Formaldehyde as a Basis for Residential Ventilation Rates[1]

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Abstract

Traditionally, houses in the U.S. have been ventilated by passive infiltration in combination with active window opening. However in recent years, the construction quality of residential building envelopes has been improved to reduce infiltration, and the use of windows for ventilation also may have decreased due to a number of factors. Thus, there has been increased interest in engineered ventilation systems for residences. The amount of ventilation provided by an engineered system should be set to protect occupants from unhealthy or objectionable exposures to indoor pollutants, while minimizing energy costs for conditioning incoming air. Determining the correct ventilation rate is a complex task, as there are numerous pollutants of potential concern, each having poorly characterized emission rates, and poorly defined acceptable levels of exposure. One ubiquitous pollutant in residences is formaldehyde. The sources of formaldehyde in new houses are reasonably understood, and there is a large body of literature on human health effects. This report examines the use of formaldehyde as a means of determining ventilation rates and uses existing data on emission rates of formaldehyde in new houses to derive recommended levels. Based on current, widely accepted concentration guidelines for formaldehyde, the minimum and guideline ventilation rates for most new houses are 0.28 and 0.5 air changes per hour, respectively.

Key words: Houses, Ventilation, Formaldehyde, Emission factors, Non-occupational exposure guidelines

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Introduction

A number of authoritative sources including the World Health Organization (2001) and the U.S. Environmental Protection Agency (1995) have declared indoor air quality (IAQ) to be a serious health hazard. Indoor exposures to air pollutants in residences are of particular concern since people on average spend the majority of their time indoors at home, often in proximity to pollutant sources (Jenkins et al., 1992). In the absence of regulations limiting the broad range of residential sources of contamination, acceptable exposures to airborne pollutants in houses primarily are maintained by providing adequate dilution ventilation. Adequate ventilation also serves to reduce other potential problems such as moisture-related damage that often results in microbial contamination.

Despite its importance, residential ventilation has not received a great deal of attention, possibly because it is often assumed that envelope leakage in combination with operable windows provides sufficient fresh air to meet the ventilation guidelines established by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE, 1989). These assumptions may have diminished validity today. Within the last quarter of a century, state and local governmental regulations put into place in response to the 1970's energy crisis and then to continuing energy concerns have resulted in much more energy-efficient houses. Energy-efficiency gains have been achieved, in part, by reducing uncontrolled infiltration. Thus, new houses in a closed condition, without any form of supplemental ventilation, may have ventilation rates substantially below ASHRAE guidance. Within the same time frame, the kinds and quantities of materials used to finish the interiors of houses have changed in response to resource limitations, product development and reformulation, and shifting consumer needs. The effects of these changes in materials on IAQ are not well documented, but probably have been both beneficial and deleterious with respect to exposures to airborne toxic chemicals. Additionally, the public's awareness and expectations regarding protection from exposures to all types of environmental pollutants have increased.

All of these factors may be contributing to a heightened level of governmental and public concern regarding residential IAQ and ventilation. Thus, there are ongoing efforts to define levels of acceptability and performance for air quality and ventilation, as evidenced by draft revisions to the ASHRAE ventilation standard. In theory, appropriate ventilation rates can be established by a modeling effort employing the emission rates of all airborne pollutants of concern, quantitative descriptions of the processes affecting pollutant dynamics, occupancy patterns and target levels for acceptable exposures to the resultant pollutant mixtures as the primary inputs. Such a comprehensive approach obviously is too complex and impractical based on our limited state of knowledge, in which we rarely know the required quantities for more than a very small number of pollutants.

In this report, we take an analogous but simplified approach and develop the rationale and a proposed procedure for establishing minimum and guideline residential ventilation rates based on a single well-studied indoor pollutant, formaldehyde, ignoring the impacts of other contaminants of concern. This proposal for defining acceptable ventilation rates for new residential construction is to use existing data on emission rates of formaldehyde to estimate concentrations for typical houses with the objective of achieving exposure concentrations that are below widely recognized guidelines for a substantial portion of the population living in new houses.

