaust fans, and other mechanical ventilation devices enough to remove indoor air pollutants and excess moisture. Building practices and building standards for energy efficiency have led to more tightly sealed homes that rely on occupants to open windows for ventilation. However, there is very little information on current ventilation practices, indoor air quality (IAQ), or indoor pollutant sources in homes.

A mail survey of new single-family detached homes was conducted to determine occupant use of windows, barriers that inhibit their use, satisfaction with IAQ, and the relationships between these factors (University of California at Berkeley, 2006). This study, sponsored by the California Air Resources Board (ARB) and the California Energy Commission (CEC), was conducted by the U.C. Berkeley Survey Research Center. In December, 2004 and January, 2005 a questionnaire was mailed to a stratified random sample of 4,972 single-family detached homes built in 2003. A total of 1,448 responses were received. An additional sample of 230 homes was obtained from builders. These additional homes were also mailed the questionnaire and were known to have mechanical ventilation systems. A total of 67 responses were received from this sample.

Table 1 summarizes the percentage of homes responding to the questionnaire that report no use of windows for ventilation on a seasonal basis. The results are presented for four categories of never-used hours per day: 24-hours per day (i.e. never opened), 23 or more hours/day, 22 or more hours/day, and 21 or more hours/day, corresponding to 0 hours, 1 or less hours, 2 or less hours and 3 or less hours of window usage per day. As can be seen in this table, a significant percentage of homeowners, ranging from 5.8% in the Spring to 29% in the Winter, report never using their windows. The percentage of homeowners reporting 21 or more hours per day of no window usage ranged from 12% in the Spring to 47% in the Winter.

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Table 1. Seasonal Percentage of New California Single-Family Detached Homes Reporting no Use of Windows* for 24, 23, 22, and 21 Hours per Day (N = 1,334)

	24 hours/day	23 or more hours/day	22 or more hours/day	21 or more hours/day
Summer	7.5	9.1	12	14
Fall	8.6	12	16	18
Winter	29	36	45	47
Spring	5.8	5.8	8.4	12

*University of California at Berkeley, Survey Research Center, and Lawrence Berkeley National Laboratory. Survey of Ventilation Practices and Housing Characteristics in New California Homes. 2006.

Price and Sherman (Price, 2006) conducted analyses of this survey data. The reasons reported most frequently by the homeowners (i.e. 20% or more of homeowners) for not opening their windows included (percentage of homes reporting reason as "very important"): security/safety (80%), maintain comfortable temperature (68%), keep out rain/snow (68%), save energy (61%), keep out insects (52%), keep out dust (42%), too windy/drafty (45%), keep out noise (39%), reduce pollutants or odors form outdoors (36%), keep out pollen/allergens (35%), privacy from neighbors (29%), and keep out wood smoke (23%).

In July 2005 as a follow-up to the mail survey, a large indoor air quality field study entitled "Ventilation and Indoor Air Quality in New Homes" and sponsored by the California Air Resources Board and the California Energy Commission, was launched to assist in answering some of the questions regarding ventilation and indoor air quality in new single-family detached homes.

This field study involved 108 new single-family homes from Northern and Southern California, including a subset of 20 homes with mechanical outdoor-air ventilation systems. The field teams measured home ventilation and indoor contaminant source characteristics, including the amount of composite wood cabinetry and furnishings, indoor contaminant concentrations, the residents' ventilation practices, IAQ perceptions, and decision factors regarding ventilation and IAQ-related actions. Measurements of indoor and outdoor air quality and ventilation parameters were made in the Summer, Fall, and Winter. Indoor air concentrations of volatile organic compounds, aldehydes including formaldehyde, $PM_{2.5}$ particulate matter, nitrogen dioxide, carbon monoxide, carbon dioxide, temperature, and relative humidity were measured over one 24-hour period. The outdoor air ventilation rates were determined concurrent with the air contaminant measurements using passive perfluorocarbon tracer (PFT) gas measurements. In addition, the field teams measured the building envelope air leakage, garage to home air leakage, forced air unit duct leakage, window use, airflow rates and usage of fan systems. Twenty of the 108 homes were tested in both the Summer and Winter seasons, four homes were tested in the Summer, Fall, and Winter and four homes were tested over multiple days including weekends.

This project had the following specific objectives:

1. Determine how occupants use windows, doors, and mechanical ventilation devices such as exhaust fans and central heating and air-conditioning systems.
2. Measure and characterize indoor air quality (IAQ), ventilation, and the potential sources of indoor pollutants.
3. Determine occupant perceptions and satisfaction with the IAQ in their homes.
4. Examine the relationships among home ventilation characteristics, measured and perceived IAQ, and household characteristics.
5. Identify the incentives and barriers that influence peoples' use of windows, doors, and mechanical ventilation devices for adequate air exchange.
6. Identify the incentives and barriers related to peoples' purchases and practices that improve IAQ, such as the use of low-emitting building materials and improved air filters.

This paper describes the methods, results, and conclusions from the Summer field sessions in 63 California single-family detached homes. In addition, this paper focuses upon the window and fan usage, envelope leakage, outdoor air exchange rates, and formaldehyde concentrations. Results from the Fall and Winter field sessions will be presented along with the Summer field sessions in the Project Final Report along with the results of the concentrations of additional air contaminants (i.e. 15 other volatile organic compounds, carbon dioxide, carbon monoxide, nitrogen dioxide, and $PM_{2.5}$ particulate matter), temperature, relative humidity, house characteristics, occupant source activities and perceptions.

METHODS

The following is a description of the field measurements and methods utilized in this study for recruiting homes and measuring the building envelope air leakage, fan and window usage, outdoor air exchange rate, and concentrations of formaldehyde.

Home Recruitment/Selection

To recruit the homes for this study we utilized the database from the U.C. Berkeley mail survey that was administered in 2004-2005 (University of California at Berkeley, 2006). In this survey homes were selected randomly from a statewide realty database for home construction. This mail survey to 5,202 new single-family detached homeowners resulted in 1,515 completed questionnaires (i.e. 29.1% response rate) of which 965 respondents (i.e. 65.9% of the respondents) indicated their willingness to participate in the second part of the study involving measurements of ventilation and indoor air quality in their homes. In addition to this sample of 965 homeowners, we purchased additional home addresses and phone numbers of new single-family detached homeowners from the neighboring areas.

To this sample we mailed out 2,763 recruitment letters asking interested homeowners to call the project participant recruiters' toll-free number. We offered a $100 incentive in addition to providing the indoor air quality testing free of charge to those who participated in the field study. We received calls from interested homeowners and called those non-responding homeowners for which we had telephone numbers.

Upon contacting the interested homeowners we administered a recruiting script and collected information on the home, occupancy, and ventilation systems and described the details of the three visits required by the field teams. Only single-family detached homes built after January 2002 that were owner-occupied primary residences for at least one year qualified for the field study. Additionally, if occupants reported tobacco smoking inside the homes they were excluded from the field study. We collected information regarding the participants' preferences for dates and times of the three field visits with the understanding that the same time periods would be required for each of the three field visits; 9 AM – 12 PM, 1 PM – 4 PM, and 4 PM- 7 PM.

