Area- Specific Airflow Rates for Evaluating the Impacts of VOC Emissions in U.S. Single Family Homes

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ABSTRACT

Product loading ratio and area-specific airflow rate are among the key parameters required for indoor air quality (IAQ) modeling and exposure health assessment of building product emissions. This paper analyzes product loading ratio variations and generates area-specific airflow rate distributions of major categories of interior building products for single family detached (SFD) homes in the U.S. The product categories addressed include ceiling, flooring, interior wallboard & paint, walls & wall coverings, doors, insulation and window treatments. The analysis employs a set of 83 SFD homes that are defined by Persily et al. (2006) as representing 80 % of U.S. housing stock built prior to 1998. We first calculate product loading ratios from floor plans of these homes. We then combine the loading ratios with the air change rates previously modeled using CONTAM by Persily et al. (2010) to develop a national, average area-specific airflow rate distribution for each product category. We further analyze the trends affecting area-specific airflow rate distributions in newer homes. Finally, we discuss the implications of these results on assessing IAQ impacts of building products, especially their application to improve product standards for volatile organic compound (VOC) emission testing and evaluation.

1. INTRODUCTION

Leadership standards for new building construction and major renovation often include indoor environmental quality (IEQ) requirements or incentives for selecting interior building products with low emissions of VOC pollutants [1, 2]. Similarly, IEQ sections of high-performance building codes often require use of specific categories of interior products with low VOC emissions [3, 4].

In order to comply with these requirements, interior products such as flooring, wall coverings, paints, and furniture are tested for their emissions of VOCs using environmental chamber equipment and procedures [5, 6]. For example, a representative, small-scale sample of a newly manufactured interior product is placed in an environmental chamber at typical indoor conditions, and an area-specific emission rate, termed emission factor (EF) in units of $\mu g/h{\bullet}m^2$, is measured at specified time points for each emitted VOC [5]. The measured VOC EFs often are interpreted by applying a mass balance to convert them into estimated indoor airborne VOC concentrations for a defined building modeling scenario. The building modeling scenario here refers to a standardized room/house with a set of defined parameters (room dimensions, occupancy density, air change rate, and product loadings) that are typical and representative for the products being considered. Then, the estimated concentrations of VOCs of concern are compared to guidelines for occupant inhalation exposures where such guidance is available. Test results for a product sample are deemed compliant with VOC emission requirements if the projected concentrations do not exceed these guidelines. An example of such a testing and evaluation procedure is the standard method developed by the California Department of Public Health (CDPH) [7]. This standard, which uses non-cancer chronic reference exposure levels (CREL) determined by the California Office of Environmental Health Hazard Assessment (OEHHA) as VOC guideline values, is widely cited as a preferred procedure for testing and evaluating building products for compliance with VOC emission requirements in building rating systems and codes [1-4].

The building modeling scenarios used to predict indoor air concentrations include a range of parameters such as building volume, air change rate and surface area of building products. The scenarios need to be representative of the built environment yet sufficiently simple for practical use. In this context, existing scenarios assume constant VOC emission and building ventilation rates, zero outdoor VOC concentrations, uniform indoor air concentrations, and no net losses of a VOC from air due to effects such as filtration, sorption on surfaces or chemical reactions. Under these assumptions, the indoor VOC concentration (C_S in μg/m^3) is estimated from the measured VOC EF (EF_A in μg/h•m^2), the area of material installed (A_m in m^2) in the building interior, and the total outdoor airflow rate (Q in m^3/h):

$$C_S = EF_A \times A_m / Q = EF_A / q_A \qquad (1)$$

Multiple sources of individual VOCs (including formaldehyde) are often present in a building [8-9]. The allowable indoor VOC concentrations from emissions of individual product category (floor, wall, etc.) can be capped at a percentage of the full guideline values in the VOC emission standard. For example, the CDPH Standard Method [7] allows each product category to contribute to no more than half of the CREL for each chemical (except formaldehyde for which the full CREL is used).In Equation (1), q_A (in m/h) is the area-specific airflow rate and can be expressed as:

$$q_A = Q / A_m = (\lambda \text{ x } V) / A_m = \lambda / (A_m / V) = \lambda / L_m \qquad (2)$$

where λ is the outdoor air change rate (Q/V) in h^{-1}, V is the building volume in m^3, and L_m is the product loading ratio (A_m/V) in m^2/m^3.

The modeling scenario specifies the loading ratio and the area-specific airflow rate for a product. These parameters in conjunction with the product VOC EF determine the estimated steady-state concentration, which is then compared to guideline values, such as the OEHHA VOC guidelines. Hence, the loading ratio and area-specific airflow rate are critical in establishing the pass/fail outcome of a VOC product emission test. Such parameters are also necessary when performing more complex indoor air quality (IAQ) modeling that accounts for other VOC loss mechanisms (i.e., chemical reaction, sorption & re-emission), temporal variation of VOC emission sources and ventilation rates, and other factors [10]. Due to different space function and design requirements, the loading ratio and area-specific airflow rate generally vary between different building environments (homes, offices, etc.). In this study, we focus on single-family detached (SFD) residential housing scenarios. This is an important environment because people, especially infants and the elderly, spend a majority of their time in homes [11]. The assignment of realistic values for homes is challenging because of the wide variety of size, layout, and envelope tightness. Additionally, residential air change rates are dependent on weather and occupant activities.

The general housing characteristics and the outdoor air change rates for single family homes in the U.S. have been the subject of several field surveys as well as simulation studies that are supported with measured data [17-20]. However, those studies have not focused on the quantities of commonly used interior building products. Nor has anyone combined residential product loading information with residential air change rates to estimate area-specific airflow rates for products. To address this need, the objective of the work described in this paper is to integrate information from the literature on the distributions of house sizes, air change rates, and interior product loadings for existing and new SFD residences in the U.S. and to generate frequency distributions of area-specific airflow rates for major categories of interior building products. The intent is then for this information to be used in IAQ modeling and exposure health assessments for building product emissions.

2. METHODS

2.1 Selection of Representative Home Datasets

The collection of existing homes defined in Persily et al. [19] was used in this study because it is the only available set of floor plans that statistically represents the majority of the U.S. housing stock. This collection or "suite" of homes is based on the U.S. Department of Energy Residential Energy Consumption Survey (RECS), which includes about 6,000 residences. The RECS database assigns a "weight" to each of these 6,000 homes that defines how many units it represents nationwide. A sampling scheme was applied to the RECS homes in which a number of relevant building characteristics were considered for the homes, each over a discrete number of values. For example, each of the homes was noted as being in one of three ranges of building floor area. In addition, the RECS SFDs were examined as to whether or not they had a forced-air system, the year built (4 ranges of values), existence of a garage or not, foundation type (basement, crawl space or slab-on-grade) and number of stories (1, 2 or 3 or more). Thus, each combination of these six characteristics, or housing unit type, covers a number of the homes in the RECS database. There were 432 types of homes covering all the combinations of the six characteristics. The individual RECS house weights were summed across the 432 building characteristic combinations (floor area, forced-air, year built, garage, foundation and stories) to associate each housing unit type with the overall, nationwide population of that type. The house types were sorted in descending order based on the unit's weight, and the homes that encompass 80 % of the total number of units in the U.S. were then selected. These house types comprise the 83 SFD homes that in combination represent 80 % of the U.S. housing stock built before 1998 and captured in the 1997 RECS database, each associated with a unique value of floor area, year built, foundation type, number of stories, and presence of a forced-air system or garage.