Perspective on Residential Ventilation Standards

There are numerous pollutants in residential indoor air, the concentrations of which may be impacted by ventilation (Grimsrud and Hadlich, 1999; Hadlich and Grimsrud, 1999). A number of gaseous and particulate pollutants are generated by occupant activities including cooking, cleaning, smoking, water use, and hobby activities. Some are combustion products generated by gas-fired appliances and vehicle emissions. Building components, interior finishes and furnishings emit other gaseous pollutants.

Although ventilation may serve as an effective control strategy for many such pollutants, a number of criteria must be met in order for an indoor air pollutant to be useful as the basis for a residential ventilation standard. In general, this pollutant must be commonly present in houses; it must be readily quantifiable; its concentrations must approach levels of concern under at least some typical situations; there must be a defined acceptable concentration level; its source strengths among houses must be distributed within a reasonably narrow range; and its source strength should be independent of air concentration and only moderately affected by environmental conditions (i.e., temperature and humidity).

Human bioeffluent readily meets most of these criteria and has served, at least indirectly, as the traditional basis for minimum ventilation standards. It exists in every occupied building; it is particularly important in high-occupant density environments; it does not vary much from person to person; and after basic hygiene is taken care of, the only practical control method is ventilation. The target level for bioeffluents, which has been well studied, depends on whether the acceptability is for visitors or occupants and on what activities the occupants may be undergoing. However, most North American houses have sufficiently low occupancies per floor area or volume that dilution of human bioeffluents does not dominate the requirement for whole-house ventilation. Thus, there is a need to examine other air pollutants for which sufficiently elevated concentrations may adversely affect occupants' health, comfort or general satisfaction and acceptance of IAQ.

A number of volatile organic compounds (VOCs) commonly present in indoor air may fall into this category. Many are carcinogens and reproductive toxins (EPA, 1994; CARB, 2001) or have other systemic effects (OEHHA, 2001). Many more are sensory irritants (ACGIH, 2000), while others have low odor thresholds (Devos et al., 1990). In existing houses, the predominant VOC sources likely are dominated by occupant activities and uses of products, which can be highly variable. In new houses, and presumably in newly remodeled houses, the structure itself can be a major source of VOC contamination. One study of unoccupied, newly constructed manufactured and entry-level site-built houses found that formaldehyde, less volatile aldehydes, and terpene hydrocarbons were the predominant air pollutants regardless of the structure type (Hodgson et al., 2000). Occupants may experience several adverse effects from the combination of these VOC emissions and low house ventilation. The less volatile aldehydes frequently exceeded their odor thresholds (ibid.) and may constitute an annoyance. More importantly, the formaldehyde concentrations often approached or exceeded levels of concern with respect to sensory irritation and cancer effects. Thus, we have focused on formaldehyde as a pollutant possibly suitable for defining a ventilation standard for new houses.

Because of the diversity of sources and human responses to mixtures of contaminants, no single pollutant can be assumed to be the only contaminant of concern. It is beyond the scope of this study to determine how various contaminants interact and when it is acceptable to ignore exposures and interactions. Since we are basing our conclusions on formaldehyde as the only contaminant of concerns, care must be taken in applying our results to situations in which other contaminants have a significant role.

Formaldehyde in Houses: Concentrations and Guidelines

The significance of formaldehyde as an indoor pollutant is well established. The U.S. EPA has classified formaldehyde as a probable human carcinogen of medium carcinogenic hazard (EPA, 1994). Formaldehyde is highly irritating to the eyes and upper respiratory tract at levels well below the odor threshold of approximately 500 ppb (OEHHA, 2001). Eye and throat irritation and chronic respiratory and allergy problems have been documented for several populations of residential occupants at concentrations of 100 ppb and lower (Ritchie and Lehnen, 1987; Broder et al., 1988; Liu et al., 1991).

Formaldehyde likely is present in all houses as an indoor-generated pollutant. It is emitted from composite wood products (building materials and furniture), fiberglass insulation, paper products, permanent-press fabrics including clothing and drapes, and cosmetics (Kelly et al., 1999). It is also emitted as a combustion product from gas and solid-fuel sources and tobacco smoke. Generally, wood products fabricated with urea-formaldehyde resin (i.e., particleboard and medium-density fiberboard) are the highest emitting persistent sources. These materials are used in large quantity in most new house construction. In one typical new manufactured house, there were ~500 kg of composite wood products with ~40 m^2 of bare surfaces comprising the cabinetry. These materials and the passage doors (25 m^2) were the highest formaldehyde sources (Hodgson et al., In press). Formaldehyde emissions from such sources are expected to persist over relatively long periods. For example, the new house study has shown that formaldehyde is emitted by materials at relatively constant rates over a period of at least nine months (Hodgson et al., 2000).

