Ventilation Performance in Wisconsin ENERGY STAR Homes

Scott Pigg, Energy Center of Wisconsin
Edward Carroll, Wisconsin Energy Conservation Corporation
Gregory Nahn, Wisconsin Energy Conservation Corporation
Joseph Nagan, Home Building Technology Services

ABSTRACT

Twenty four new Wisconsin homes—18 of which had participated in the Wisconsin ENERGY STAR Homes program—were monitored for two weeks during the heating season to assess the use and effectiveness of mechanical ventilation equipment as well as overall ventilation rates. The results show that kitchen and bath exhaust fans do not provide significant background ventilation in practice, being used about 12 minutes per day per person on average. Use of central ventilation systems varied from less than one to more than 40 cfm per person on average. Carbon dioxide levels and passive tracer gas tests suggest overall ventilation rates in the homes from about 7.5 to more than 60 cfm per person. As operated, only one of the 24 homes met the overall ventilation standards of ASHRAE 62.2p as it is currently proposed, despite almost all of the homes having sufficient mechanical ventilation capacity relative to the standard.

Introduction

There is a widespread perception that new homes are tighter than older homes in terms of infiltration. Field research confirms that new homes are indeed tighter on average. A 1999 field study involving a random sample of 299 Wisconsin single-family homes showed median air leakage of 6.0 air changes per hour at 50 Pascals (Pigg and Nevius, 2000). The 43 new homes in the sample, however, had a median air change rate of 3.9, and more than three-quarters were below the statewide median value.

Homes built to the standards of the Wisconsin ENERGY STAR Homes program are tighter still. This program, which has operated in regions of the state since 1999, and has certified almost 1,000 homes statewide as of March 2002, requires that certified homes have measured air leakage (cfm at 50 Pascals pressure difference) of no more than one-fourth the total shell area of the building (Carroll et al., 2002). Blower door tests for more than 900 homes certified by the program as of March 2002 show a median air change rate of 2.4 at 50 Pascals, with more than 95 percent of program homes falling below 4.0 ACH, and about one-third below 2.0 ACH.

The tightness of new homes is a cause of concern for both homeowners and builders. A 1995 survey of Wisconsin builders and insulation contractors revealed widespread concern about whether new Wisconsin homes are too tight, and are resulting in poor indoor air quality and moisture problems (ECW, 1996).

To address these concerns, the Wisconsin ENERGY STAR Homes program requires that certified homes have mechanical ventilation equipment capable of providing continuous ventilation of 20 cfm for the first bedroom, plus 10 cfm for each additional bedroom. Most homes in the program meet this requirement with bath exhaust fans or heat recovery ventilators. (In addition, to address combustion safety issues associated with tight homes, unvented combustion equipment is not allowed, and heating systems and water heaters are required to be power-vented.)

What was not known, however, was the extent to which homeowners use the mechanical ventilation equipment provided, or whether these homes are in fact adequately ventilated. To address this issue, we implemented a field study in 24 new Wisconsin homes in early 2001, 18 of which were certified by the Wisconsin ENERGY STAR Homes program. Funding for the study came from the State of Wisconsin and We Energies, Wisconsin's largest electric and gas utility. The field study results are the focus of this paper.

A brief discussion of what is meant by "adequate" ventilation is warranted. An often-cited guideline is ASHRAE 62-1989 (ASHRAE, 1989), which calls for 0.35 air changes per hour but not less than 15 cfm per person in residences, and notes that this is typically expected to be provided by natural infiltration—an unlikely occurrence for new Wisconsin homes. ASHRAE has been working for several years on a revised standard (62.2p) specifically for residential buildings. The most recent version of this standard calls for providing mechanical ventilation capacity equivalent to 7.5 cfm/occupant plus one cfm per 100 square feet of floor space, with an assumption that an additional two cfm per 100 square feet will occur through natural ventilation (ASHRAE 2002). Using bedrooms plus one as a proxy for occupancy, this guideline works out to a total ventilation requirement of about 33 cfm per person (or 0.28 air changes per hour) for the typical program home. Separate data on actual occupancy levels and square footage for several hundred new Wisconsin homes (Pigg, 2002) indicates that actual occupancy per unit floor area averages about 24 percent less than the bedrooms-plus-one formula would indicate. Since the proposed standard does not provide for reducing the ventilation capacity when actual occupancy is less than the bedroom proxy, it appears that the standard would require about 40 cfm per person of total ventilation for a typical home in the Wisconsin program, of which 20 cfm per person would need to be supplied by mechanical ventilation.