2.2 Building Product Loading Ratios

In order to determine product loading ratios for the SFD homes defined in Persily et al. [19], we reviewed the floor plans of these homes, which include 35 distinct types, summarized in Table 1. This set of 35 floor plans was derived from the 83 SFD homes described above by ignoring house features that are not considered in the present analysis such as the presence of a garage or crawl space, or house age, which affects airtightness but not floor plan. The plans are broadly classified by floor area (107 m^2, 180 m^2, and 276 m^2) and numbers of stories. Within each category (A – G), the floor plans vary in terms of the types and numbers of rooms. Differences among the homes classified with the same floor plans include the envelope airtightness values and the presence of a basement. The room types defined in the floor plans include bedroom, bathroom, kitchen, living room, dining room, family room, and den. In this study, we treated the stairs as a room type and defined all other areas not explicitly counted by room type as "hallways". Using scaled digital floor plan files, we then calculated the areas of floor, ceiling, partition walls, perimeter walls, interior doors and exterior doors for each room in each of the 35 plans. For parameters needed to calculate installed product areas but not otherwise defined, we used the following assumptions: 1) both interior and exterior doors have a height of 2.03 m, and 2) the total window area to conditioned floor area ratio is 17 % based on an on-site survey of 800 homes constructed between 1998 and 1999 in California [21].

The product areas in the individual rooms were summed to calculate the installed areas and the corresponding loading ratios of the major interior building products for each floor plan. Product loading ratio definitions and calculation procedures for each product category are shown in Table 2. The detailed analysis for floor plan A-1 is provided in Supplemental Material as an example (see Figure S.1 and Table S.1). Variations in product loading ratios among the different floor plans are summarized in Table 3 using simple descriptive statistics (minimum, maximum, median, quartiles and mean). These loading ratio statistics are presented for all 35 floor plans, as well as separately for the three floor-area categories.

2.3 Air Change Rates

In a previous study, Persily et al. ran annual airflow simulations for the 209 dwelling types in 19 U.S. cities to generate hourly air change rate distributions for specific house types, house ages, and regions of the country, and these were then summarized on a nationwide basis [20]. Given the representativeness of the dwellings, the selection of cities that cover the range of U.S. climates, and the analysis of the simulation results to account for the prevalence of each dwelling type in each climate, the frequency distributions generated are the only representative dataset of air change rates for the U.S. That analysis employed the multizone airflow and contaminant transport model CONTAM [22], and employed a number of assumptions [20], including that all windows and exterior doors were closed.

In this study, we adopted the same window and door assumption. This is because air change rates from infiltration through building envelope leakage alone provide conservative estimates of outdoor airflow rates for dilution of interior product VOC sources. We obtained the annual hourly air change rate simulation results for each of the 83 SFD residences for the 19 representative U.S. cities from the original study [20]. We combined the results for each home based on its geographical prevalence in the original surveys to determine a national average air change rate frequency distribution for each home as the percentage of hours in air change rate bins. The discrete national average air change rate frequency distribution data for each home was then fit to a lognormal distribution by minimizing the sum of errors between the given and predicted lognormal frequency distributions (MS Excel). The national average air change rate distribution for all homes was calculated as "weighted" averages of the distribution for each individual home using the "weight" assigned from RECS database, which defined the number of homes in the U.S. by type [19].

2.4 Area-specific Airflow Rate Distributions

In order to determine area-specific airflow rate distributions, the lognormal air change rate frequency distribution for each home was divided by the product loading ratios determined for that home to derive area-specific airflow rate distributions for all product categories for the home. National average, area-specific airflow rates representing all SFD homes built before 1998 were then calculated as "weighted" averages of the distributions for all 83 homes using the same weighting data as described in Sections 2.1 and 2.3.

3. RESULTS

3.1 Product Loading Ratio Statistics

The loading ratio distribution statistics for major interior product categories in SFD homes built prior to 1998 are summarized in Table 3. The calculations were made for all floor plans combined and for the floor plans in each of the three house size categories. For the floor and ceiling categories, the loading ratio is the same for all floor plans because the ratio is determined solely by the ceiling height of 2.44 m. The loading ratio for the windows category also is the same for all floor plans because it is determined by the assumed window area to floor area ratio of 17 %. For wall-related product categories, the loading ratios are influenced by both house size and interior layout. In general, larger houses tend to have lower surface-to-volume ratios resulting in less wall-related material usage per unit volume of the house. For example, the median loading ratios for the walls & wallcoverings category in 107 m^2, 180 m^2 and 276 m^2 homes are 0.97 m^2/m^3, 0.87 m^2/m^3 and 0.78 m^2/m^3, respectively. These differences are statistically significant based on ANOVA single factor analysis. However, the variations (ratio of maximum to minimum loading ratios) for non-door products are within a factor of three within each house size category, suggesting modest variation in product loading ratios. For doors, the loading ratios are < 0.1 m^2/m^3 regardless of house size and layout. For exterior doors, the maximum loading ratio for all the floor plans is only 0.014 m^2/m^3.

3.2 Air Change Rate Distributions

Newer SFD homes tend to have tighter envelopes than older homes [23, 24]. Persily et al. divided the suite of SFD homes into four age intervals by construction year (before 1940, 1941–1969, 1970–1989, and 1990 or newer) and assigned envelope air leakage values to these intervals based on the results of the studies referenced above [20]. Since newer homes have lower air leakage values, the frequency distribution plots of air change rate for homes in the four intervals show a corresponding trend of progressively decreasing air change rates [20]. Figure 1(a) compares the national average air change rate frequency distribution of homes 1990 or newer to that of all homes built prior to 1998. The median air change rate for homes 1990 or newer (0.22 h^{-1}) is 50 % lower than that for all homes prior to 1998 (0.44 h^{-1}). These air change rates also fit a lognormal distribution:

$$F_X(x) = \frac{1}{2} erfc\left[-\frac{\ln(x)-\ln(GM)}{\ln(GSD)\cdot\sqrt{2}}\right] \quad (3)$$

where, F_x represents the accumulative frequency distribution, erfc is the complementary error function and x is the air change rate. The resulting geometric mean (GM) and standard deviation (GSD) are 0.41 h^{-1} and 2.05 h^{-1}, respectively, for all homes built prior to 1998. For homes built 1990 or newer, the corresponding values are 0.22 h^{-1} and 2.18 h^{-1}, respectively.

More recently constructed homes in the U.S. have even tighter envelopes than those built before 1998 [17]. For example, Figure 1(b) shows measured air change rates for a set of 23 homes with no window opening and no mechanical outdoor air ventilation from a study of 108 SFD California homes built between 2002 and 2004 [17]. For these homes, the median air change rate is 0.17 h^{-1}.

3.3 Area-specific Airflow Rate Distributions

The cumulative frequency distributions of area-specific airflow rates for the categories of interior building products in a weighted average SFD home are presented in Figure 2. The lognormal character of the distributions is expected, as the air change rates are lognormally distributed. Table 4 summarizes the area-specific airflow rate distribution statistics for the same product categories shown in Figure 2. The geometric mean (GM) and standard deviation (GSD) were calculated based on the optimized fit to a lognormal distribution and also are reported in Table 4.

The area-specific airflow rate for a product category can vary by more than a factor of two due to the wide range of housing characteristics. For example, the 25 %, 50 % and 75 % percentile values for the walls & wallcoverings category are 0.29 m/h, 0.47 m/h and 0.74 m/h, respectively. The results also show that the area-specific airflow rates vary by three orders of magnitude among different product categories. The interior wallboard & paints and walls & wallcoverings categories have the lowest area-specific airflow rates. On the other hand, the area-specific airflow rates for products with relatively small installed areas can be substantial. Specifically, the 90th percentile area-specific airflow rates for exterior doors, interior doors and windows are 99.4 m/h, 18.8 m/h and 14.5 m/h, respectively, while the 90th percentile dilution airflow rates for all other product categories are below 5 m/h.