Upon administering these recruiting questions to interested homeowners, we then selected the homes for the field study within the constraints of the field study design which required one-half of the homes to be in Northern California climate regions and one-half in Southern California climate regions, with a minimum of 20 homes having mechanical outdoor air ventilation. To minimize the number of outdoor air contaminant measurement locations and to provide for reasonable logistics, the study design for this research project also required testing clusters of 2-3 homes (e.g. within the same zip code or within 2 miles), with one outdoor air sampler collected for each cluster of homes.

Field Team Work Assignments

The fieldwork was divided among three field teams, each consisting of two field technicians. All fieldwork was conducted according to the specific standard operating procedures (SOPs) developed for each of the three field teams.

Field Team 1 installed PFT sources at selected locations in the home and dataloggers on windows and fans, administered the occupant fan and window logs, the Indoor Contaminant Source Activity Sheet, and the Occupant Questionnaire one week in advance of the field work performed by Field Teams 2 and 3. Field Team 2 followed Field Team 1 seven days later, allowing the PFT sources to equilibrate, installed and started the air sampling equipment at indoor and outdoor locations, including the PFT samplers, and collected detailed information on home construction characteristics and indoor air contaminant sources. Field Team 3 followed Field Team 2 the next day (22-26 hours later and was responsible for the removal of the air sampling equipment, the PFT samplers, and window/door and fan logs and loggers as well as collecting detailed information on building envelope air leakage, garage-home air leakage, duct air leakage, and ventilation system air flow rates.

Ventilation Measurements

The approach for measuring ventilation applies a combination of one-time tests and weekly monitoring. Collection methods are summarized in this section for the following ventilation parameters:

- windows and doors
- mechanical exhaust fans and appliances
- forced air heating/cooling system
- mechanically supplied outdoor air system
- other ventilation fans
- building leakage area
- infiltration parameters

The use of windows and doors, and operation of mechanical systems were monitored for a 1-week period by occupant logs and/or HOBO data logging instruments.

The following is a description of the methods that will be used to collect data on each of the ventilation parameters reported on in this paper.

Occupant Use of Windows/Doors for Ventilation. Ideally we would install proximity sensors such as those used in robotics to record both the time the window/door is open and the extent of the opening. Since the proximity sensors available at the time this project was initiated cost more than was available in the equipment budget, we used a combination of electronic loggers and occupant logs to record the ft^2-hours of window/door openings. Homeowners were asked to identify the windows/doors, if any, they may use during the one-week test period. Window state loggers (i.e. log open or closed) were installed on the two most frequently used windows/doors as reported by the homeowner to record the time and duration of the window/door openings. Occupant written logs were posted with removable non-residue tape on all window/doors that the occupant reported they may use during the one-week test period. The windows/doors that the homeowner reported as unlikely to be used during the one-week test period were not equipped with occupant logs. For convenience, a pencil was affixed with Velcro tape to each log form. The occupants used these logs to record the time, duration, and distance of the window/door opening. The combination of the loggers and logs on two windows also provides us information on the accuracy of the occupants' written logs of window/door openings.

The ft^2-hours of openings for each window/door were reported in 24-hour time periods counting back for a one-week period from the time that Team 3 entered the home and stopped the 24-hour IAQ contaminant and PFT outdoor air exchange rate measurements.

Measurements of all window and door openings were collected by Team 1. The width and length were measured by opening each window or door and using a tape measure. In addition, a state logger was also installed on the garage-home door to record openings and closings. The 24 hour average and one week average window usage was then calculated and expressed in terms of the average ft^2 of window opening.

Exhaust Fans. Electronic loggers and/or written logs were deployed for all exhaust fans that the homeowners reported they may use during the one-week test period. These included bathroom, laundry/utility, clothes dryer, and kitchen exhaust fans. The exhaust fans that the homeowners reported as unlikely to be used during the one-week test period were not equipped with electronic loggers or written logs.

For bathroom exhaust fans, ac-field loggers were placed above the exhaust grille just beneath the motors on the two bathroom fans that the homeowner reported they may use during the one-week test period. For the two bathroom exhaust fans with electronic loggers no occupant written logs were installed. For any additional bathroom or utility/laundry exhaust fans that the occupant reported they may use during the one-week test period, occupant written logs were posted with removable non-residue tape near the fan switch. For convenience, a pencil was affixed with Velcro tape to each log form. The occupants used these logs to record the time and duration of the fan operation. For exhaust fans that the homeowner reported as unlikely to be used during the one-week test period no logs were posted.

For clothes dryer exhaust fans, we installed an EMF logger directly on the dryer power cords.

For kitchen exhaust fans, since these fans typically have multiple fan speeds and there was no practical electronic logger that could log both operation and fan speed, we installed an occupant log sheet for the occupants to log the time, duration, and fan speed associated with the usage of kitchen exhaust fans. For convenience, a pencil was affixed with Velcro tape to each log form.

All exhaust fan airflow rates were measured in the home (e.g., bathroom, utility/laundry room, and kitchen hood fans) using a calibrated airflow hood. Due to difficulty accessing an acceptable location to measure the dryer exhaust airflow rate in some homes, the flow rate for those homes was determined by collecting the dryer manufacturer and model information and obtaining the dryer blower flow rate data from the manufacturer. Team 2 estimated the number of bends (e.g., 90^0, 45^0) and the length of the exhaust ductwork in the field. The manufacturers' airflow rate and duct characteristics were then used to estimate the actual dryer airflow rate. The 24 hour average and one week average exhaust fan usage was then calculated and expressed in terms of air changes per hour.

Mechanically Supplied Outdoor Air Flow Rates. The approach used to measure airflow rates was to use a calibrated airflow hood for fully ducted heat recovery ventilator (HRV) systems and a hot wire anemometer centerline air speed measurement for systems with an outdoor air duct connected directly to the return air duct of the forced air unit (DOA). For systems measured with a hot wire anemometer the airflow rate was calculated as the area of the duct times 0.9 of the measured air speed.

For homes with night ventilation cooling systems that are integrated with the forced air heating/cooling unit (FAU), a motorized damper switches the air drawn into the forced air system between home air (i.e. from the central return air grille) and outdoor air (i.e. from an outdoor air intake). The ventilation damper for the night ventilation cooling system was monitored using a relay and an electronic state logger. We fastened lead wires with alligator clips to the damper 24 VDC motor wiring connections for the damper. For homes with independent night ventilation cooling systems we installed an electronic AC-field logger to monitor the fan operation time. The 24 hour average and one week average mechanical outdoor air usage was then calculated and expressed in terms of air changes per hour, percent on time, and cfm.

Home Building Envelope Air Leakage Area. The building envelope air leakage area was determined at each house using a depressurization multipoint blower door test with Automated Pressure Testing (APT) instrumentation. For these tests the homes were configured with all windows and exterior doors closed, all interior doors open (except doors to attached garages), fireplace dampers closed, and all intermittent exhaust fans and FAUs off. Any continuously operating mechanical outdoor air or exhaust air fans were left operating. Testing was conducted in accordance with ASTM E779-03 (ASTM, 2003a), Standard Test Method for Determining Air Leakage by Fan Pressurization.