At the other end of the spectrum, Wisconsin' commercial building code requires only 7.5 cfm/person of mechanical ventilation in office buildings (Wisconsin has no code-mandated requirement for ventilation rates in residences, though spot exhaust ventilation is required in bathrooms and kitchens).

For the purposes of this paper, we define an average of 15 cfm or higher per person as acceptable (from an indoor air quality perspective), 7.5 to 15 cfm/person as borderline, and below 7.5 cfm/person as unacceptably low.

Approach

Homes for the study were recruited from several sources. Program homes were mostly recruited randomly from a list of program participants, after stratifying by ventilation system type. We were looking for a combination of homes with and without central ventilation systems, and representing a variety of central systems. A few of the program homes were recruited purposively in order to obtain representation of relatively rare configurations, such as central exhaust systems. Non-program homes were recruited by telephone from a purchased random sample of construction permits issued between June 1999 and May 2000. Table 1 shows some basic facts about each home in the study. Overall, the homes appear to be fairly typical of the program participant and non-participant populations.

Table 1. Site Characteristics

Site	Test Period (2001)	Stories above grade	Bedrooms	Volume[a] (ft^3)	Floor Area[a] (ft^2)	Occupants
Program Homes						
D11	02/03 - 02/17	1	3	22,700	2,720	2
D12	02/05 - 02/19	2	3	19,000	2,290	2
D14	02/06 - 02/19	2	3	35,900	3,570	4
D22	03/10 - 03/24	2	3	22,600	2,570	2
D23	03/08 - 03/22	2	3	29,900	3,410	2
D24	03/08 - 03/22	2	3	26,600	3,130	4
F11	03/20 - 04/04	1	3	22,300	2,730	5
F12	03/20 - 04/04	2	3	24,100	2,720	5
F14	03/21 - 04/04	2	3	36,800	4,890	4
G11	03/03 - 03/16	1	4	28,600	3,210	4
G13	03/02 - 03/16	1	3	48,200	4,910	2
G14	03/03 - 03/16	2	4	50,000	5,330	4
G22	03/29 - 04/12	1	3	27,700	3,280	4
G23	03/30 - 04/12	1	3	20,200	2,450	4
G24	03/30 - 04/12	1	3	20,700	2,550	4
W11	02/16 - 03/03	1	2	15,000	1,800	2
W12	02/18 - 03/04	2	4	40,800	4,750	4
W14	02/19 - 03/04	2	4	32,800	3,780	5
Non-Program Homes						
D13	02/05 - 02/19[b]	1	3	16,700	2,000	4
D21	03/10 - 03/25[c]	2	4	39,900	3,590	4
F13	03/21 - 04/04	2	3	18,900	2,220	2
G12	03/02 - 03/16	2	4	34,100	4,100	4
G21	03/29 - 04/12	1	3	19,500	2,400	4
W13	02/18 - 03/04	2	4	26,500	3,340	6

[a] Based on interior measurements. These averaged about 85% of values from exterior measurements.

[b] Analysis excludes one day and night with no occupancy.

[c] Analysis excludes the final week of data with no occupancy.

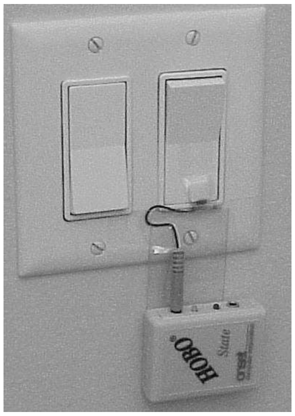
Monitoring was conducted in six overlapping two-week rounds, with each round involving four homes in a particular geographic area. The sample was designed to cover the main geographic regions of program activity at the time. Two rounds were conducted in the Madison (Sites D1*x* and D2*x*) and Green Bay/Appleton areas (Sites G1*x* and G2*x*). One round was conducted in Waukesha county (Sites W1*x*), an area of suburban development west of Milwaukee. Finally, one round was conducted in Fond du Lac County (Sites F1*x*). Each round involved three program homes and one non-program home.