3.4 Trends Affecting Area-specific Airflow Rate Distributions in newer SFD homes

Besides tighter construction as described in Section 3.2, newer SFD homes are also larger. Figure 3 shows the median floor area for new single-family houses built in the years 1973 to 2012 based on the data from U.S. Census [25]. The average median floor area for homes built from 1990 to 1998 is 180 m^2 compared to an average of 161 m^2 for all homes in the 1973 to 1998 interval. And, the average for homes built after 1998 is 202 m^2, representing a 25 % increase over the average for all prior homes in the data set. Data also suggest that ceiling heights in newer homes are higher. In the study of 108 SFD California homes built between 2002 and 2004 [17], the median average ceiling height was about 2.74 m, which is larger than the 2.44 m ceiling height defined in the Exposure Factors Handbook Chapter 19 [26] and used by Persily et al. [19].

In the absence of statistically representative floor plans for newer U.S. SFD homes, we conducted an additional analysis using homes defined in Persily et al. [19] that were built in 1990 or after to explore the trend. The nine homes in this subset have larger floor areas and lower air change rates on average compared to the entire set of 83 homes. We further assumed that these homes have a ceiling height of 2.74 m and door height of 2.13 m in order to account for the trend of increased ceiling height. We then repeated the analysis described in Section 2.4 to determine area-specific airflow rate distributions for this subset of homes but normalized the "weight" of each home by the total number of homes that were built in 1990 or after. The national average area-specific airflow rate distributions for this subset of homes are reported in parentheses in Table 4. When compared to the national averages for all homes built prior to 1998, there is a trend of lower area-specific airflow rates for the newer homes in all product categories. For example, the median area-specific airflow rates for the walls & wallcoverings category for houses built between 1990 and 1997 is 0.26 m/h, which is only 55 % of that for the houses built prior to 1998.

3.5 Area-specific Airflow Rate Apportionment for Individual Floor Types

Results in Tables 3 and 4 assume a single type of flooring product. In reality, most homes utilize more than one type of flooring. In order to more realistically estimate the contributions of different floor products to indoor VOC concentrations, it is preferable to determine the loading ratios and area-specific airflow rates for each floor type. For illustration, we analyzed the areas of each individual flooring product measured in the study of 108 SFD California homes built between 2002 and 2004 [17]. The flooring products were grouped into four major types consisting of carpet, hardwood (both solid and manufactured), resilient flooring, and tile & mineral-based products. The average coverage percentages are 63 %, 10 %, 8 % and 19 % for carpet, hardwood, resilient flooring, and tile & mineral-based products, respectively. The distribution statistics are presented in Table 5. These results may not be representative of the national housing stock as they were obtained in newer homes in one geographical region.

4. DISCUSSION

4.1 Comparison with Exposure Factors Handbook and CDPH Residential Model

The Exposure Factors Handbook (EFH) Chapter 19 [26] summarizes information on building characteristics that are needed to support assessments of pollutant exposures in indoor environments. The EFH provides recommendations for building volumes obtained from the 2008 RECS that are applicable to both single-family and multi-family residences. For residence volumes, a mean value of 492 m^3 is recommended as the central estimate. For the assumed 2.44–m ceiling height, this volume converts into a 202 m^2 floor area. Although we do not report volume or area distributions, the houses in our analysis are smaller on average since the data derive from older surveys. The EFH recommendation for residential air change rate is 0.45 h^{-1}. This is the median value derived using a non-statistically representative database of perfluorocarbon tracer gas measurements [27]. The median value reported by Persily et al. [20] for single family homes built prior to 1998, and from which the SFD homes in this study were extracted, is 0.44 ACH, which is consistent with the EFH recommended value. The EFH also recommends loading ratios for wall areas from 0.98 m^2/m^3 to 2.18 m^2/m^3 and floor areas from 0.36 m^2/m^3 to 0.44 m^2/m^3. These loading ratios are calculated based on typical-size individual rooms assuming no doors, windows or other openings. As shown in Table 3, the wall area ratios for SFD homes range from 0.69 m^2/m^3 to 1.19 m^2/m^3 and the floor area ratio is fixed at 0.41 m^2/m^3. The range of wall area ratios reported here is lower because it is based on the whole-house average loading with areas of doors, opening and windows subtracted.

The 50th percentile area-specific airflow rates for homes built 1990–1997 calculated in this study are compared in Table 6 to those for the new single-family residence informative scenario defined in an appendix of the CDPH Standard Method [7]. The informative scenario is based on the product areas or quantities used in a typical 211 m^2 single family home constructed in 2000 [28] with a 0.23 h^{-1} air change rate derived from the requirements in ASHRAE Standard 62.2-2007 [29]. The differences are within ± 15% for most of product categories with large installed areas. The large difference for acoustic insulation is in part the result of different calculation methods. In the CDPH residential model, acoustic insulation is calculated for an optional upgrade as the sum of insulation required for all partition walls and floors/ceilings [7]. Here, the loadings of acoustic insulation were calculated assuming the product was used only in partition walls.

In summary, our results provide additional area-specific airflow rate distribution information that is not contained in either the EFH or the CDPH Standard Method. This information can be used to support and further improve exposure scenarios and VOC emission test standards. Our analysis also allows practitioners who are using VOC emissions to model indoor concentrations the option of either selecting typical residential values or choosing a percentile value (or a range of values) for this key model parameter based on their modeling goals and risk acceptance levels.

4.2 Limitations of the Study

4.2.1 Model Assumptions

The mass balance model used here to estimate indoor VOC concentrations as the result of building product emission assumes that there are no net losses of a VOC due to sorption on surfaces or to homogeneous chemical reactions. Sink effects reasonably can be disregarded for assessments of chronic inhalation exposures because VOC sorption effects on indoor surfaces are mostly reversible over time. However, research has demonstrated that sorption/desorption interactions with indoor surfaces can significantly influence VOC concentration fields and exposures on short time scales [30, 31]. Thus, the effect of sorption/desorption should be considered in models for VOC emissions that are intended to address acute inhalation exposures. Removal of a VOC by homogenous and heterogeneous chemical reaction (e.g., driven by ozone) is dependent upon the reaction rate and should be considered when the rate is significant relative to ventilation.

Additionally, the steady-state form of the mass balance model utilizes the VOC EF measured at the end of a chamber test period and does not account for changes in VOC emissions with time. In VOC emission standards, the chamber tests typically last for relative short times (i.e., 3 days to 28 days) [7, 32, 33]. However, emissions of VOCs from building product sources, even those controlled by diffusive process, gradually decay over their lifetimes as the sources are depleted. Consequently, estimates of IAQ impacts based on VOC EF measured from relatively short-term tests are conservative and likely will overpredict indoor exposures.

4.2.2 Floor Plans and Air Change Rates Used in the Analysis

The floor plans for the homes defined in Persily et al. [19] were developed based only on several key characteristic variables (housing type, number of stories, heated floor area, year built, foundation type, garage, type of heating equipment, number of bedrooms, number of bathrooms and number of other rooms) and have idealized rectangular or square shapes. In reality, housing characteristics are much more variable. Also, this collection of homes does not consider many characteristics related to VOC emission from building and other indoor products. For example, information on indoor furnishings and cabinetry that are often significant sources of VOC emissions is not included.