Tracer Gas Measurements of Home Outdoor Air Exchange Rate. The outdoor air exchange rate in the homes was measured with a tracer gas technique during the 24-hour air contaminant measurements. This technique uses a passive constant injection PFT. The tracer gas sources were placed by Field Team 1 at locations in each home for approximately one week in advance of the tracer gas sampling; to allow for the emission rates of the sources to equilibrate. The number of sources and placement locations were determined for each home based on room volumes and layout to approximate a uniform indoor concentration. Since the emission rates from the PFT sources are temperature dependent we deployed an air temperature data logger, as described below, to log the indoor air temperature at 1-minute intervals. This temperature data was then input into an equation for the PFT emission rate as a function of temperature to calculate the temperature corrected PFT emission rates. The PFT used for these tests was para-methylcyclohexane (p-PMCH). The PFT samplers used for these test were capillary adsorption tube sampler (CATS). These are small passive samplers that were co-located at the indoor air contaminant site (e.g. family/living room). The 24 hour average outdoor air exchange rate was then calculated as described in ASTM E741-00 (ASTM, 2000) and expressed in terms of air changes per hour.

Indoor Air Quality Measurements

The following describes the indoor air quality parameters presented in this paper: 24-hour time-integrated measurements of formaldehyde and real time measurements of indoor air temperature.

The concentration of formaldehyde was measured for a 22-26 hour period at one indoor breathing height location in the family/living room area of each of the field study homes. In addition, the concentration of formaldehyde was measured in the outdoor air, typically the backyard, at one home for each 2-3 home cluster. Integrated sample flow rates were measured at the beginning and end of the sampling period using calibrated rotometers.

A special low noise air sampler, as depicted in Figure 1, was used to collect the integrated and real-time air contaminant concentrations. For the integrated air samples, this air sampler consisted of an air sampling pump contained in an acoustically shielded fiberglass lock box mounted to a tripod. The air sampling pump included an internal flow sensor that provides automatic electronic air flow control such that the sample air flow rate is maintained to within ± 5%, and 115 VAC battery eliminators to allow operation over the proposed 24-hour sampling periods. A power-on time meter provided a measurement of the time that 110 VAC power is supplied to the air sampler so that if a power interruption occurred the duration of the interruption would be known. The air sampling pumps automatically restart upon restoration of the power following a power interruption. In addition, a power cord restraint cover was installed at the connection of the power cord to the power receptacle to guard against inadvertent disconnection of the power cord plug from the receptacle.

For the outdoor air sampler a special rain/radiation shield was fabricated from galvanized sheet metal to enclose and protect the air samplers. This rain/radiation shield has screened and louvered vents on two sides to allow circulation of outdoor air within the enclosed area. Figure 2 is a photograph of the air sampler with the rain/radiation shield installed.

The following is a detailed description of the air sampling and analytical techniques for each of the IAQ parameters reported in this paper.

Formaldehyde. Formaldehyde was selected for measurement as it is commonly emitted from composite wood products (e.g. particle board, medium density fiber board, plywood, glues and adhesive, permanent press fabrics, paper product coatings, and some type of insulation materials, etc.) and is a known human carcinogen (IARC, 2004). Formaldehyde was measured according to ASTM Standard D5197-03 (ASTM, 2003b). This method involves drawing air at a constant rate with a pump through a solid sorbent cartridge (i.e. Waters Associates Sep-PAK, silica gel impregnated with dinitrophenylhydrazine, DNPH). In addition, since ozone is known to interfere with this sample analyses, an ozone scrubber was installed directly upstream of the solid sorbent cartridge. This scrubber consists of a solid sorbent cartridge filled with granular potassium iodide (i.e. Waters Associates

Figure 1 *Quiet indoor air sampler for formaldehyde, VOCs,* $PM_{2.5}$, NO_2, *CO,* CO_2, *temperature, and relative humidity, typically installed in a home living/dining room area for a 22–26 hour sampling period.*

Figure 2 *Outdoor air sampler for formaldehyde, VOCs,* $PM_{2.5}$, NO_2, *CO,* CO_2, *temperature, and relative humidity, with outdoor radiation/rain shield.*

Sep-PAK Ozone Scrubber). Additionally, a scrubber (i.e., Anasorb CSC, coconut charcoal sorbent tube) was placed downstream of the sampler to scrub the emissions of residual acetonitrile released by the DNPH sample cartridge. The samplers were extracted with acetonitrile and analyzed using HPLC. Samples were collected at a flow rate of approximately 20 cc/min, provides a detection limit of 0.7 $\mu g/m^3$ for formaldehyde. This concentration detection limit is well below both the Cal/EPA OEHHA Chronic Inhalation Reference Exposure Levels (OEHHA, 2003) of 3 $\mu g/m^3$ for formaldehyde as well as the ARB Indoor Air Quality Guidelines (California Air Resources Board, 2005) of 33 $\mu g/m^3$ for formaldehyde for an 8-hour exposure. Laboratory results for each sampler were corrected using the average of the field blanks for each batch of samplers that was submitted to the lab for analyses. For field blanks where the concentration was below the minimum detection limit of the instrumentation a value equal to one-half the minimum detection limit was used to calculate the average of the field blanks.

Temperature. Temperature was measured with real-time instrumentation using a thermistor sensor for air temperature. An electronic sensor was used which has built-in data logging capabilities. The data logger was programmed to record temperature at one-minute intervals. The temperature sensor has an accuracy of 1 ^oF (0.6 ^oC), a resolution of 0.1 ^oF (0.06 ^oC), and a range of 32-122 ^oF (0-50 ^oC). Prior to the field effort the instruments temperature sensors were compared to a NIST-certified mercury thermometer and the sample data logged over the 24-hour period was corrected using single point calibration.

Wind Speed. We obtained hourly wind speed data from the local airport weather station nearest to the sample cluster.

QUALITY ASSURANCE / QUALITY CONTROL

Per our Quality Assurance / Quality Control Plan for the PFT outdoor air exchange rate measurements and the aldehyde samples we collected and analyzed 10% field blanks and 10% duplicates.

The average blank mass observed in the PFT CAT samplers, the volatile organic compound and aldehydes samplers were subtracted from the indoor sample masses for calculating the air concentrations. We collected a total of 5 PFT CAT field blanks and 6 formaldehyde field blanks. For field blanks with masses below the minimum detection limit, a value of 1/2 the minimum detection limit was input to calculate the average blank value.

A total of 6 PFT CAT duplicate sample pairs, 7 volatile organic compound and aldehyde duplicate sample pairs were deployed side by side. The absolute precision for each pair of samples was calculated as the absolute difference between each pair of duplicate samples. The relative precision for each pair of samples was calculated as the relative standard deviation divided by the average. The average absolute and relative precisions were calculated from the averages of the individual precisions calculated from each sample duplicate pair.

RESULTS

Home Recruitment/ Selection

We mailed a total 1,355 recruitment letters to new single-family detached homes in Northern California and 1,408 recruitment letters to new single-family detached homes in Southern California.

We then established clusters for those homes based on their relative distance and on which of the three inspection times each home noted as being required or preferred.

Between August 7–25, 2006 we scheduled field measurements for a total of 32 Northern California homes, our target for the three-week Summer North field session. Between September 5–22, 2006 we scheduled field measurements for a total of 31 homes, one home short of the 32-home target for the three-week Summer South field session. For each field session, homes were clustered into groups of 2-3 homes with one outdoor air sampling location for each cluster.

Home and Site Characteristics Collection

The 63 homes recruited for the Summer Field sessions were primarily from track developments by production builders, were built in 2002 or later, and have been owner-occupied for at least one year. All homes were slab on grade with attached garages. The exterior envelope was typically stucco. All homes had forced air unit heating systems, most of which also had cooling capabilities, and most were located in the attic.