We took an approach that fell between intensive testing and monitoring of a few homes versus more cursory testing in many homes. The study protocol called for conducting testing and deploying data loggers for as many parameters as feasible by a two-person crew in a single three-hour site visit. The protocol involved:

- Measurement of interior square footages and volumes.
- A blower door test of air leakage, including zone pressure diagnostic tests of air leakage between house and garage and house and unfinished basement areas.
- Measurement of exhaust device flows (using a balometer).
- Deployment of source emitters and sampling tubes for passive tracer gas tests of air exchange.
- Deployment of data loggers to monitor the operation of exhaust fans, central ventilation equipment, water heaters, clothes dryers, furnaces, and in some cases fuel-fired kitchen ranges and gas fireplaces.
- Deployment of sensors and data loggers to monitor indoor CO_2 concentration, temperature and relative humidity in two locations: the master bedroom and a main living space such as a living room or great room.
- Measurement of outdoor CO_2 levels (also measured at the end of the monitoring period).
- Deployment of additional data loggers to monitor temperatures at thermostats, in basements, and outdoors.
- Completion of field forms to capture details of mechanical equipment, occupant assessment of the typical use of exhaust devices, and factors that might affect the interpretation of the CO_2 data (such as presence of pets and indoor plants).

The operational status of fans, clothes dryers and mechanical equipment was recorded with state-recording data loggers that simply logged the date and time each piece of equipment was turned on and off. The status of various devices was sensed in different ways, however. Relays on gas valves or inducer fans were typically used to monitor furnaces and water heaters. Dryers were monitored with vibration-sensing data loggers. Bath fans were monitored by mounting a small magnet on the switch rocker; the magnetic field then opened or closed the contacts of a nearby miniature magnetic reed switch depending on the switch position (Figure 1). This arrangement was somewhat more obtrusive than we would have liked, but it was the only solution we found that could be implemented within the time limits of the site visit. We experienced a few sensor failures with this arrangement, and a few rarely used bathrooms went unmonitored, but overall data recovery from bath fan use was good.

Figure 1. Bath Fan Monitoring



Kitchen range exhaust hoods proved particularly difficult to monitor. In a few cases, we improvised sail-switch type sensors that closed a set of contacts whenever there was air flow in the exhaust duct. In other cases, we simply asked the occupants to record whenever they used the range hood. However, a number of range hoods went unmonitored; the homeowners for most of these sites told us they rarely used the range hood (Site D14 stands as one exception).

Heat recovery ventilators were typically monitored by recording temperatures (at two points in the system) and total current draw every two minutes. All other temperature, relative humidity and CO_2 concentration sensors were sampled and recorded every ten minutes.

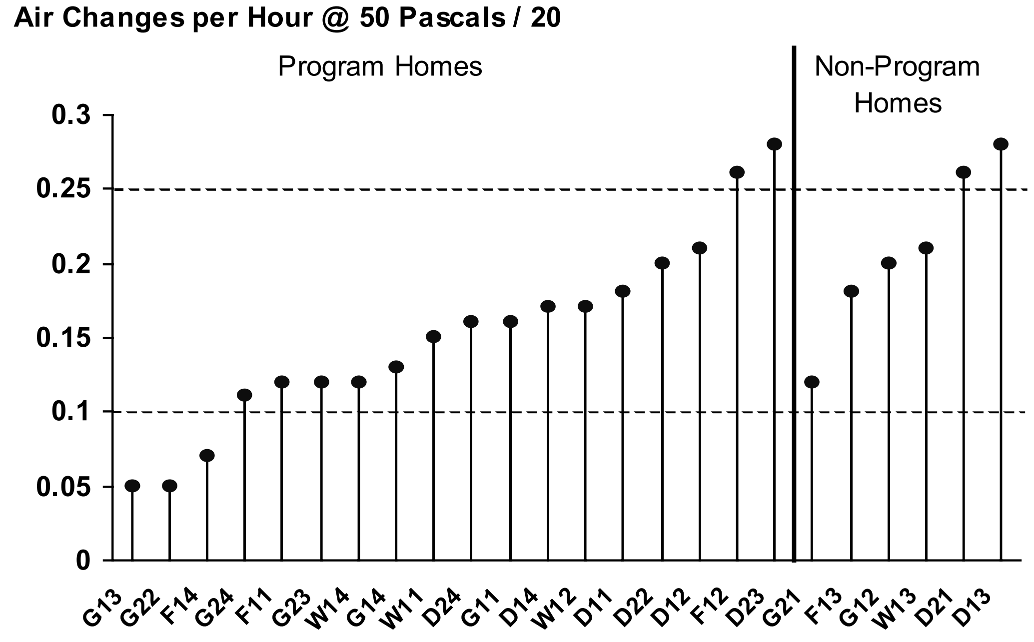
In addition to all of the above, the homeowners maintained an hourly log of occupancy by household member, with provisions for noting the presence of visitors and whether anyone was engaging in strenuous activity that might significantly affect CO_2 generation.