A number of methods exist to quantify formaldehyde in air. Passive devices requiring no specialized sampling equipment can measure concentrations integrated over a day or week. Such devices can be mailed to residential occupants and are well suited for conducting large-scale field surveys of houses (Sexton et al., 1986).

There are limited data on concentrations of formaldehyde in new houses built within the last decade. The new house study characterized the concentrations and emission rates of formaldehyde and other VOCs, among a set of four new manufactured and seven new site-built houses (Hodgson et al, 2000). The manufactured houses were produced by a single facility in Florida and differed with respect to size and interior finishes. The site-built houses were detached single-family dwellings designed as entry-level housing. These were located in three geographically separate projects in the eastern and southeastern United States. The exterior wall types were wood frame, concrete blocks or insulating concrete form. All of the houses were complete including carpeting (the manufactured houses additionally were furnished as sales models), but unoccupied. Sampling for VOCs was initially conducted within one to two months of completion. The manufactured houses and one site-built house were re-sampled at two other times. Indoor VOC samples were collected during periods in which house ventilation rates were near steady-state conditions. Outdoor samples were simultaneously collected, and house ventilation rates were concurrently measured by tracer-gas decay. Formaldehyde was collected on treated silica gel cartridges and analyzed by high performance liquid chromatography (ASTM, 1997a). The indoor minus outdoor (in-out) concentrations in these 12 houses plus two additional new manufactured houses are presented in Table 1. The concentrations in the manufactured and site-built houses were comparable, probably reflecting the use of similar materials and methods for construction and finishing of interiors. Thus, the 14 houses were treated as a single group. The average in-out concentration was 40 ppb (25 ^{o}C, 1 torr) with a range of 13-73 ppb and a geometric mean of 37 ppb. Outdoor air typically contributes several ppb to indoor concentrations. These results are in reasonable agreement with concentrations measured in another set of new site-built houses in Colorado (Lindstrom et al., 1995). Prior to occupancy, formaldehyde concentrations in these nine houses were 7-54 ppb with a geometric mean (GM) of 21 ppb. Five months after occupancy, concentrations were 27-66 ppb with a GM of 40 ppb. The cause of this shift could not be evaluated since ventilation was not measured.

Several governmental agencies have established guidelines for non-occupational exposures to formaldehyde that are intended to protect residential occupants (Table 2). The highest acceptable concentration of 100 ppb has been designated as an action or ceiling level (CDNHW, 1987; ARB, 1991). This value primarily was selected based on formaldehyde's status as a probable human carcinogen (EPA, 1994) but also takes into account other possible health risks including eye and upper respiratory tract irritation. The cost and technical feasibility of attainment were also considered. When the action level is exceeded, it is recommended that steps be taken to reduce concentrations even if occupants are not experiencing symptoms. A concentration of 50 ppb or less has been listed as a target level to reduce cancer risk with the proviso that concentrations be reduced to the lowest practicable levels because of the lack of an absolutely safe threshold (CDNHW, 1987; ARB, 1991). This lower level also should serve to reduce the occurrence of irritant effects.

Formaldehyde is regulated in the workplace as a sensory irritant. The current occupational short-term exposure level (ceiling) is 300 ppb (ACGIH, 2000). It has been proposed that an uncertainty factor of five to ten resulting in a guideline level of 30 to 60 ppb is sufficient to prevent irritation complaints among continuously exposed individuals in the general population (Paustenbach, 1997). This range is consistent with the target level for non-occupational exposure.