There were a total of 21 homes of the 63 homes sampled with some type of mechanical outdoor air ventilation system and 42 homes without any mechanical outdoor air ventilation.

Of the 21 homes with mechanical outdoor air systems, a total of 7 had Heat Recovery Ventilators (HRVs) with fully ducted exhaust air and outdoor air ducts which operated separately from the FAU. Of these 7, four homes were pure HRVs (without other mechanical outdoor air systems, e.g. nighttime cooling systems, window fans), of which three were operated on the day of the air test. There were also a total of 10 homes with mechanical outdoor air systems with outdoor air ducts (DOA) connected to the FAU return duct (i.e. the outdoor air duct is typically installed in the hall way central return air inlet filter housing cabinet). These homes were all pure DOA systems with two that were non-operable for a total of 8 operational DOA mechanical outdoor air systems. The remaining homes with mechanical outdoor air ventilation systems included 3 nighttime cooling systems, 1 evaporative cooling system, and 4 mixed systems (e.g. 3 nighttime cooling /HRV systems and 1 nighttime cooling system with a window fan).

The controls for the 10 DOA systems consisted of 8 controlled by the thermostat fan switch and 2 controlled by a combination of thermostat and a fan cycler. The thermostats were each equipped with fan and mode switches. The fan switch has both “on” and “auto” operational positions. If the system is allowed to operate with the fan switch in the “auto” position, the fan cycles on and off to control the thermal loads, and does *not* provide outdoor air ventilation to the space continuously. When the fan switch is in the "on" position, the ventilation system provides outdoor air to the space continuously. The mode switch can be set to select for "cooling/heating/auto" operational mode or "off" mode. Each of the 10 DOA systems controlled by thermostats had the fan switch in the "auto" position with mode switch in the "cooling/heating/auto" operational mode except for one system where the mode switch was set for "off". The 2 DOA systems controlled by a combination of thermostat and a fan cycler included one which had the outdoor air system disabled and one with a fan cycler which turned the fan on 11 minutes every 30 minutes. All 10 of the DOA controls were located in the living space.

The controls for the 7 HRV systems consisted of 6 controlled by a wall on/off switch and one controlled by a 12 hour manual twist timer. A total of 3 of the 7 HRV controls were located in the living space with the remaining 4 located in the attic.

The conditioned floor areas of these homes ranged from 1,283 ft^2 (119 m^2) to 5,064 ft^2 (4710m^2) with a median of 2,260 ft^2 (210 m^2). The conditioned air volumes of these homes ranged from 10,667 ft^3 (302 m^3) to 55,613 ft^3 (1575 m^3) with a median of 24,495 ft^3 (694 m^3).

Ventilation Measurements

Occupant Use of Windows and Doors for Ventilation. The amount of window/door opening as expressed as the average opening in square feet over the 24-hour air quality sampling period as well as the average of the previous seven 24-hour periods is presented in Table 2. Homes without mechanical outdoor air ventilation had a median window/door opening of 7.9 ft^2 (0.73 m^2) for the air quality test period and a median of 8.5 ft^2 (0.79 m^2) over the previous one-week period. Homes with DOA systems had a median window/door opening of 10.4 ft^2 (0.97 m^2) for the air quality test period and a median of 8.9 ft^2 (0.83 m^2) over the previous one-week period. Homes with HRV systems had a median window/door opening of 20.7 ft^2 (1.75 m^2) for the air quality test period and a median of 18.8 ft^2 (1.97 m^2) over the previous one-week period. A total of 6 of the 63 homes (i.e. 10%) did not open their windows/doors at all during the 24-hour test period and a total of 10 homes (i.e. 16%) opened their windows/doors less than an average of 0.5 ft^2 (0.05 m^2), or a window open less than 2 inches (5 cm) over the 24-hour test period. The small amount of window/door usage in these homes during the 24-hour test day was also reflected in the week prior measurements.

Exhaust and Outdoor Air Fan Flow Rates. The amount of exhaust and outdoor air fan operation was expressed as the average air changes per hour (ach) over the 24-hour air quality sampling period is presented in Table 3 along with the percent "on" time and the flow rate of outdoor air in cfm for the mechanical outdoor airflow rates. Homes without mechanical outdoor air ventilation systems had a median exhaust air exchange rate of 0.01 ach and no mechanical outdoor air ventilation. Homes with DOA systems had a median exhaust air exchange rate of 0.00 ach and a median outdoor air supply rate of 0.02 ach. Homes with HRV systems had a median exhaust air exchange rate of 0.35 ach and a median outdoor air supply rate of 0.44 ach. The median percent fan "on" time was 18% for the DOA systems and 100% for the HRV systems, while the median outdoor airflow rates, when the systems were operating, were 40 cfm (19 L/s) for the DOA systems and 153 cfm (72 L/s) for the HRV systems.

ASHRAE 62.2 –2004 (ASHRAE, 2004) recommends that homes in climates with more than 4,500 ^oF-day (2,482 ^oC-days) infiltration degree days be provided with a mechanical outdoor air ventilation with a rate equal to the sum of 0.01cfm/ft^2 of floor area (0.05 L/s·m^2) and 7.5 cfm (3.5 L/s) per the number of bedrooms plus one. Infiltration degree-days is the sum of the annual infiltration related cooling and heating loads (ASHRAE, 1998). We note that none of the homes in this study were in a climate zone exceeding 4,500 ^oF-day (2,482 ^oC-days) infiltration degree-days.

Table 2. Window and Door Opening Expressed as the Average Opening in Square Feet over the 24-Hour Air Quality Sampling Period and the Average of the Previous Seven 24-Hour Periods in New Single-Family Detached Homes in California—with and without Mechanical Outdoor Air Ventilation

	No Mechanical Outdoor Air [a] Homes (n=42)		DOA Mechanical Outdoor Air [b] Homes (n=8)		HRV Mechanical Outdoor Air [c] Homes (n=3)	
	Test Day 24 hr Average (ft^2)	Week 24 hr Average (ft^2)	Test Day 24 hr Average (ft^2)	Week 24 hr Average (ft^2)	Test Day 24 hr Average (ft^2)	Week 24 hr Average (ft^2)
Minimum	0.0	0.0	0.0	0.2	12.1	14.2
25% Quartile	1.7	1.9	3.3	5.0	16.4	16.5
50% Median	7.9	8.5	10.4	7.8	20.7	18.8
75% Quartile	17.5	19.2	19.2	23.9	33.6	28.7
Maximum	102.0	52.5	52.8	43.7	46.4	38.6

[a] 42 homes with no mechanical outdoor air systems and no nighttime ventilation cooling systems.
[b] 8 homes with operational mechanical ducted outdoor air (DOA) ventilation systems and no nighttime ventilation cooling systems.
[c] 3 homes with operational mechanical heat recovery ventilator (HRV) outdoor air ventilation systems and no nighttime ventilation cooling systems.