Results

Air Leakage

The distribution of air leakage for the study homes largely mirrors the available data on the population distribution. Program homes have a median estimated natural infiltration rate (roughly estimated as 1/20th of the air leakage at 50 Pascals) of about 0.15 air changes per hour, compared to about 0.2 ACH_{nat} for non-program homes. The study homes fall into three (somewhat arbitrarily defined) categories of air leakage; very tight (<0.1 ACH_{nat}), moderately tight (0.1 to 0.25 ACH_{nat}), and relatively (for new construction) loose (>0.25 ACH_{nat}) (Figure 2). Three program homes fall into the very tight category, and two each of program and non-program homes would be considered to be relatively loose.

Figure 2. Air Leakage



Use of Mechanical Ventilation Equipment

The study homes employed three basic ventilation strategies, which are discussed below.

Spot exhaust only. These homes—which make up about half of the homes certified by the program and the majority of non-program new homes in Wisconsin—have bath and (usually) kitchen exhaust fans, but no central exhaust ventilation system. Mechanical ventilation occurs only when an occupant turns on an exhaust fan, which is usually in response to a specific action such as taking a shower or cooking. Flow tests of bath exhaust fans in the study homes showed an average of about 45 cfm exhaust ventilation per fan, with a range from 9 to 100 cfm. The 15 study homes with vented kitchen range hoods had a median flow (at the highest speed setting) of 130 cfm, and a range from about 60 to 360 cfm. More extensive program tracking data on about 1,000 program homes show an average of about 47 cfm for bath fans and 84 cfm for kitchen exhaust fans.

Heat recovery ventilator (HRV). These homes use a central heat recovery ventilator to provide (in most cases) both spot and background ventilation capability. The typical home has exhaust air pickups in bathrooms and the kitchen and separate ductwork to the HRV. Fresh air is typically routed to the furnace return air plenum. Background ventilation is typically controlled by a dehumidistat, though cycle timers are also used (e.g., 20 minutes on, 40 minutes off). Spot ventilation control is usually in the form of mechanical crank timers or electronic timers in bathrooms that run the HRV at a higher speed when activated. The HRV may be interlocked with the furnace air handler so that the air handler is activated whenever the HRV operates (most are not). About 40 percent of program homes have an HRV, which are thought to be less common in non-program new homes.

Central exhaust. These homes—which represent about 10 percent of program homes—have a central exhaust system that does not use heat recovery or provide for ducted intake of fresh air. As with HRVs, the exhaust system can provide background or spot ventilation.

Table 2 shows how the study sites fall within these categories, and how much ventilation the various devices provided during the two-week monitoring period for each site. The data show that for the most part, spot exhaust fans were used relatively sparingly in the study homes; the median home has less than 30 minutes of total bath fan run time per day, and only about 6 minutes of range hood exhaust per day on average.

When averaged over the entire monitoring period, spot exhaust fans provided less than 2 cfm per occupant for most of the homes. This does not mean that spot exhaust fans are useless; the primary function of these fans is to remove moisture and odors quickly from a point close to where they are generated. The data do demonstrate, however, that occupant-controlled spot exhaust fans mostly do not provide significant overall ventilation in practice.

With the exception of one low run-time HRV site (D11), the HRV and central-exhaust homes show higher overall mechanical ventilation than the spot-exhaust only homes. In these homes, mechanical ventilation provided from 3.5 to more than 40 cfm per occupant on average.