Some governmental agencies are moving toward establishing lower exposure guidelines for hazardous chemicals. For example, the California Office of Environmental Health Hazard Assessment (OEHHA) has recently established acute and chronic (non-cancer) reference exposure levels (RELs) for formaldehyde and a number of other chemicals (OEHHA, 1999, 2001). The acute REL for formaldehyde of 75 ppb is for a one-hour exposure and is intended to be protective against mild eye irritation. The supporting data are from a study of humans, and a ten-fold intraspecies uncertainty factor was applied. Chronic RELs are intended to be concentrations at or below which adverse health effects are unlikely to occur in a continuously exposed and diverse general population. The chronic REL for formaldehyde is based on a review and analysis of effects including eye and nasal irritation. The primary basis for the REL are data from workers exposed over a period of years and the derivation of a no adverse effects level (NOAEL) of 32 μg m^{-3} (26 ppb). A ten-fold intraspecies uncertainty factor was applied to arrive at the REL. of 3 μg m^{-3} (2.4 ppb). These values have yet to gain widespread acceptance, but may be indicative of a general trend of lower guideline concentrations.

Although formaldehyde meets many of the requirements stated in this paper, there are potential drawbacks to using it for defining a ventilation standard for new houses. Most importantly, the data on formaldehyde concentrations in new and existing North American houses are quite limited and has not been generated by population-based studies. Thus, we do not know whether the current data are representative of larger populations and do not know the forms of the concentration distributions in these populations. Accordingly, we anticipate that as additional information on emission rates and acceptable exposure levels is produced, the conclusions of this study will be revisited.

Formaldehyde also exhibits multifaceted dynamic behavior in houses probably making it difficult to establish target concentrations by simply manipulating ventilation rates. Formaldehyde emissions from composite wood products fabricated with urea-formaldehyde resin have been shown to be dependent upon air concentration and environmental conditions with higher emissions occurring at lower concentrations and elevated temperature and humidity (Matthews et al., 1986; Silberstein et al., 1988). Modeling shows these effects can be substantial (Silberstein et al., 1988; ASTM, 1996). This indicates there may be relatively large diurnal and seasonal variations in formaldehyde concentrations within individual houses in response to changes in ventilation and climatic conditions. However, sorption of formaldehyde to gypsum wallboard and other interior surfaces when concentrations are high with subsequent re-emission at higher ventilation rates should buffer short-term (one- to several-day) changes in formaldehyde concentrations (Matthews et al., 1987). The extent to which formaldehyde emission rates vary over time in current new houses in response to changes in ventilation and climatic conditions is unknown. The results of one recent field experiment showed that formaldehyde emission rates were relatively constant despite an approximate two-fold change in ventilation with measurements made at the end of week-long periods of constant ventilation at 0.32 and 0.14 h^{-1} (Hodgson et al, 2000). Formaldehyde is also a product of the reaction of ozone and terpene hydrocarbons (e.g., d-limonene) present in new houses (Weschler and Shields, 1997). Models predict that formaldehyde production from this reaction increases as the ventilation rate decreases even though indoor ozone concentrations are lower (Weschler and Shields, 2000).

Defining Ventilation Requirements Based on Formaldehyde Emissions

We propose that formaldehyde emissions can be used as the basis for establishing appropriate ventilation rates for new house construction to protect occupants from the adverse effects of this chemical. Our approach is to apply available data on formaldehyde emission factors (i.e., whole-house emission rates normalized by house floor areas) in new houses in a steady-state mass-balance model to predict ventilation rates that would be suitable for controlling formaldehyde concentrations at or below recognized acceptable concentrations. In applying the model, we make simplifying assumptions. Formaldehyde emission factors are treated as if they are independent of concentration. The potential bias introduced by this assumption is conservative in that it protects health. The magnitude of the bias will vary by source. However, for relatively small changes in ventilation rate (i.e., two- to three-fold changes) at concentrations below 100 ppb, a net effect of less than 20% is inferred from Silberstein et al., 1988. Temperature and humidity effects are ignored following the logic that temporal averages likely will approach typical indoor conditions. Additionally, houses are treated as single well-mixed zones. Two levels of acceptability, minimum ventilation and guideline ventilation have been defined. We use the term "minimum ventilation" to refer to the lowest ventilation rate that would protect most people from exposures above the action level concentration (i.e., 100 ppb) assuming typical emission rates. With this approach, we recognize there will be non-trivial situations under some conditions in which concentrations will exceed the action level. However, the intent of the minimum rate within a regulatory context is to provide a high level of protection while attempting to ensure the requirement will not put unreasonable burden on users. We use the term "guideline ventilation" to refer to the level of ventilation that would reduce many people's exposure to or below the target level (i.e., 50 ppb). Thus, the guideline ventilation would provide more protection and reduce the chance that concentrations would exceed the action level because more variability in emission rates would be accommodated. The potential needs of highly susceptible or sensitive individuals are not necessarily addressed by either the action or target levels.