Table 3. Exhaust and Outdoor Air Fan Ventilation as Expressed as the Average Air Changes per Hour (ach) over the 24-Hour Air Quality Sampling Period as Well as the Average of the Previous Seven 24-Hour Periods in New Single-Family Detached Homes in California with and without Mechanical Outdoor Air Ventilation

	No Mechanical Outdoor Air [a] Homes (n=42)	DOA Mechanical Outdoor Air [b] Homes (n=8)		HRV Mechanical Outdoor Air [c] Homes (n=3)	
	Exhaust Fan 24 hr Average (ach)	Exhaust Fan 24 hr Average (ach)	Mechanical Outdoor Air 24 hr Average (ach) / (%ON) / (cfm)	Exhaust Fan 24 hr Average (ach)	Mechanical Outdoor Air 24 hr Average (ach) / (%ON) / (cfm)
Minimum	0.00	0.00	0.00 / 0 / 27	0.11	0.12 / 32 / 149
25% Quartile	0.00	0.00	0.01 / 0 / 30	0.23	0.38 / 66 / 151
50% Median	0.01	0.00	0.02 / 18 / 40	0.35	0.44 / 100 / 153
75% Quartile	0.01	0.02	0.04 / 25 / 48	0.43	0.46 / 100 / 156
Maximum	0.10	0.03	0.07 / 40 / 71	0.51	0.47 / 100 / 159

[a]42 homes with no mechanical outdoor air systems and no nighttime ventilation cooling systems.
[b]8 homes with operational mechanical ducted outdoor air (DOA) ventilation systems and no nighttime ventilation cooling systems.
[c]3 homes with operational mechanical heat recovery ventilator (HRV) outdoor air ventilation systems and no nighttime ventilation cooling systems.

Table 4. Building Envelope Air Leakage Area as Calculated from Building Envelope Depressurization Tests and as Expressed as ACH_{50} and SLA in New Single-Family Detached Homes in California with and without Mechanical Outdoor Air Ventilation

	No Mechanical Outdoor Air [a] Homes (n=42)		DOA Mechanical Outdoor Air [b] Homes (n=7)		HRV Mechanical Outdoor Air [c] Homes (n=3)	
	ACH_{50} (ach)	SLA	ACH_{50} (ach)	SLA	ACH_{50} (ach)	SLA
Minimum	3.5	1.7	3.2	1.4	4.3	2.1
25% Quartile	4.0	2.4	4.0	2.5	4.4	2.2
50% Median	4.7	2.7	4.3	2.8	4.6	2.4
75% Quartile	5.3	3.0	5.0	3.0	4.8	2.6
Maximum	8.4	5.5	6.1	3.7	4.9	2.8

[a]42 homes with no mechanical outdoor air systems and no nighttime ventilation cooling systems.
[b]7 homes with operational mechanical ducted outdoor air (DOA) ventilation systems and no nighttime ventilation cooling systems (one home without blower door measurements excluded).
[c]3 homes with operational mechanical heat recovery ventilator (HRV) outdoor air ventilation systems and no nighttime ventilation cooling systems.

California Title 24 (California Energy Commission, 2005) requires that in homes designed for a Specific Leakage Area (SLA) of less than 3.0, a mechanical supply of outdoor air be provided to deliver 0.047 cfm/ft^2 (0.24L/s·m^2) of floor area.

For the 8 homes with working DOA systems, only 2 of 8 (25%) met the ASHRAE 62.2 recommendations and only 1 of 8 (13%) met the California Title 24 requirements. For the 7 homes with operational HRV systems, 7 of 7 (100%) met the ASHRAE 62.2 recommendations and 6 of 7 (86%) met the California Title 24 requirements.

Home Building Envelope Air Leakage Area. The building envelope air leakage area as calculated from the building envelope depressurization tests and as expressed as ACH_{50} and SLA is presented in Table 4. Homes without mechanical outdoor air ventilation had a median ACH_{50} of 4.7 and a median SLA of 2.7. Homes with DOA systems had a median ACH_{50} of 4.3 and a median SLA of 2.8. Homes with HRV systems had a median ACH_{50} of 4.6 and a median SLA of 2.4. These represent homes with moderately tight building envelopes. A total of 43 (69%) of the 62 homes with building envelope leakage area measurements had SLA values less than 3.0, for which California Title 24 (California Energy Commission, 2005) requires mechanical outdoor ventilation of 0.047 cfm/ft^2 (0.24 L/s·m^2). We note that this requirement only applies to those builders taking credit for building a home with an SLA less than 3.0. It is unknown if any of the homes in this study were built taking a credit for an SLA less than 3.0. There was also one home with an SLA value of less than 1.5, for which California Title 24 additionally requires that the mechanical ventilation outdoor ventilation be sufficient to maintain a negative indoor air pressure with respect to outdoors of no more than 5 pascals with all continuous ventilation systems operating.

Tracer Gas Measurements of Home Outdoor Air Exchange Rate. The 24-hour average outdoor air exchange rates as measured by the passive PFT tracer gas measurements are presented in Table 5. Homes without mechanical outdoor air ventilation systems had a median outdoor air exchange rate of 0.33 ach. Homes with DOA systems had a median outdoor air exchange rate of 0.36 ach. Homes with HRV systems had a median outdoor air exchange rate of 1.43 ach.

Indoor Air Quality Measurements

Formaldehyde. The 24-hour average indoor concentrations of formaldehyde are presented in Table 6. Homes without mechanical outdoor air ventilation had a median concentration of 38.3 μg/m^3. Homes with DOA systems had a median concentration of 58.5 μg/m^3. Homes with HRV systems had a median concentration 10.0 μg/m^3. The median outdoor formaldehyde concentration for the 24 home-clusters where outdoor formaldehyde concentrations were measured was 2.2 μg/m^3.

For comparison purposes the geometric mean indoor concentration of formaldehyde in new single-family homes (Hodgson et. al., 2000) ranged from 34 μg/m^3 for manufactured homes (n=7, 21-47 μg/m^3) to 36 μg/m^3 for site-built homes (n=4, 14-58 μg/m^3). We note that these homes, while new and finished including all cabinetry, were not furnished or occupied.

QUALITY ASSURANCE/QUALITY CONTROL

Blank Sample Analyses. A total of 5 field blanks for PMCH were analyzed for the combined Summer South and Summer North field sessions. The analyses of the field blanks resulted in masses of PMCH below the minimum detection

Table 5. Average 24-Hour Outdoor Air Exchange Rates as Calculated from Passive PFT Tracer Gas Measurements in New Single-Family Detached Homes in California with and without Mechanical Outdoor Air Ventilation

	No Mechanical Outdoor Air [a] Homes (n=41)	DOA Mechanical Outdoor Air [b] Homes (n=8)	HRV Mechanical Outdoor Air [c] Homes (n=3)
	Outdoor Air Exchange Rate (ach)	Outdoor Air Exchange Rate (ach)	Outdoor Air Exchange Rate (ach)
Minimum	0.13	0.10	0.33
25% Quartile	0.20	0.20	0.88
50% Median	0.33	0.36	1.43
75% Quartile	0.66	0.46	2.86
Maximum	6.47	0.58	4.28

a41 homes with no mechanical outdoor air systems and no nighttime ventilation cooling systems (one home without a PFT measurement excluded).
[b]8 homes with operational mechanical ducted outdoor air (DOA) ventilation systems and no nighttime ventilation cooling systems.
[c]3 homes with operational mechanical heat recovery ventilator (HRV) outdoor air ventilation systems and no nighttime ventilation cooling systems.