Table 2. Mechanical Ventilation Use by Site

Site and Group	# Spot Fans	Total Exhaust Capacity (cfm)		Mean Daily Operation (minutes)				Mean Ventilation Rate (cfm/occupant)			
					Bath Spot (combined total)						
		Spot	Central	Kitchen Spot	Total	Per Occupant	Central System	Kitchen Spot	Bath Spot	Central System	Total
Spot Exhaust Only											
W13 Non	3	183	na	na	6.2	1.0	na	na	0.0	na	0.0
D22 Prog	3	193	na	1.8	0.2	0.1	na	0.1	0.0	na	0.1
D12 Prog	4	164	na	0.0	9.3	4.6	na	0.0	0.1	na	0.1
W12 Prog	5	371	na	---	16.0	4.0	na	---	0.2	na	0.2
G21 Non	2	67	na	na	44.1	11.0	na	na	0.2	na	0.2
D13 Non	2	92	na	na	42.3	10.6	na	na	0.3	na	0.3
F13 Non	3	152	na	na	26.4	13.2	na	na	0.4	na	0.4
D23 Prog	5	296	na	6.4	29.3	14.6	na	0.2	0.3	na	0.5
G12 Non	6	291	na	19.8	10.7	2.7	na	0.5	0.1	na	0.6
D14 Prog	5	320	na	---	146	36.4	na	---	1.1	na	1.1
W11[a] Prog	2	204	na	---	84.4	42.2	na	---	1.3	na	1.3
G11 Prog	6	436	na	12.6	82.2	20.6	na	0.2	1.1	na	1.4
D24 Prog	5	359	na	64.5	56.0	14.0	na	2.8	0.1	na	2.9
G22[b] Prog	4	183	na	0.0	634	159	na	0.0	3.3	na	3.3
Group median		**199**	**na**	**6.4**	**35.8**	**12.1**	**na**	**0.2**	**0.25**	**na**	**0.45**
HRV											
D11 Prog	1	165	77	---	na	na	20.8	---	na	0.6	0.6
W14 Prog	0	0	70	na	na	na	530	na	na	5.2	5.2
F14 Prog	1	58	134	na	26.9	6.7	215	na	0.3	5.0	5.3
G13 Prog	1	285	158	1.7	na	na	104	0.2	na	5.7	5.9
G14[c] Prog	4	477	163	8.7	2.6	0.6	381	0.5	0.0	6.5	7.1
F12 Prog	1	106	97	---	na	na	1418	---	na	13.8	13.8
F11 Prog	1	142	70	---	na	na	1408	0.1	na	19.6	19.6
D21[d] Non	0	0	163	na	na	na	1440	na	na	40.8	40.8
Group median		**124**	**146**	**5.2**	**14.8**	**3.6**	**455**	**0.4**	**0.15**	**6.1**	**6.5**
Central Exhaust											
G24 Prog	0	0	140	na	na	na	385	na	na	9.4	9.4
G23 Prog	0	0	165	na	na	na	850	na	na	24.3	24.3
Group median		**0**	**153**	**na**	**na**	**na**	**617**	**na**	**na**	**16.8**	**16.8**

na = not applicable to this site.
--- = no data for this site.
[a] Single switch controls bathroom light and exhaust fan.
[b] This site has a bathroom exhaust fan that is connected to a central dehumidistat.
[c] HRV is "punched in" to furnace supply and return; no separate ductwork to living space.
[d] Two HRV units run continuously at this site; there are no controls for the HRVs.

"On average" is a key caveat here; we observed that the run-time data for several of the HRV and central exhaust sites showed many short cycles (less than 30 minutes) indicative of spot control from the bathrooms, and a few long cycles under dehumidistat control that lasted for hours or even days. The exceptions are the systems that essentially ran continuously (>1,400 minutes per day), and site G14, which ran on a 20-minute on, 40-minute off cycle for the first 11 days of monitoring. As a side note, it is unlikely that the HRV for Site G14 would have run at all during the monitoring period, had one of us not shown the homeowner how to operate the HRV in this home that was also equipped with a full complement of bath exhaust fans.

Applying the ASHRAE 62.2 standard to the 24 homes in the study results in required mechanical ventilation of 40 to 90 cfm depending on the size and number of occupants in the home, with an average of about 65 cfm. Only three homes (D21, F12, and G23) met the calculated mechanical ventilation requirement during the period of monitoring, though all but one home (W14) had sufficient ventilation capacity to do so.