In the studies of new manufactured and site-built houses discussed above and presented in Table 1, ventilation rates were held relatively constant over the prior day and were measured concurrently with the collection of formaldehyde samples. This allowed the calculation of whole-house emission rates by steady-state mass balance (ASTM, 1997b). The predominant formaldehyde sources in one manufactured house were found to be bare particleboard surfaces of cabinet casings and countertops, bare medium-density particleboard components of cabinetry, high-density particleboard passage doors and to a smaller extent, the plywood subfloor in carpeted areas (Hodgson et al., In press). The formaldehyde emission factors for these sources were generally consistent with the results of a study of formaldehyde emissions from contemporary materials used in California houses (Kelly et al., 1999). Geographical consistency among formaldehyde emissions by product type is anticipated because the same formaldehyde-based resin systems are used even though wood species may vary. The main formaldehyde sources in a house are generally related to the number and size of kitchens, bathrooms, and utility rooms and to the overall number and size of rooms. Thus, normalization of the whole-house emission rates by occupied floor areas appears to be a reasonable way to scale houses of different sizes. The derived formaldehyde emission factors (pl m^{-2} h^{-1}) are included in Table 1. Since the emission factors for manufactured and site-built houses were similar and did not change substantially with time for houses with multiple measurements, the 14 houses were treated as a single group. The average emission factor was 37 ± 14 (1 std. dev.) pl m^{-2} h^{-1} (RSD = 37%) with a range of 8-53 pl m^{-2} h^{-1} and a geometric mean of 34 pl m^{-2} h^{-1}. The measurements were made at an average ventilation rate of 0.40 h^{-1}. If we assume all of the houses represent a population average, then the multiple data points measured for each house (indicated in parentheses, n = 23) should be included. In this case, the average factor is 36 ± 13 pl m^{-2} h^{-1} (RSD = 36%) with a geometric mean of 33 pl m^{-2} h^{-1} and a median of 34 pl m^{-2} h^{-1}. These values indicate the underlying distribution is between normal and log normal; but for simplicity, we have applied normal statistics.

To our knowledge, no other contemporary data set of residential formaldehyde emission factors is available. One study was conducted in 1985 throughout the Pacific Northwest. It measured formaldehyde concentrations and ventilation rates by passive techniques in 61 occupied houses, half of which were built to achieve low air infiltration rates (Turk et al., 1987). In-out concentrations up to 340 ppb were encountered. For the 40 houses approximately one-year old or newer with ventilation rates of at least 0.13 h^{-1}, the average emission factor calculated from the data is 74 ± 45 pl m^{-2} h^{-1} (RSD = 61%) with a geometric mean of 62 pl m^{-2} h^{-1} and a median of 69 pl m^{-2} h^{-1}. These relatively high concentrations and emission factors likely are no longer applicable due to changes in the manufacturing of composite wood products. Thus, little can be inferred regarding formaldehyde distributions in contemporary houses, except to say that emission factors have improved substantially in the last 20 years.

For a minimum ventilation rate, we recommend that 99% of the population of new houses have sufficient ventilation to keep the occupants' average exposures below the 100-ppb action level. The 99% confidence level (one-tailed probability, df = 22) for the emission factor is 68 pl m^{-2} h^{-1}. This translates into a floor-area normalized ventilation rate of 0.68 m^3 m^{-2} h^{-1}. For a house with a typical North American 8-ft (2.44-m) ceiling height, the recommended minimum ventilation rate is then 0.28 air changes per hour (h^{-1}). If the median emission factor of 34 pl m^{-2} h^{-1} and the 50-ppb target level are used, the same ventilation rate of 0.68 m^3 m^{-2} h^{-1} is derived. These analyses suggest that if the minimum ventilation rate was adopted, approximately 50% of new houses would have concentrations near or below the lower target level, while the large majority of new houses would have concentrations below the action level.