The air change rate distributions for this set of homes were based on annual hourly simulations conducted using CONTAM. While this model has been validated in many residential applications [34, 35], the simulations on which these analyses are based are still highly dependent on the modeling assumptions. It would be preferable if the predicted frequency distributions could be compared with actual measurements, but no national, representative air change rate distributions yet exist for comparison.

Additionally, the effects of window opening on air change rate were not considered in this analysis. Opening of windows by occupants could result in higher air change rates. Window opening is more likely to occur when outdoor temperatures are within a comfortable range and will have larger impacts on the results for houses located in mild climates.

Our analysis for newer homes only considered homes built in the 1990s, since no representative floor plans for more recent homes yet exists although airtightness data on existing and new homes continues to be collected [36]. As a result of tighter construction and the adoption of

ASHRAE 62.2-2010, which requires supplemental mechanical ventilation to achieve a required total ventilation rate [37], the ventilation characteristics of new homes, and the resulting VOC levels, remain uncertain until more data is available on the actual air change rates, layouts and product loading for new homes.

5. IMPLICATIONS FOR ACCESSING IAQ IMPACTS OF BUILDING PRODUCTS

The analysis presented in this paper is the first to generate area-specific airflow rate distributions for major categories of interior building products for SFD homes in the U.S. This information is useful for calculating the indoor VOC concentrations, and presumably other IAQ impacts, of building products. As noted, the Exposure Factors Handbook Chapter 19 [26] provides a variety of information to aid in the assessment of inhalation exposures to pollutants in indoor settings. Within this context, the weighted, national distributions of area-specific airflow rates for SFD residences presented herein represent a significant contribution. -

More specifically, the information can be used to develop and refine residential VOC exposure scenarios for use in product VOC emission standards. Under ideal circumstances, all indoor materials should be tested for VOC emissions, and a -product tested would be labeled with numerical emission factors-so that its expected impacts on indoor VOC concentrations could be calculated for specific building projects. However, the need for easy implementation and the competitive market forces among product manufacturers have motivated the use of simplified exposure models and the development of pass/fail systems for judging the acceptability of product's potential IAQ impacts in VOC emission standards [7, 32, 33]. The distributions of area-specific airflow rates for major categories of building products from this analysis provide a scientific basis for making further policy decisions when developing such standards. Future work in this area should address the following issues:

- Treatment of products with low loading ratios: The intention of material emission test standards is to encourage the development and use of low-emitting products. However, when using Equation (1) to estimate the indoor VOC concentration associated with a specific building product, some product types (such as doors and windows) may pass the emission test easily even with high emissions per unit area due to their relatively low loading ratios. To deal with this issue, one policy option may be for standards to ignore these categories as their contributions to indoor air quality may be low. However, it's possible that some products in these categories may have high emission factors for VOCs of concern. Policies can be established to prevent such products from disproportionately contributing to indoor air pollution. For example, they might be treated as part of wall systems and modeled using the total wall area (most conservative approach) or they might be assigned an artificially low area-specific airflow rate that is more consistent with other product categories.

- Apportionment for partial product loadings: The informative SFD residential scenario in the CDPH Standard Method [7] uses a conservative assumption of 100 % coverage for a single flooring product. Similarly, a single wall paint and a single wall covering are assumed to be used throughout the home. When more data and analysis on the apportionment of products within categories become available, it may be possible to define area-specific airflow rates to account for the partial coverage of specific product types. One policy approach that accommodates different products may be to use the 90th percentile conditions, for example the 90th percentile coverage rates for flooring products seen in Table 5. A precedent exists in the work of Carter and Zhang [38], who used the 90th percentile conditions for total furniture surface area identified from more than 5,000 workstations when defining models for estimating the impacts of office furniture emissions on VOC concentrations in offices.
- Existing vs. new homes: Although this analysis only considered homes built in the 1990s and earlier, Table 4 and Figure 2 illustrate an overall trend of less outdoor airflow per unit product area in newer homes compared to older existing homes. Both existing and newer homes needs to be considered in product VOC emission standards. To keep the modeling scenarios simple, one policy approach may be to use the worst case scenario to represent all homes, which is most likely to be the new SFD home scenario although further research is needed on the future direction of trends in residential ventilation. Differentiating between existing and new residences should also be considered when conducting more detailed IAQ modeling for specific applications.

DISCLAIMER

Conclusions and opinions are those of the individual authors and do not necessarily reflect the policies or official views of the California Department of Public Health.

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REFERENCES

[1] U.S. Green Building Council. LEED 2009 for New Construction & Major Renovations. 2009. Accessible: http://www.usgbc.org/Docs/Archive/General/Docs5546.pdf (last accessed in June, 2013).

[2] ASHRAE. ANSI/ASHRAE/USGBC/IES Standard 189.1-2011. Standard for the Design of High-Performance Green Buildings. 2011. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

[3] The International Code Council. The 2012 International Green Construction Code. 2012.

[4] CBSC. California Green Building Standards Code. 2013. California Building Standards Commissioning, Sacramento, CA. Accessible: http://www.bsc.ca.gov/Home/CALGreen.aspx (last accessed in June, 2013).

[5] ASTM. ASTM Standard D5116, Standard Guide for Small-Scale Environmental Chamber Determinations of Organic Emissions from Indoor Materials/Products. 2006. American Society for Testing and Materials, West Conshohocken, PA.

[6] ASTM. ASTM Standard D6670, Standard Practice for Full-Scale Determination of Volatile Organic Emissions from Indoor Materials/Products. 2007. American Society for Testing and Materials, West Conshohocken, PA.

[7] CDPH. Standard Method for the Testing and Evaluation of Volatile Organic Chemical Emissions from Indoor Sources Using Environmental Chambers, Version 1.1. 2010. California Department of Public Health, Richmond, CA. Accessible: http://www.cal-iaq.org/phocadownload/cdph-iaq_standardmethod_v1_1_2010%20new1110.pdf (last accessed in June, 2013).

[8] Gunschera J, Mentese S, Salthammer T, and Andersen JR. Impact of building materials on indoor formaldehyde levels: Effect of ceiling tiles, mineral fiber insulation and gypsum board. 2013. Building and Environment (64), p 138-145.

[9] Missia Dafni A, Demetriou E, Michael N, Tolis EI, and Bartzis JG. Indoor exposure from building materials: A field study. 2010. Atmospheric Environment, 44 (35), p 4388-4395.

[10] Liang WH, Gao P, Guan J, and Yang XD. Modeling volatile organic compound (VOC)

concentrations due to material emissions in a real residential unit. Part I: Methodology and a preliminary case study. 2012. Building Simulation, 5(4), p 351-357.

[11] Klepeis NE, Tsang AM, and Behar JV. Analysis of the National Human Activity Pattern Survey (NHAPS) Respondents from a Standpoint of Exposure Assessment. 1996. Final Report, EPA/600/R-96-074. U.S. Environmental Protection Agency, Washington, DC.

[12] Osawa H, and Hayashi M. Status of the indoor air chemical pollution in Japanese houses based on the nationwide field survey from 2000 to 2005. 2009. Building and Environment, 44 (7), p 1330-1336.

[13] Liu Q, Liu Y, and Zhang M. Personal exposure and source characteristics of carbonyl compounds and BTEXs within homes in Beijing, China. 2013. Building and Environment, (61), p 210-216.

[14] Guo H, Kwok NH, Cheng HR, Lee SC, Hung WT, and Li YS. Formaldehyde and volatile organic compounds in Hong Kong homes: concentrations and impact factors. 2009. Indoor Air 19 (3), p 206-217.