Table 6. Average 24-Hour Indoor Formaldehyde Concentrations in New Single-Family Detached Homes in California with and without Mechanical Outdoor Air Ventilation

	No Mechanical Outdoor Air [a] Homes (n=42)	DOA Mechanical Outdoor Air [c] Homes (n=7)	HRV Mechanical Outdoor Air [c] Homes (n=3)	Outdoor All [d] Homes (n=23)
	Indoor Formaldehyde Concentrations (μg/m^3)	Indoor Formaldehyde Concentrations (μg/m^3)	Indoor Formaldehyde Concentrations (μg/m^3)	Outdoor Formaldehyde Concentrations (μg/m^3)
Minimum	4.7	34.6	7.8	0.7
25% Quartile	22.2	42.2	8.9	1.5
50% Median	38.3	58.5	10.0	2.2
75% Quartile	73.8	87.0	23.4	3.1
Maximum	143.6	135.5	36.7	8.0

[a]42 homes with no mechanical outdoor air systems and no nighttime ventilation cooling systems.
[b]7 homes with operational mechanical ducted outdoor air (DOA) ventilation systems and no nighttime ventilation cooling systems (one home with a formaldehyde sample failure excluded).
[c]3 homes with operational mechanical heat recovery ventilator (HRV) outdoor air ventilation systems and no nighttime ventilation cooling systems.
[d]23 homes with outdoor air measurements (i.e., one home selected for each cluster of 2-3 homes).

limit in 3 of the 5 samples. Two of the field blanks had PMCH concentrations of 0.043 pL and 0.022 pL (0.001 pL minimum detection limit and a typical mass of 22 pL for a home with an outdoor air exchange rate of 0.2 ach).

A total of 6 field blanks for formaldehyde were analyzed for the combined Summer South and Summer North field sessions. The analyses resulted in masses below the minimum detection limit (15 ng minimum or 0.5 μg/m^3 for a typical air sample volume of 30 L) for each sample.

Duplicate Sample Analyses. A total of 6 duplicate PFT measurements of outdoor air exchange rate were analyzed for the combined Summer South and Summer North field sessions. The average absolute precision was 0.02 ach and ranged from 0.01 to 0.03 ach. The average relative precision was 3%. A total of 5 duplicate formaldehyde samples were analyzed for the combined Summer South and Summer North field sessions. For formaldehyde the average absolute precision was 5.3 μg/m^3 and the average relative precision was 10%.

DISCUSSION

Price and Sherman (Price, 2006) showed in the UCB Mail Survey that many homeowners never open their windows or doors for ventilation, ranging from 5.8% in the Spring to 29% in the Winter. The reasons cited by the homeowners for not opening windows were numerous and included security/ safety, noise, dust, and odor concerns. A total of 6 of the 63 homes (i.e. 10%) did not open their windows/doors at all during the 24 hour test period and a total of 10 homes (i.e. 16%) opened their windows/doors less than an average of 0.5 ft^2 (0.05 m^2), or a window open less than 2 inches (5 cm) over the 24 hour test period. The window/door opening recorded during the air testing 24-hour period in the homes was were similar to the average opening recorded for the week period prior to the air testing. The window/door opening recorded in homes without mechanical outdoor air ventilation and with DOA mechanical ventilation systems were similar, with the median 24 hour average window/door opening ranging from 7.9 ft^2 (0.73 m^2) for the 42 non-mechanically ventilated homes to 8.3 ft^2 (0.77 m^2) for the 8 DOA mechanically ventilated homes. The median window/door opening in the 3 HRV mechanically ventilated homes was significantly higher, 20.7 ft^2 (1.92 m^2).

In Figure 3 we compare the impact of window/door opening on the outdoor air exchange rate observed in homes during the 24-hour test period for the 41 Summer field session homes without mechanical outdoor air ventilation (one home without a PFT measurement excluded). The impact of window/door opening on the outdoor air exchange rate was calculated as the difference between the measured outdoor air exchange rate and the calculated outdoor air exchange rate without consideration for open windows/doors. The calculated outdoor air exchange rate was determined by combining the building envelope air leakage rate with the measured mechanical ventilation rates (i.e. bathroom, kitchen, and dryer exhausts) according to the superposition model described in the ASHRAE Handbook – Fundamentals (ASHRAE, 2005). The building envelope air leakage rate was determined from the measured building envelope leakage area, the stack and wind coefficients, the indoor-outdoor temperature difference, and the wind speed using the Basic Model described in the ASHRAE Handbook – Fundamentals (ASHRAE, 2005). This calculation excludes outdoor air exchange rates resulting from openable window/door areas. The window/door opening was calculated as the average opening in square feet for the 24-hour test period. As can be seen in Figure 3, the calculated outdoor air exchange rates agree with the measured outdoor air exchange rates reasonably well (i.e. ± 0.2 ach) up to an average 24-hour window/door opening of 15 ft^2 (1.4 m^2).

When window/door openings increase above an average 24-hour opening of more than 15 ft^2, the impact of the added outdoor air exchange rates is a mix of homes with little increased air exchange rate (i.e. <0.5 ach) and homes with substantially increased air exchange rates (i.e. 2-5 ach). A linear curve fit of the impact upon the outdoor air exchange rate as a function of the square feet of open window/door area results in a correlation coefficient of just 0.38.

The mechanical exhaust rates (e.g. bathroom fans etc.) measured in homes without mechanical outdoor air ventilation and with DOA systems were both low and similar, with the median 24 hour average exhaust rates ranging from 0.01 ach for the 42 non-mechanically ventilated homes to 0.02 for the 8 homes with DOA systems. The mechanical exhaust rates in the 3 homes with HRV systems were significantly higher, 0.35 ach. The higher exhaust rates in the homes with HRV systems are because HRV systems include an exhaust fan while DOA systems have no exhaust fan.

Homes with HRV systems had significantly higher mechanical outdoor air delivery rates, 0.44 ach, than the homes with DOA systems, 0.02 ach (p = 0.10). The reasons for

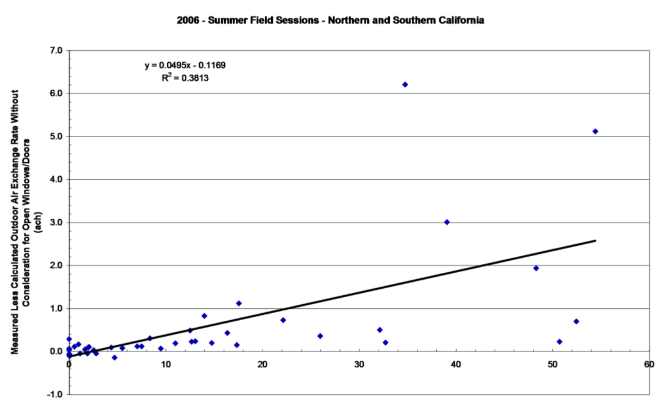

Figure 3 *Window/door opening impact on outdoor air exchange rates in 41 new single-family detached homes in California without mechanical outdoor air ventilation.*

the significantly lower outdoor air delivery rates associated with the DOA systems is a combination of their low median fan operation times, 18% for the DOA systems and 100% for the HRV systems, and the low median outdoor air flow rates 40 cfm (68 m^3/hr) for the DOA systems and 153 cfm (260 m^3/hr) for the HRV systems. The low median fan operation times associated with the DOA systems is a result of the fact that 6 of the 8 systems were operated by the thermostat fan switch in "auto" mode which, only operates the fan when the thermostat calls for heating or cooling. The 2 DOA systems controlled by a combination of thermostat and a fan cycler included one which had the outdoor air system disabled and one with a fan cycler which turned the fan on 11 minutes every 30 minutes.