For a guideline ventilation rate, a less-restrictive statistical distribution can be applied. We recommend that at least 90% of the population of new houses have sufficient ventilation to produce average occupant exposures of 50 ppb, or less. The 90% confidence level (one-tailed probability, df = 22) for the emission factor is 53 pl m^{-2} h^{-1}. This translates into a ventilation rate of 1.06 m^3 m^{-2} h^{-1}. For a house with an 8-ft (2.44-m) ceiling height, the recommended guideline ventilation rate is then 0.43 h^{-1}. For simplicity and to include an additional margin of safety to accommodate higher emissions or added sources of variability, we recommend adopting a guideline ventilation rate 0.5 h^{-1}.

Discussion

These analyses attempt to maintain long-term average exposures at or below the specified limits and implicitly assume house ventilation is relatively constant. However, if the ventilation system is very intermittent or highly seasonally dependent (i.e., natural ventilation), there may be periods of very low ventilation ($\leq$ 0.1 h^{-1}) resulting in concentrations in excess of the 100-ppb action level. There also may be periods of elevated temperature and/or humidity resulting in concentrations above 100 ppb. Such high levels may be limited, in part, by the concentration dependence of the formaldehyde emission rate. It is likely that occupants will not immediately detect or recognize these peak concentrations since the formaldehyde odor threshold is well above the action and target levels. Thus, occupants cannot be relied upon to increase ventilation when needed by operating a mechanical system, or by opening a window when the concentration exceeds the desired levels. An obvious solution is to employ mechanical systems that provide reasonably constant ventilation. Engineered passive ventilation or hybrid ventilation approaches that make efficient use of natural driving forces may work equally well.

As mentioned earlier, the need to maintain adequate ventilation may shift to other pollutants or combinations of pollutants. For example, emissions from unvented combustion sources may exceed the ventilation needed to control formaldehyde sources. In a densely occupied house, more ventilation may be required to dilute human bioeffluents. The amount and frequency of smoking will determine the amount of ventilation needed to limit non-smoking occupants' exposures to environmental tobacco smoke. In areas of high soil radon concentrations, radon mitigation measures may take precedence. Other circumstances involving a variety of pollutant sources are possible. In some cases, a similar exercise of using source information to predict ventilation rates to achieve acceptable air concentrations can be applied. Additionally, architects, other design professionals and builders have a general responsibility to recognize the potential indoor air quality impacts of their design and construction decisions and to take action to limit risks to occupants. They may either choose to provide ventilation sufficient to maintain health and comfort or to reduce or eliminate unwanted sources of contamination.

In fact, source control readily applies to formaldehyde in new house construction. A number of relatively simple and low-cost procedures have been identified that are anticipated to reduce formaldehyde concentrations in new house construction (Hodgson et al., In press). These procedures include modification of cabinetry and counter-top construction and use of some alternate materials. By implementing and validating these and other source control procedures, house designers and builders should be able to provide assurance that formaldehyde concentrations will be below the target level even when their houses are operating at the minimum ventilation rate. In addition, such procedures are probably the only practical way to meet lower guideline concentrations that are being developed by at least one governmental agency (i.e., CA State Office of Environmental Health Hazard Assessment).

Our estimates have assumed complete mixing of formaldehyde emissions. In general, this is a robust assumption, but in some cases it needs to be reconsidered. For example, the concentration of formaldehyde in a den with a lot of wood products may be much higher than in the rest of the house. Conversely, if many of the sources are in rooms with exhaust ventilation, such as a kitchen, the formaldehyde may be exhausted before it can fully mix. Where sources are evenly distributed, such as in flooring, ventilation efficiency issues can be neglected.