In addition to mechanical ventilation provided specifically for that purpose, some mechanical ventilation also occurs as a consequence of operating dryers and power-vented combustion equipment such as water heaters and furnaces. Although only one home had a power vented furnace that was not sealed combustion, all but one home had power-vented water heaters that used inside air for combustion and hence acted as a ventilation device. We were able to monitor water heaters in 21 of the homes. These water heaters averaged 32 to 246 daily minutes of run-time per home, with an overall median of 84 minutes. On average these water heaters exhausted about 50 cfm when operating; this translates into about 1 cfm/occupant of ventilation on average from water heater operation. However, since water heaters are mostly located in unfinished basement space, it is arguable how much water heater operation affects air exchange in living spaces.

Clothes dryers in these homes, on the other hand, were mostly located in utility rooms on the first floor (though four were in basements, and one was on the second floor). Though our approach to recording run-time for these (using vibration sensing data loggers) proved problematic, we were able to recover usable run-time data for 16 homes. The results indicate a median run-time per day of 80 to 100 minutes, with individual homes averaging from less than 10 minutes of run-time per day to more than 250 minutes. We estimate that clothes dryers provide an overall average ventilation rate of 0.6 to 0.8 cfm/occupant. This figure averages weekends—when dryers are more likely to be operated—with weekdays that are less likely to see dryer operation.

Finally, most of the homes in the study met a code requirement for exhaust make-up air with a duct run between the outdoors and the furnace return. Negative pressure in the return during furnace operation would typically draw fresh air into the home, though we did not quantify this for the homes in the study.

Carbon Dioxide Levels

Occupant-generated carbon dioxide levels can be a useful indicator of ventilation rates. For a fixed rate of CO_2 generation in a home and a fixed air exchange rate, there is an associated equilibrium CO_2 elevation above outdoor levels, which can be expressed on a per-person basis (Persily, 1997). For the CO_2 generation rate of an average adult engaged in light activity (0.011 cfm), an air exchange rate of 15 cfm/occupant would be expected to result in an equilibrium indoor CO_2 concentration of 733 ppm above ambient (which we found to average about 400 ppm). Similarly, an air exchange rate of 7.5 cfm/occupant would result in an elevation of 1467 ppm above ambient.

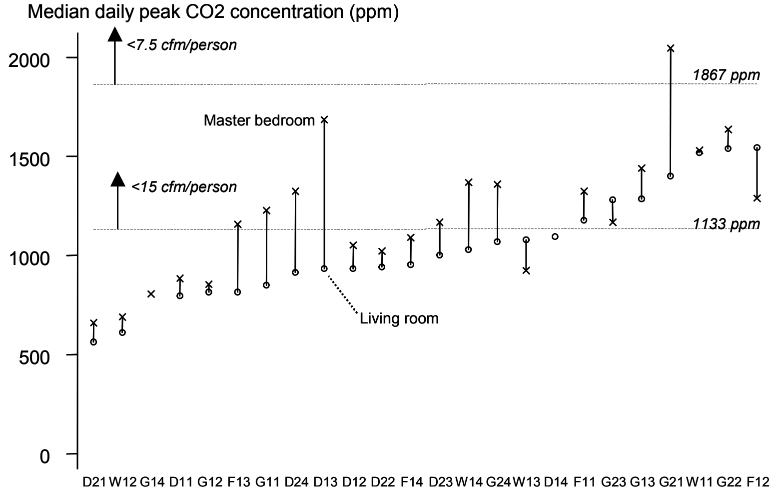
But not all occupants are average adults (or even adults period) and activity levels can be expected to vary. Moreover, it may take 8 hours or longer for CO_2 levels to reach equilibrium at air exchange rates typical of new homes. If equilibrium is not reached, then ventilation rates will be overestimated from measured CO_2 levels. At the same time, peak

CO_2 levels in a home provide an upper limit on the ventilation rate, assuming that assumptions about the average CO_2 generation rate hold (Persily, 1997). In short, high CO_2 levels are indicative of inadequate ventilation, but low levels do not necessarily mean adequate ventilation.

Figure 3 shows the median daily peak CO_2 concentration measured in the main living space and the master bedroom for the homes in the study. The figure also shows thresholds corresponding to equilibrium levels that correspond with 7.5 and 15 cfm per occupant. The data suggest that about a third of the homes have living room ventilation rates that are less than 15 cfm/occupant, and more than half have a master bedroom ventilation rate of less than this value. Only one home shows a (bedroom) CO_2 concentration indicating less than 7.5 cfm/occupant.