[15] Jo WJ, and Sohn JY. The effect of environmental and structural factors on indoor air quality of apartments in Korea. 2009. Building and Environment, 44 (9), p 1794-1802.

[16] Willem H, Hult EL, Hotchi T, Russel ML, Maddalena RL, and Singer BC. Ventilation Control of Volatile Organic Compounds in New US Homes: Results of a Controlled Field Study in Nine Residential Units. 2013. LBNL-6022E. Lawrence Berkeley National Laboratory, Berkeley, CA.

[17] Offermann FJ. Ventilation and Indoor Air Quality in New Homes. 2009. Final Report, CEC-500-2009-085. California Air Resources Board and California Energy Commission, Sacramento, CA.

[18] Weisel CP, Zhang J, Turpin BJ, Morandi M, Colome S, Stock T, and Spektor DM. Relationships of Indoor, Outdoor, and Personal Air (RIOPA), Part I. Collection Methods and Descriptive Analysis. Research Report 130 Pt 1. Health Effects Institute, Boston, MA.

[19] Persily A, Musser A, and Leber D. A Collection of Homes to Represent the U.S. Housing Stock. 2006. NISTIR 7330. National Institute of Standards and Technology, Gaithersburg, MD.

[20] Persily A, Musser A, and Emmerich SJ. Modeled infiltration rate distributions for U.S. housing. 2010. Indoor Air (20), p 473–485.

[21] Regional Economic Research, Inc. Residential New Construction Study. 2001. Final report prepared for Pacific Gas & Electric (PG&E). Accessible: http://www.calmac.org/ (last

accessed in June, 2013).

[22] Walton GN and Dols WS. CONTAMW 2.4 User Guide and Program Documentation. NISTIR 7251, 2005. National Institute of Standards and Technology, Gaithersburg, MD.

[23] Sherman M and Dickeroff D. Air-tightness of U.S. Dwellings. 1998. ASHRAE Transactions. 104(2):1359-1367.

[24] Chan, WR, Nazaroff WW, Price PN, Sohn MD and Gadgil AJ. Analyzing a database of residential air leakage in the United States. 2005. Atmospheric Environment, 39 (19), p 3445-3455.

[25] U.S. Census. Median and Average Square Feet of Floor Area in New Single-Family Houses Completed by Location. 2013. U.S. Census Bureau, Washington, DC. Accessible: http://www.census.gov/construction/chars/completed.html (last accessed in June, 2013).

[26] U.S. EPA. Exposure Factors Handbook 2011 Edition (Final). 2011. EPA/600/R-09/052F. U.S. Environmental Protection Agency, Washington, DC.

[27] Koontz MD, Rector, HE. Estimation of distributions for residential air exchange rates: Final report. 1995. U.S. Environmental Protection Agency, Office of Pollution Prevention and Toxics, Washington, DC.

[28] U.S. DOE. Buildings Energy Data Book. 2010. U.S. Department of Energy, Washington, DC. Accessible: http://buildingsdatabook.eren.doe.gov/docs%5CDataBooks%5C2010_BEDB.pdf (see Table 2.5.7, last accessed in June, 2013).

[29] ASHRAE. ANSI/ASHRAE Standard 62.2-2007, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings, 2007. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA.

[30] Singer BC, Hodgson, AT, Hotchi T, Ming KY, Sextro RG, Wood EE et al. Sorption of organic gases in residential rooms. 2007. Atmospheric Environment, 41(15), p 3251-3265.

[31] Nazaroff WW, Coleman BK, Destaillats H, Hodgson AT, Liu D-L, Lunden MM et al. Indoor Air Chemistry: Cleaning Agents, Ozone and Toxic Air Contaminants. 2006. Final Report: Contract No. 01-336. California Air Resources Board, Sacramento, CA.

[32] AGBB. Health-related Evaluation Procedure for Volatile Organic Compounds Emissions (VOC and SVOC) from Building Products. 2012. Ausschuss zur gesundheitlichen Bewertung von Bauprodukten, Committee for Health-related Evaluation of Building Products Germany. Accessible: www.umweltbundesamt.de/produkte-e/bauprodukte/agbb.htm (last accessed in

June, 2013).

[33] BIFMA. ANSI/BIFMA M7.1. Standard Test Method for Determining VOC Emissions. 2011. Business and Institutional Furniture Manufacturers Association, Grand Rapids, MI.

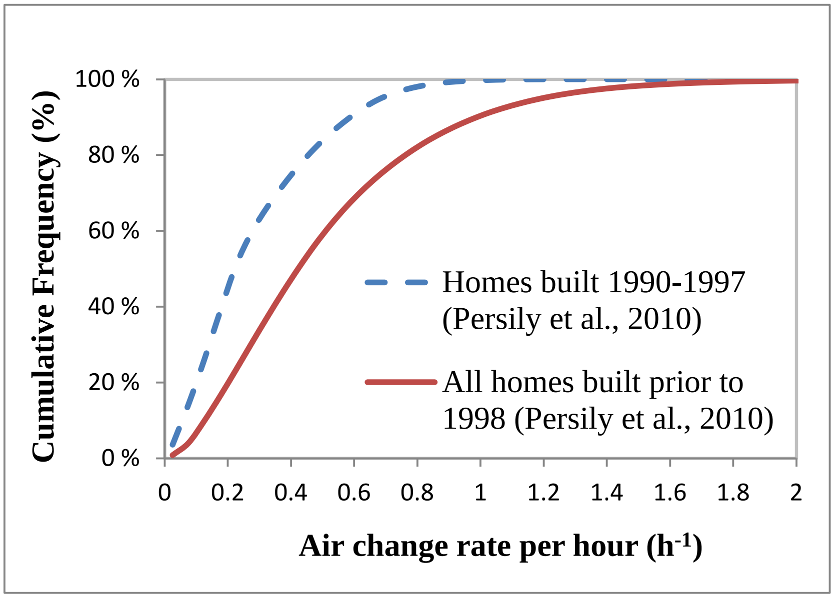
[34] Emmerich SJ. Validation of Multizone IAQ Modeling of Residential-Scale Buildings: A Review. 2001. ASHRAE Transactions 107 (2), p 619-628.

[35] Emmerich SJ, Howard-Reed C and Nabinger SJ. Validation of multizone IAQ model predictions for tracer gas in a townhouse. 2004. Building Services Engineering Research and Technology, 25(4), p 305-316.

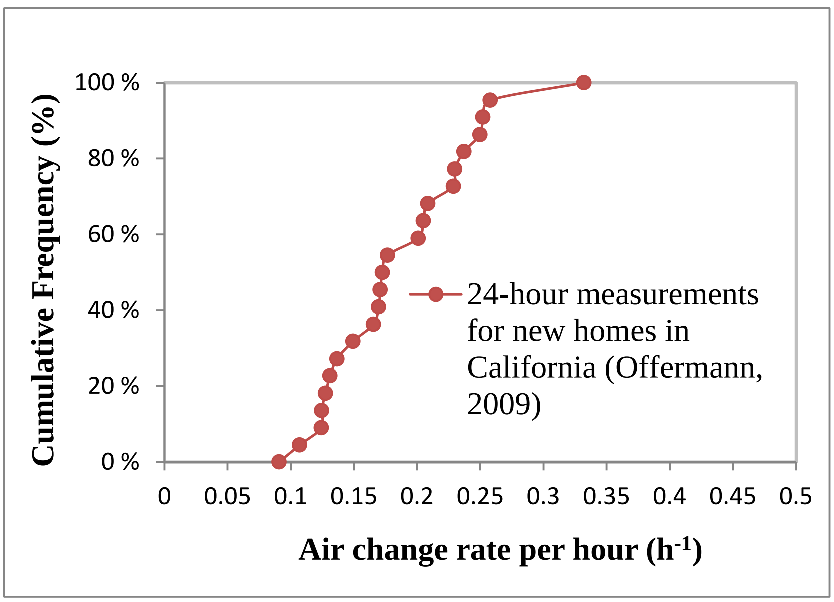
[36] Chan WR, Joh J, and Sherman, MH. Analysis of Air Leakage Measurements from Residential Diagnostics Database. 2012. LBNL-5967E. Lawrence Berkeley National Laboratory, Berkeley, CA.