Summary and Conclusions

We have developed a rationale for using formaldehyde emissions as a relatively robust method for establishing minimum and guideline ventilation rates for new houses. Using published data, the effective emission rate of formaldehyde in typical new houses was estimated to be 36 pl m^{-2} h^{-1} with a relative standard deviation of 36%. The data further indicates this value does not decrease substantially over time at least during the stage of early occupancy. To maintain 99 percent of new houses below a widely accepted action level or ceiling concentration of 100 ppb, we have determined that the minimum long-term ventilation rate should be 0.68 m^3 m^{-2} h^{-1}. For a house with a typical 8-ft ceiling this is equivalent to a ventilation rate of 0.28 h^{-1}. A formaldehyde concentration of 50 ppb promulgated as a target level by two government agencies was selected as the basis for a recommended guideline ventilation rate. This lower concentration provides an additional margin of safety. On average, the 50-ppb target level should easily be achieved with a long-term ventilation rate of 1.2 m^3 m^{-2} h^{-1}, or 0.5 h^{-1} for a house with an 8-ft ceiling. An alternate approach for lowering the risks associated with formaldehyde exposure is to reduce formaldehyde sources in new house construction. It is possible that this could be achieved with some relatively simple and low-cost procedures.

Mechanical or engineered passive systems that provide relatively constant ventilation at the required rates may be needed to prevent periods of very low ventilation. Because the formaldehyde concentrations of concern are well below the odor threshold, ventilation systems that rely on occupant determination of need only should be used to raise the ventilation rate above 0.68 m^3 m^{-2} h^{-1}. Designers and occupants should also be aware that under some circumstances or conditions the need for ventilation might be driven by the presence of other pollutants. In these cases, ventilation rates need to be adjusted appropriately adjusted and/or source control measures need to be implemented.

These recommendations would be strengthened by probability-based studies of formaldehyde concentrations and ventilation rates in new houses. If collected properly, these data could be used to calculate emission factors. It is possible that such studies could be conducted for relatively large numbers of houses using passive monitoring techniques. Furthermore, additional studies of the concentration and environmental parameter dependence of formaldehyde emissions should be conducted to confirm the applicability of previous results to current new house construction.

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Table 1. Ventilation rates, indoor minus outdoor formaldehyde concentrations and formaldehyde emission factors for seven manufactured (M1-7) and seven (A-C3) site-built houses.

Site	House I.D.	Floor Area (m^2)	Vol. (m^3)	Ventilation[a] (h^{-1})	In-Out Conc.[a] (ppb)	Emission Fact.[a] (pl m^{-2} h^{-1})
1	M1	112	273	0.67 (0.57,0.67,0.78)	21 (17,28,19)	35 (24,46,36)
2	M2	169	412	0.56 (0.71,0.45,0.53)	31 (32,31,31)	43 (55,34,40)
3	M3	141	344	0.35 (0.35,0.36,0.35)	37 (37,38,35)	32 (31,34,30)
4	M4	131	320	0.41 (0.39,0.50,0.35)	40 (36,45,39)	41 (34,54,33)
5	M5[b]	160	414	0.28	73	53
6	M6[b]	177	431	0.58	36	51
7	M7[b]	146	355	0.34	62	51
8	A	111	272	0.27	13	8
9	B1	97	237	0.46	31	35
10	B2	92	224	0.50	38	47
11	B3	90	220	0.48	40	47
12	C1	110	286	0.25	52	34
13	C2	110	286	0.13	50	17
14	C3	110	286	0.26 (0.32,0.32,0.14)	38 (25,28,60)	22 (21,24,22)
Average		125	311	0.40	40	37
Std. Dev.		29	70	0.15	15	14
RSD, %		23	23	39	38	37
Median		112	286	0.38	38	38
Geo. Mean		1220	304	0.37	37	34

a. Average and (individual) values for houses with measurements made on different dates.
b. M5 reported by Hodgson et al. (In press); M6 and M7 previously unreported; all other houses reported by Hodgson et al. (2000).

Table 2. North American non-occupational exposure guidelines for formaldehyde.

Organization	Type	Level (ppb)	Level ($\mu g\ m^{-3}$)	Description
CA State Air Resources Board[a]	Govt.	100		Action level
Health Canada[b]	Govt.	100	120	Action level
CA State OEHHA[c]	Govt.	77	94	1-h Acute REL[d]
CA State Air Resources Board[a]	Govt.	50		Target level
Health Canada[b]	Govt.	50	60	Target level
CA State OEHHA[e]	Govt.	2.4	3	Chronic REL

a. ARB, 1991
b. CDNHW, 1987
c. OEHHA (Office of Environmental Health Hazard Assessment), 2000
d. Reference Exposure Level
e. OEHHA, 2001