The building envelope air leakage areas (ACH_{50} and SLA) were similar in homes without mechanical outdoor air ventilation and with DOA or HRV systems. The median ACH_{50} was 4.7 for the non-mechanically ventilated homes and 4.3 for the homes with DOA systems and 4.6 for those with HRV systems. These are moderately tight homes and compare to a recent study (Wilson and Bell, 2003) of building envelope air leakage in California homes which found a median ACH50 of 5.2 in 37 new homes built in November-December, 2002 and a median ACH50 of 8.6 for 13 homes constructed prior to 1987.

The mechanical exhaust rates (e.g. bathroom fans etc.) measured in homes without mechanical outdoor air ventilation and with DOA systems were both low and similar, with the median 24 hour average exhaust rates ranging from 0.01 ach for the 42 non-mechanically ventilated homes to 0.02 for the 8 homes with DOA systems. The mechanical exhaust rates in the 3 homes with HRV systems were significantly higher, 0.35 ach.

The 24-hour average outdoor air exchange rates as measured by PFTs in homes without mechanical outdoor air ventilation and with DOA mechanical ventilation systems were both low and similar, with the median outdoor air exchange rates ranging from 0.33 ach for the 42 non-mechanically ventilated homes to 0.36 for the 8 homes with DOA systems. The median outdoor air exchange rates in the 3 homes with HRV systems was higher, 1.43 ach. A t-test comparison of the means shows that the mean outdoor air exchange rates in homes with DOA systems is significantly lower than the mean in non-mechanically ventilated homes ($p = 0.05$).

A total of 31 of the 62 homes (i.e. 50%) with PFT measurements had outdoor air exchanges rates below 0.35 ach. If we look separately at the number of homes with outdoor air exchange rates less than 0.35 air changes per hour, we find that 59% (24 of 41) of homes without mechanical outdoor air ventilation systems, 50% (4 of 8) of homes with DOA systems, and 33% (i.e. 1 of 3) homes with HRV systems had outdoor air exchange rates less than 0.35 ach. We note that the one HRV system with an outdoor air exchange rate less than 0.35 ach was only operated 32% of the time via a manual switch by the homeowner.

The median 24-hour average indoor formaldehyde concentrations in homes with DOA systems was 52.2 μg/m^3, which is higher than the median concentration of 38.3 μg/m^3 in homes without mechanical outdoor air systems and the median concentration of 10.0 μg/m^3 in homes with HRV systems. A t-test comparison of the means shows that the mean indoor formaldehyde concentrations in homes with HRV systems is significantly lower than the mean in homes without mechanical outdoor air systems rates ($p = 0.05$) and the mean in homes with DOA systems ($p = 0.02$).

In Figure 4 we compare the indoor formaldehyde concentrations and the outdoor air exchange rates in 41 homes without mechanical outdoor air ventilation systems and in 17 homes with working mechanical outdoor air ventilation systems (i.e. 7 pure DOA, 3 pure HRV, and 7 other and mixed mechanical outdoor air systems). Also included in Figure 4 are the median ASHRAE 62.2 and California Title 24 recommendations for mechanical outdoor air ventilation as calculated for the specific homes in this study. The ASHRAE 62.2 median calculated rate was 0.15 ach while the California Title 24 median calculated rate was 0.30 ach.

We note that ASHRAE 62.2 assumes that natural infiltration will add to the mechanically supplied outdoor air exchange rate a total of 2 cfm/100 ft^2 (10 L/s-100 m^2) or 0.15 ach, assuming and 8 ft (2.4 m) ceiling height. However, we also note that if the indoor-outdoor temperature difference and wind speed are low, the natural infiltration rates can be much less than 0.15 ach. For a two-story home with a building envelope leakage equal to the median of the sample of homes in this study (i.e. ACH50 of 4.8 or SLA of 2.9), the natural infiltration rate for an indoor-outdoor temperature difference of 2°F (1°C) and a wind speed of 2 mph (3 km/hr), is just

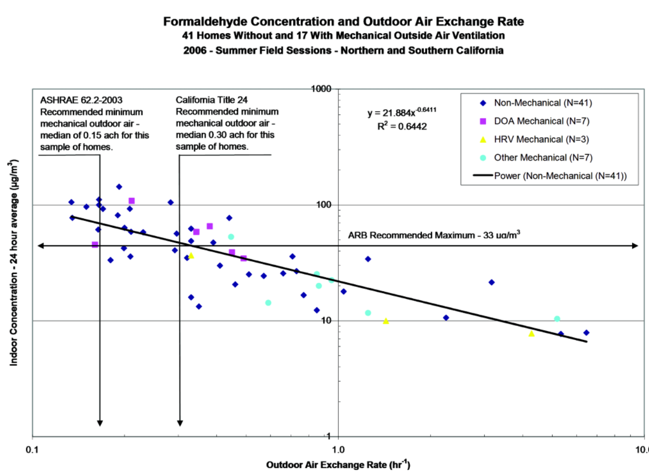

Figure 4 *Indoor formaldehyde concentrations and outdoor air exchange rates in new single-family detached homes in California, 41 homes without and 17 homes with mechanical outdoor air ventilation. Power curve fit of non-mechanically ventilated home data.*

0.08 ach. This is calculated according to the ASHRAE Basic Model (ASHRAE, 2005). Furthermore, if the mechanical outdoor air ventilation system is not a balanced system, such as the DOA systems in this study, then the natural infiltration rates can be substantially muted when the system is operating. For those systems equipped with fan cyclers set to operate the system for 33% operation time, the added natural infiltration is reduced from 0.08 ach to 0.06 ach as calculated according to the ASHRAE recommended calculation for combining infiltration and mechanical ventilation outdoor rates (ASHRAE, 2005). If an unbalanced system is set up to run at a low continuous rate then the added natural infiltration rate can be reduced from 0.08 ach to less than 0.01 ach.

We also have included in Figure 4 the California Air Resources Board recommended maximum indoor 8-hour formaldehyde exposure guideline of 33 μg/m^3 (California Air Resources Board, 2005). This guideline was developed to protect sensitive subgroups of the population to non-cancer irritant effects. In 2005, the World Health Organization designated formaldehyde as a known human carcinogen (IARC, 2004).

As can be seen in Figure 4, there are few homes with outdoor air exchange rates of at least 0.5 ach that have indoor concentrations of formaldehyde above the recommended maximum indoor concentration of 33 μg/m^3; just 2 of 21 homes, or 10%, of the homes. For homes with outdoor air exchange rates of at least 0.30 ach (i.e. the median rate recommended by California Title 24 for the homes in this study), a total of 14 of 38 homes, or 37%, have indoor concentrations of formaldehyde above 33 μg/m^3. For homes with outdoor air exchange rates of at least 0.15 ach (i.e. the median rate recommended by ASHRAE 62.2 for the homes in this study), a total of 32 of 57 homes, or 56%, have indoor concentrations of formaldehyde above 33 μg/m^3.

All of the 61 homes with indoor formaldehyde measurements had indoor formaldehyde concentrations above the Chronic Reference Exposure Levels (OEHHA, 2003) of 3 μg/m^3. A total of 37 of the 61 homes (i.e. 61%) had indoor concentrations exceeding California Air Resources Board recommended maximum indoor 8-hour formaldehyde exposure guideline of 33 μg/m^3. A total of 9 of the 61 homes (i.e. 15%) had indoor concentrations exceeding the Acute Reference Exposure Levels (OEHHA, 2000) of 94 μg/m^3.