[37] ASHRAE. ANSI/ASHRAE Standard 62.2-2010, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings, 2010. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA.

[38] Carter RD, Zhang JS. Definition of standard office environments for evaluating the impact of office furniture emissions on indoor VOC concentrations. 2007. ASHRAE Transactions 113(2), p 466-477.



(a) Existing SFD homes in U.S.



(b) New SFD homes built between 2002 and 2004 in California

Figure 1. Cumulative frequency distributions of air change rates with windows and doors closed

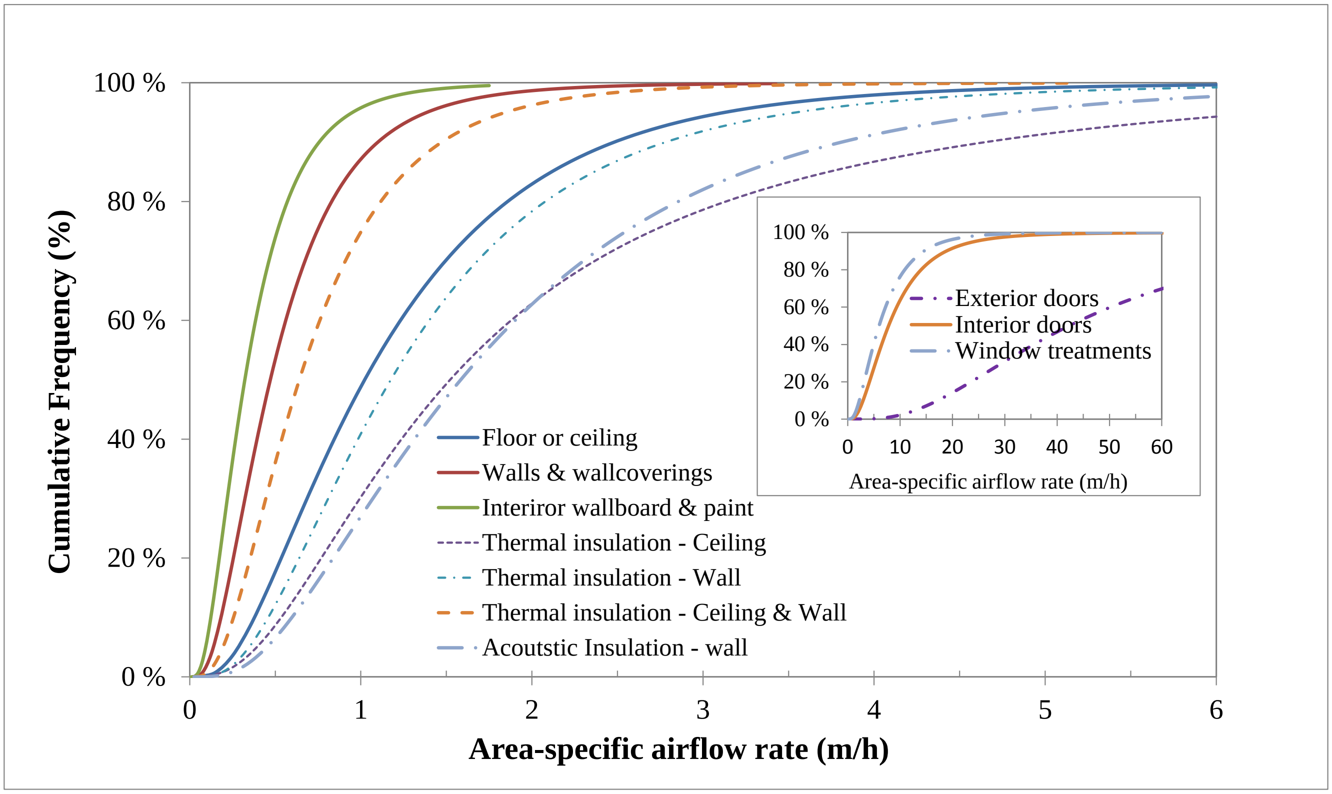


Figure 2. Cumulative frequency distributions of area-specific airflow rates for major categories of interior building products in SFD residences built prior to 1998. The inset graph shows the area-specific airflow rates for products with low loading ratios.

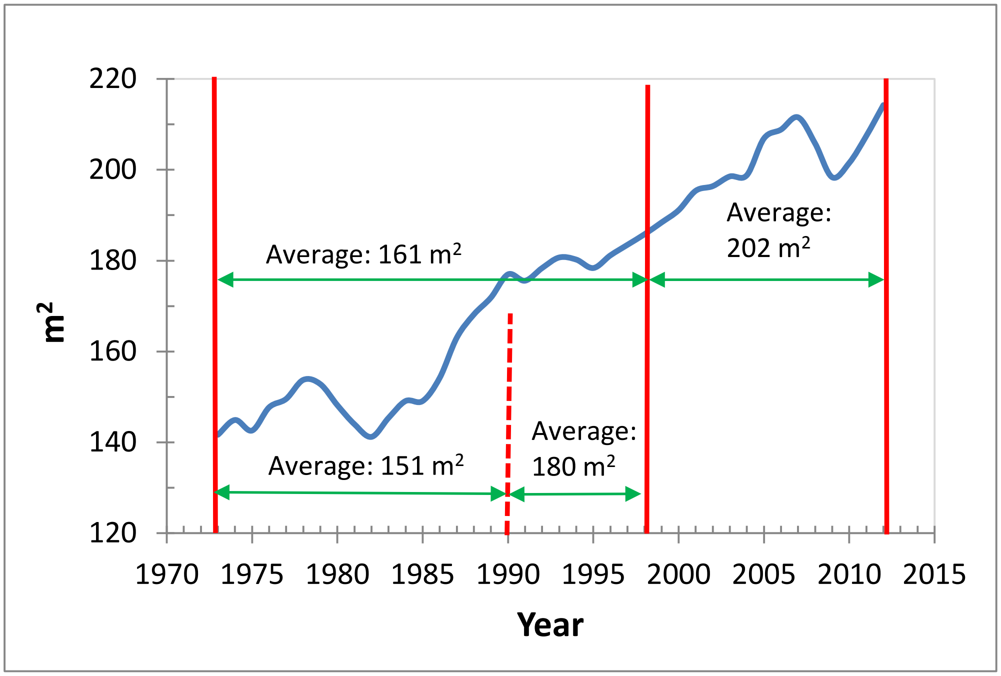


Figure 3. Median floor area of newly constructed single-family houses (U.S. Census, 2013)

Table 1. Summary of floor plans for SFD homes defined in Persily et al. [11]

Floor plan type	Floor area (m^2)	Number of stories ᵻ	Number of different home layouts (N)
A	107	1	9
B	180	1	5
C	276	1	2
D	107	2	4
E	180	2	8
F	276	2	5
G	180	2 (split level)	2
Total number of floor plans			35

ᵻ Basement is not counted as a story.