In general, bedroom CO_2 peak levels are higher than living room levels, and seven homes show bedroom peaks that are substantially higher. These tend to be homes with substantial night setbacks to the thermostat, which result in little nighttime furnace runtime, and thus little bedroom air circulation. Similar elevated bedroom CO_2 levels have been observed elsewhere (White and Lawton, 1996).

Figure 3. Peak Carbon Dioxide Concentration



Tracer Gas Tests

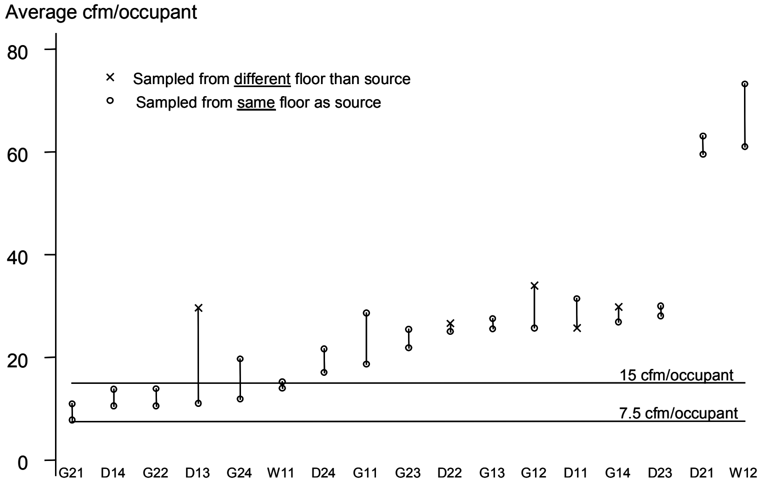
We conducted passive tracer gas tests on most of the homes in the study, following methods described in Dietz et al. (1986). In these tests, a constant-injection tracer gas source is left in the home, along with one or more passive sampling tubes. Analysis of the amount of tracer gas in the sampling tubes provides a measure of the average concentration of the tracer gas in the home, the reciprocal of which is a measure of air exchange rates. Because the method relies on the reciprocal of the average concentration to approximate air exchange (which is actually related to the average reciprocal concentration) errors can result if air exchange rates vary significantly during the sampling period. These errors are typically less than 30 percent (ASHRAE, 1993).

An additional source of uncertainty for this study was the degree to which the entire house can be considered to be a single well-mixed zone. Dietz et al. provide evidence of good mixing within a floor, but not necessarily across floors. However, concerns about overloading the sampling tubes (probably misplaced, in retrospect) led us to typically leaving only a single source emitter in each home. Air exchange estimates based on sampling tubes on floors with no source emitter might therefore overestimate the actual rate.

Despite these potential accuracy issues, the results (for the 17 homes for which useable data were obtained) suggest reasonable results for average air exchange rates that are consistent with the CO_2 data (Figure 4). None of the homes showed ventilation rates of less than 7.5 cfm/occupant, though several fall below the 15-cfm/occupant threshold.

Two homes have very high ventilation rates, and were in fact the only two sites that met the overall ventilation requirements of ASHRAE 62.2p. One of these (Site D21) has two HRVs that run continuously. The measured ventilation rate for these HRVs (164 cfm) works out to about 41 cfm/occupant; presumably infiltration accounts for the remainder of the air exchange measured by the PFT tests. The other (Site W12) shows little mechanical ventilation and has measured air leakage that is in the middle of the study range. However, this home is a two-story home in an exposed location on a ridge top. A calculation of the likely infiltration rate during the monitoring period using the LBL model (ASHRAE, 1993) suggest a natural ventilation rate of almost 50 cfm per person for this home during the monitoring period.