If we look separately at the number of homes with indoor formaldehyde concentrations exceeding the 33 μg/m^3 guideline, we find that 62% (26 of 42) of homes without mechanical outdoor air ventilation systems, 100% (i.e. 7 of 7) of homes with DOA systems, and 33% (i.e. 1 of 3) homes with HRV systems exceeded this guideline. We note that the one HRV system with elevated indoor formaldehyde concentrations was only operated 32% of the time via a manual switch by the homeowner.

If we look solely at the homes in which the occupants do not use their windows at all, the following are the results. A total of 5 homes without a mechanical outdoor air ventilation system had no window/door usage. The mean outdoor air ventilation rate in these homes was 0.22 ach (0.10 – 0.46 ach) and the mean indoor formaldehyde concentration was 84.6 μg/m^3 (21-111 μg/m^3). There was only one home with a working mechanical outdoor air ventilation system and without any window/door usage. The outdoor air ventilation rate in this home was 1.28 ach and the indoor formaldehyde concentration was 12 μg/m^3.

CONCLUSIONS

Many homeowners never open their windows or doors for ventilation, ranging from 5.8% in the Spring to 29% in the Winter. The reasons cited by the homeowners for not opening windows were numerous and included security/safety, noise, dust, and odor concerns. A total of 6 of the 63 homes (i.e. 10%) did not open their windows/doors at all during the 24 hour test period and a total of 10 homes (i.e. 16%) opened their windows/doors less than an average of 0.5 ft^2 (0.05 m^2), or a window open less than 2 inches (5 cm) over the 24 hour test period.

Our analyses of the impact of window door opening on outdoor air ventilation rates reveals a mix of homes with little increased outdoor air exchange rate (i.e. <0.5 ach) and homes with substantially increased air exchange rates (i.e. 2-5 ach). Clearly the impact of openable windows and doors on the outdoor air exchange rate in homes is not a dependable source of outdoor ventilation rates and is affected many other variables including the indoor-outdoor temperature difference, wind speed and direction, and the configuration of the opened windows to one another (e.g. upper with or without lower, windward with or without leeward).

Homes with HRV systems had higher median mechanical outdoor air delivery rates, 0.44 ach, than the homes with DOA systems, 0.02 ach. Homes with HRV systems also had higher median outdoor air exchange rates as measured with PFTs (i.e. 1.46 ach) than the median for homes without mechanical outdoor ventilation systems (i.e. 0.33 ach).

The 24-hour average indoor formaldehyde concentrations in homes with DOA systems was 52.2 μg/m^3, which is higher than the median concentration of 38.3 μg/m^3 in homes without mechanical outdoor air systems and the median concentration of 10.0 μg/m^3 in homes with HRV systems.

A total of 37 of the 61 homes (i.e. 61%) had indoor concentrations exceeding California Air Resources Board recommended maximum indoor 8-hour formaldehyde exposure guideline of 33 μg/m^3. For homes with outdoor air exchange rates of at least 0.30 ach, a total of 14 of 38 homes, or 37%, have indoor concentrations of formaldehyde above 33 μg/m^3. For homes with outdoor air exchange rates of at least 0.15 ach a total of 32 of 57 homes, or 56%, have indoor concentrations of formaldehyde above 33 μg/m^3.

We conclude that the new single-family detached homes in California are built relatively tight and in those homes where the windows/doors are not opened for ventilation (e.g. for security, noise, odor, dust, thermal comfort concerns) the outdoor air exchange rates are typically low (e.g. 0.2 ach) and indoor concentrations of air contaminants with indoor sources such as formaldehyde can be significantly elevated.

The results presented in this paper suggest that consideration should be given to installing mechanical outdoor air ventilations systems in new single-family residences to provide a dependable and continuous supply of outdoor air to the residence. The energy costs associated with operating a mechanical outdoor air ventilations system is estimated to cost between $100 - $300/yr in fan power energy and increased heating/cooling energy costs depending upon the outdoor air flow rate and climate.

The HRV mechanical outdoor air systems performed well in increasing the home outdoor air exchange rates and reducing indoor formaldehyde concentrations while the DOA systems did not perform well as a result of a combination of the low outdoor air flow rates and low fan operation times associated with these systems.

The results presented in this paper represent the results from the Summer field sessions only. Results from the Fall and Winter field sessions will be presented along with the Summer field sessions in the project final report and will also include the results of the concentrations of 21 other volatile organic compounds, carbon dioxide, carbon monoxide, temperature, relative humidity, and in the Winter North field session the concentrations of nitrogen dioxide and $PM_{2.5}$ particulate matter will be included.

LEGAL NOTICE

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REFERENCES

ASHRAE. 1988. *ASHRAE Standard 119-1988 (RA 94)*, *Air Leakage performance for Detached Single-Family Buildings.* Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 2004. *ASHRAE Standard 62.2-2004*, *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings.* Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 2005. *2005 ASHRAE Handbook – Fundamentals, Chapter 27.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASTM. 2000. ASTM International Standard E 741-00, *Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution*. West Conshohocken: American Society for Testing and Materials Standards.

ASTM. 2003a. ASTM Active Standard E779-03, *Standard Test Method for Determining Air Leakage Rate by Fan Pressurization*. West Conshohocken: American Society for Testing and Materials Standards.

ASTM. 2003b. ASTM Active Standard D5197-03, *Standard Test Method for Determination of Formaldehyde and Other Carbonyl Compounds in Air (Active Sampler Methodology).* West Conshohocken: American Society for Testing and Materials Standards.

California Air Resources Board. 2005. Report to the California Legislature: Indoor Air Pollution in California. Sacramento: California Environmental Protection Agency.

California Energy Commission. 2005. Title 24, Part 6, of the California Code of Regulations: California's Energy Efficiency Standards for Residential and Nonresidential Buildings. Sacramento: California Energy Commission.

Hodgson, A.T., A. F. Rudd, D. Beal, and S. Chandra. 2000. Volatile Organic Compound Concentrations and Emission Rates in New Manufactured and Site-Built Houses. Indoor Air Volume (3):178-192.

IARC (International Agency for Research on Cancer). 2004. IARC Classifies Formaldehyde as Carcinogenic to Humans. Available from www.iarc.fr/ENG/Press_Releases/archives/pr153a.html.

OEHHA (Office of Environmental Health Hazard Assessment), 2000. All Acute Reference Exposure Levels

Adopted by OEHHA as of May, 2000. Available from www.oehha.ca.gov/air/acute_rels/allAcRELs.html.

OEHHA (Office of Environmental Health Hazard Assessment), 2003. All Chronic Reference Exposure Levels Adopted by OEHHA as of August 2003. Available from www.oehha.ca.gov/air/chronic_rels/AllChrels.html.

Price, P.N. and Sherman, M.H. 2006. Ventilation Behavior and Household Characteristics in New California Houses. Indoor Environment Department, Lawrence Berkeley Laboratory, University of California, Berkeley.

University of California at Berkeley, Survey Research Center., and Lawrence Berkeley National Laboratory. 2006. Survey of Ventilation Practices and Housing Characteristics in New California Homes. California Air Resources Board, Contract 03-326, Sacramento, CA.

Wilson, A.L. and Bell, J. 2003. Infiltration, Blower Door and Air Exchange Measurements in New California Homes. IAQ Problems and Engineering Solutions Specialty Conference, Research Triangle Park, NC, AWMA, July 21, 2003.