Table 2. Definition and calculation method for loading ratio of each product category

Product Category	Definition and/or Calculation Method
Flooring (sum of all types)	Sum of all floor area including finished basement
Ceiling	Sum of ceiling area; calculated as equal to flooring area
Walls & wallcoverings	Sum of the surface area of all walls; calculated as equal to the “gross” wall area obtained from floor plan minus surface area of all openings, doors and estimated window area[†]
Interior wallboard & paint	Sum of ceiling and wall area
Thermal insulation - ceiling	Ceiling area of top floor only
Thermal insulation - wall	Sum of exterior wall area; calculated as equal to the “gross” exterior wall area obtained from floor plan minus surface area of exterior doors and estimated window area[†]
Thermal insulation - ceiling & wall	Sum of ceiling and wall insulation areas
Acoustic insulation -wall	Application on all interior partition walls assumed; calculated as equal to ½ of (the surface area of all walls minus that of exterior walls)
Exterior doors	Surface area of exterior doors, including only surface exposed to interior
Interior doors	Surface area of interior doors, including both faces
Window treatments [†]	Same as estimated window area

[†] Estimated window area equals 17 % of floor area

Table 3. Loading ratio distribution statistics for major categories of interior building products in SFD residences [†]

Product Category	Product Loading Ratio (m^2/m^3)					
	Min	25 %	50 %	75 %	Max	Mean
Flooring (all types)	0.41					
Ceiling	0.41					
Walls & wallcoverings	0.69 (0.78; 0.69; 0.69) [††]	0.79 (0.88; 0.79; 0.72)	0.87 (0.97; 0.87; 0.78)	0.97 (1.14; 0.96; 0.80)	1.19 (1.19; 1.02; 0.83)	0.89 (0.99; 0.86; 0.77)
Interior wallboard & paint	1.10 (1.19; 1.10; 1.10)	1.20 (1.28; 1.20; 1.13)	1.28 (1.38; 1.28; 1.19)	1.38 (1.55; 1.37; 1.21)	1.60 (1.60; 1.43; 1.24)	1.30 (1.40; 1.27; 1.18)
Thermal insulation - Ceiling	0.14 (0.14; 0.14; 0.14)	0.14 (0.21; 0.14; 0.14)	0.21 (0.41; 0.21; 0.21)	0.41 (0.41; 0.21; 0.41)	0.41 (0.41; 0.41; 0.41)	0.26 (0.31; 0.22; 0.24)
Thermal insulation - Wall	0.18 (0.33; 0.24; 0.18)	0.33 (0.33; 0.34; 0.18)	0.34 (0.33; 0.35; 0.28)	0.45 (0.46; 0.45; 0.34)	0.60 (0.60; 0.45; 0.34)	0.36 (0.40; 0.37; 0.27)
Thermal insulation - Ceiling & Wall	0.48 (0.67; 0.54; 0.48)	0.55 (0.67; 0.55; 0.48)	0.59 (0.74; 0.59; 0.48)	0.67 (0.74; 0.59; 0.59)	0.74 (0.74; 0.65; 0.59)	0.62 (0.71; 0.58; 0.51)
Acoustic insulation - wall	0.23 (0.23; 0.21; 0.22)	0.23 (0.26; 0.23; 0.23)	0.26 (0.28; 0.25; 0.26)	0.28 (0.33; 0.26; 0.27)	0.36 (0.36; 0.32; 0.28)	0.27 (0.29; 0.25; 0.25)
Exterior doors	0.004 (0.007; 0.004; 0.006)	0.006 (0.014; 0.004; 0.006)	0.008 (0.014; 0.008; 0.006)	0.014 (0.014; 0.008; 0.006)	0.014 (0.014; 0.013; 0.006)	0.009 (0.013; 0.007; 0.006)
Interior doors	0.03 (0.04; 0.03; 0.03)	0.04 (0.05; 0.05; 0.04)	0.05 (0.07; 0.05; 0.04)	0.07 (0.08; 0.06; 0.05)	0.09 (0.09; 0.07; 0.05)	0.05 (0.06; 0.05; 0.04)
Windows	0.07 [†††]					

[†] Analysis is based on the set of 35 SFD floor plans [11].

[††] First value in each cell is based on all floor plans (N=35); values in ( ) are based on the floor plans of 107 m^2 (N = 13), 180 m^2 (N = 15) and 276 m^2 (N = 7), respectively.

[†††]Based on an assumed window-floor ratio of 17 %.

Table 4. Area-specific airflow rate percentiles for major categories of interior building products in SFD residences †

Product Category	Area-specific airflow rate (m/h)								
	5%	10%	25%	50%	75%	90%	95%	GM †††	GSD †††
Flooring (all types)	0.28 (0.19) ††	0.38 (0.25)	0.61 (0.38)	1.02 (0.63)	1.66 (1.05)	2.48 (1.66)	3.13 (2.15)	1.01 (0.63)	2.04 (2.12)
Ceiling	0.28 (0.19)	0.38 (0.25)	0.61 (0.38)	1.02 (0.63)	1.66 (1.05)	2.48 (1.66)	3.13 (2.15)	1.01 (0.63)	2.04 (2.12)
Walls & wallcoverings	0.14 (0.08)	0.18 (0.10)	0.29 (0.16)	0.47 (0.26)	0.74 (0.42)	1.10 (0.67)	1.39 (0.86)	0.47 (0.26)	1.98 (2.09)
Interior wallboard & paint	0.09 (0.06)	0.12 (0.07)	0.20 (0.11)	0.32 (0.18)	0.51 (0.30)	0.76 (0.47)	0.95 (0.61)	0.33 (0.19)	1.91 (2.04)
Thermal insulation - Ceiling	0.39 (0.34)	0.53 (0.45)	0.88 (0.68)	1.52 (1.08)	2.70 (1.68)	4.65 (2.53)	6.33 (3.26)	1.58 (1.00)	2.31 (2.05)
Thermal insulation - Wall	0.35 (0.19)	0.46 (0.25)	0.72 (0.40)	1.18 (0.69)	1.86 (1.20)	2.78 (1.91)	3.54 (2.49)	1.14 (0.77)	1.99 (2.05)
Thermal insulation - Ceiling + Wall	0.19 (0.13)	0.25 (0.16)	0.40 (0.25)	0.64 (0.40)	1.00 (0.65)	1.47 (1.00)	1.84 (1.30)	0.67 (0.42)	1.86 (2.01)
Acoustic insulation - wall	0.45 (0.28)	0.60 (0.35)	0.95 (0.52)	1.58 (0.83)	2.55 (1.34)	3.81 (2.07)	4.80 (2.69)	1.68 (0.88)	1.89 (1.99)
Exterior doors	13.2 (9.27)	17.2 (11.9)	26.5 (18.0)	42.3 (28.2)	66.6 (44.7)	99.4 (69.4)	126.2 (91.6)	43.1 (25.3)	1.92 (2.19)
Interior doors	2.19 (1.31)	2.93 (1.65)	4.72 (2.49)	7.80 (4.01)	12.5 (6.66)	18.8 (10.6)	24.0 (13.9)	6.03 (3.36)	2.20 (2.24)
Windows	1.65 (1.15)	2.21 (1.49)	3.57 (2.27)	5.99 (3.76)	9.71 (6.33)	14.5 (9.94)	18.3 (12.9)	5.74 (3.77)	1.96 (2.06)

† Analysis is based on the set of 83 SFD homes [11].

†† First value in each cell is based on all 83 homes; value in ( ) is based on 9 homes built 1990 or newer.