Figure 4. Tracer Gas Measurements of Average Ventilation



Humidity

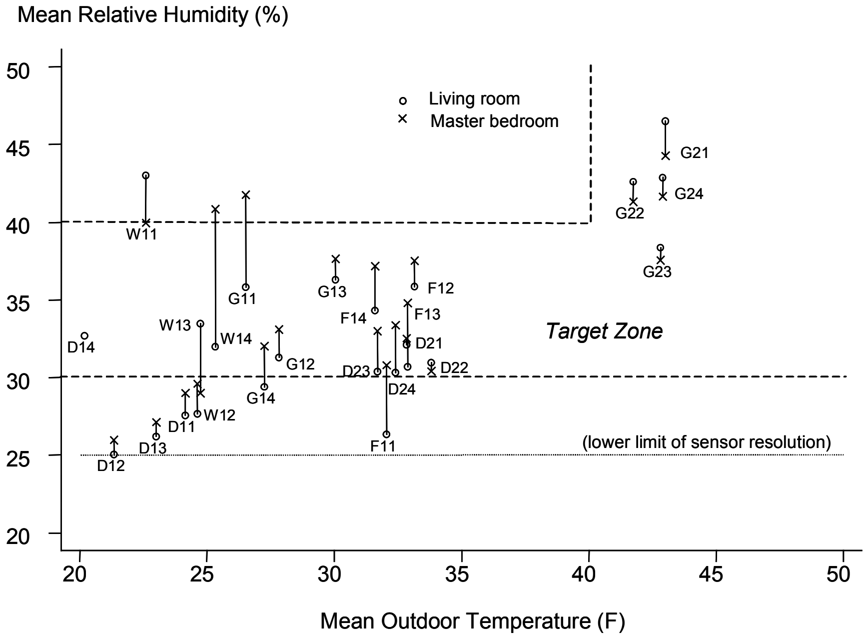
Controlling humidity is probably the most important homeowner concern with respect to ventilation. Low humidity can lead to skin and respiratory problems as well as static electricity problems. Conversely, high humidity can create conditions for mold, dust mites and other pathogens, and can produce condensation on windows.

Relative humidity in homes tends to vary with outdoor temperature, since cold outdoor air can hold less moisture than warmer air. This trend is generally evident in the data from the study homes, most of which fell on a trend line roughly defined as relative humidity equal to outdoor temperature (Figure 5). In particular, the last group of homes that were monitored in early April (G21-G24) shows higher relative humidity and outdoor temperature than the other homes in the study.

We consider 30 to 40 percent relative humidity to be the appropriate target zone for Wisconsin homes at outdoor temperatures between 20 and 40F. Above 40F, somewhat higher relative humidity can be tolerated without risk of window condensation. At very cold temperatures, condensation may be excessive at the upper end of the above range. By this criterion, most of the homes in the study had reasonable humidity levels. Six homes had relative humidity below this target zone; these were mostly homes monitored at colder temperatures. (Relative humidity for these homes might actually be lower than the data suggest, because the sensors used to measure relative humidity were not capable of recording relative humidity below about 25 percent.).

Three homes had relative humidity above the target zone, and two of these (W14, G11) involved high humidity in bedrooms but not the main living space. The one home for which relative humidity in general exceeded the 40 percent threshold was the smallest home in the study with the highest occupancy density (especially considering that this household also had two large dogs). This home also had a 15-gallon aquarium.

Figure 5. Mean Relative Humidity versus Outdoor Temperature



Conclusions

Overall, the data reveal no homes that were severely under-ventilated (<7.5 cfm/person) on average during monitoring. The CO_2 and tracer gas data suggest that about a third of the homes in the study fall into a borderline category between 7.5 and 15 cfm/person, and an additional third have borderline ventilation in bedrooms.

It is important to recognize that most of the homes were monitored under typical mid-winter conditions. Worst-case ventilation conditions occur in the spring and fall when the house is closed up for the heating season but indoor and outdoor temperatures are about equal. In this sense the four homes monitored in early April (G2*x*) were tested under less favorable ventilation conditions than the other homes. Indeed three of these four homes tended to be on the low end of the observed range of ventilation rates.

It is clear from this study that central ventilation systems provide significantly more mechanical ventilation on average than homes without such systems. All but one of the homes with a central system had at least 5 cfm/person provided by mechanical ventilation alone over the monitoring period, compared to mostly trivial overall mechanical ventilation in homes without central systems or automatic controls.

Nonetheless, that only three homes used mechanical ventilation to the extent stipulated by ASHRAE 62.2p—and only one home with two continuously operating HRVs appears to substantially meet the overall ventilation requirement—suggests that homeowners generally do not perceive the need for ventilation at 62.2p levels. Indoor humidity is probably the main factor that affects how people use their ventilation systems, and there was little evidence of excessive humidity among the study homes. In fact, given that humidity ranged from reasonable to somewhat dry for most of the homes in the study, we have some concerns that ventilating these homes to 62.2p levels might lead to excessive dryness during the winter unless enthalpy recovery or mechanical humidification is also employed.

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