††† Area-specific airflow rates are fit to a log-normal distribution (MS Excel) for which the geometric mean(GM) and standard deviation (GSD) are reported. The cumulative frequency distribution of a log-normal distribution can be calculated as $F_X(x) = \frac{1}{2} erfc\left[-\frac{\ln(x)-\ln(GM)}{\ln(GSD)\cdot\sqrt{2}}\right]$, where erfc is the complementary error function and x dictates the area-specific airflow rate.

Table 5. Loading ratio percentiles for individual flooring types in new SFD California residences ᵻ

Floor Product Type	Percentage Coverage (%)ᵻᵻ						
	Min	25%	50%	75%	90%	95%	Max
Carpet	15	55	66	74	80	83	85
Hardwood ᵻᵻᵻ	0	0	0	19	38	46	63
Resilient flooring	0	0	2	14	26	31	39
Tile + mineral-based product	0	4	19	32	39	50	63

ᵻ Analysis is based on homes studied by Offermann [9].

ᵻᵻ Percentage coverage is calculated as the ratio of each floor type to the sum of all floor types.

ᵻᵻᵻ Both solid and engineered wood are included.

Table 6. Comparison between median area-specific flow rates for homes in this study built 1990-1997 and informative residential scenario in CDPH Standard Method

Product Category	Area-specific airflow rate (m/h)		
	50th percentile in current study	Informative residential scenario in CDPH Standard Method [7]	Difference (%) ᵻ
Flooring (all types)	0.63	0.60	5
Ceiling	0.63	0.59	8
Walls & wallcoverings	0.26	0.23	15
Interior wallboard & paint	0.18	0.16	10
Thermal insulation ᵻᵻ	0.40	0.45	-11
Acoustic insulation ᵻᵻᵻ	0.83	0.37	124
Exterior doors	28.2	16.8	68
Interior doors	4.01	3.41	18
Windows	3.76	3.34	13

ᵻ Calculated using the informative residential scenario in CDPH Standard Method as the base.

ᵻᵻ Calculated as the sum of ceiling and wall insulation.

ᵻᵻᵻ Calculation methods differed (see text).

SUPPORTING INFORMATION

Area-Specific Airflow Rates for Evaluating the Impacts of VOC Emissions in U.S. Single-Family Homes

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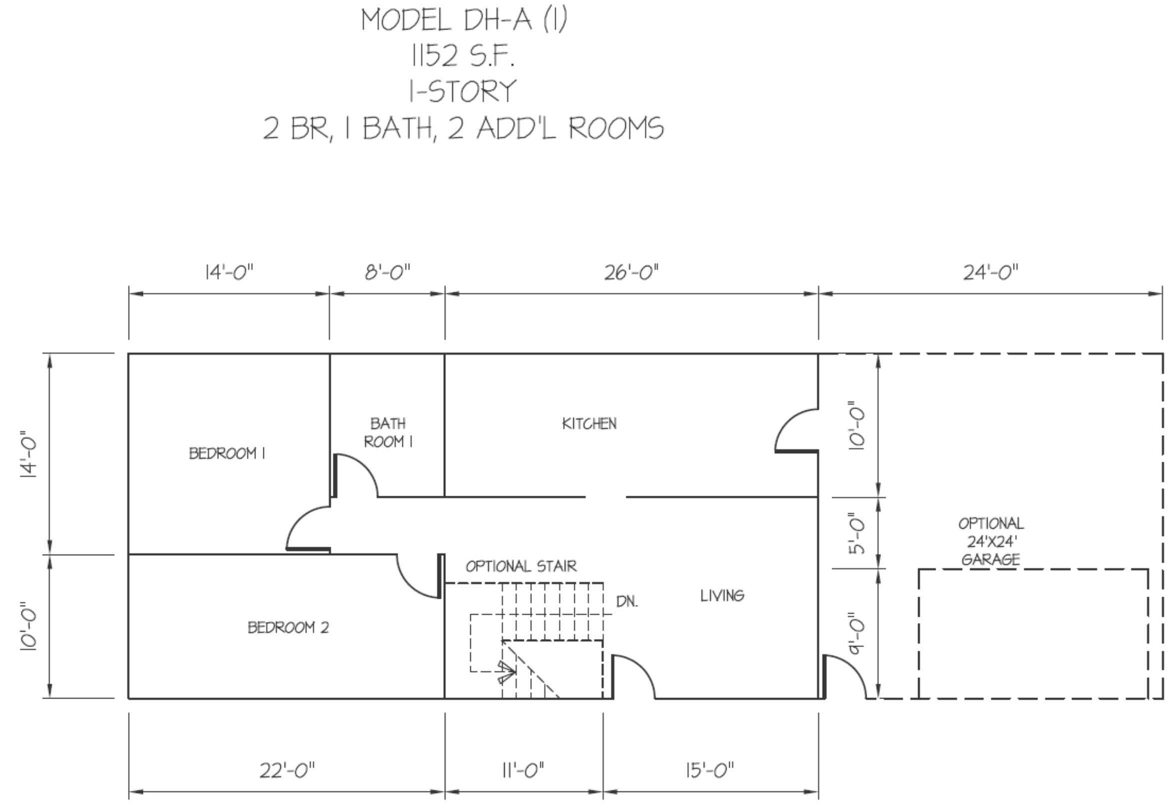

Figure S.1 Example Floor Plan A-1

Floor Plan	Room	Width (m)	Length (m)	Height (m)	# Doors† (interior)	# Doors (exterior)	# Openings	Floor Area (m^2)	Volume (m^3)	Door Area (interior) (m^2)	Vertical Opening Area (m^2)	Wall Area (no window considered) (m^2)	Door Area (exterior) (m^2)	Exterior Wall Area (no window considered) (m^2)
	1 Bed	4.27	4.27	2.44	1	0	0	18.21	44.43	1.86	0	39.79	0	20.82
	2 Bed	6.71	3.05	2.44	1	0	0	20.44	49.87	1.86	0	45.74	0	23.80
	1 Bath	2.44	3.05	2.44	1	0	0	7.43	18.13	1.86	0	24.92	0	5.95
A-1	Kitchen	7.92	3.05	2.44	0	1	1	24.15	58.94	0	2.23	49.46	1.86	24.92
	Living	7.92	4.27	2.44	0	1	2	33.82	82.51	0	5.20	52.44	1.86	27.89
	Hall	2.44	1.22	2.44	3	0	1	2.97	7.25	5.57	2.97	9.30	0	0
	TOTAL				6	2	2	107.02	261.14	11.14	10.41	221.65	3.71	103.38

Product Area/Quantity (m^2)

Floor Plan	Flooring	Ceiling	Walls & wall coverings‡	Interior wallboard & paint‡	Thermal insulation - ceiling	Thermal insulation - wall‡	Thermal insulation – ceiling + wall‡	Acoustic insulation -wall	Exterior doors	Interior doors	Window treatments‡
A-1	107.0	107.0	203.5	310.5	107.0	85.2	192.2	59.1	3.7	11.1	18.2

Product Loading Ratios (m^2/m^3)

Floor Plan	Flooring	Ceiling	Walls & wall coverings‡	Interior wallboard & paint‡	Thermal insulation - ceiling	Thermal insulation - wall‡	Thermal insulation – ceiling + wall‡	Acoustic insulation -wall	Exterior doors	Interior doors	Window treatments‡
A-1	0.41	0.41	0.78	1.19	0.41	0.33	0.74	0.23	0.014	0.04	0.07

† Interior doors have both faces exposed; each face is counted as one “door”.

‡ Based on an assumed window-floor ratio of 17 %.

Table S.1 Example Product Loading Ratio Calculation for Floor Plan A-1