

# Volatile Organic Compounds in Indoor Air: A Review of Concentrations Measured in North America Since 1990

ALFRED T. HODGSON<sup>a,1</sup> and HAL LEVIN<sup>a,b</sup>

<sup>a</sup> *Indoor Environment Department, Environmental Energy Technologies Division, E.O. Lawrence Berkeley National Laboratory, Berkeley, CA, USA*

<sup>b</sup> *Building Ecology Research Group, Santa Cruz, CA, USA*

## **Abstract**

Central tendency and upper limit concentrations of volatile organic compounds (VOCs) measured in indoor air are summarized and reviewed. Data were obtained from published cross-sectional studies of residential and office buildings conducted in North America from 1990 through the present. VOC concentrations in existing residences reported in 12 studies comprise the majority of the data set. Central tendency and maximum concentrations are compared between new and existing residences and between existing residences and office buildings. Historical changes in indoor VOC concentrations since the Clean Air Act Amendments of 1990 are explored by comparing the current data set with two published reviews of previous data obtained primarily in the 1980s. These historical comparisons suggest average indoor concentrations of some toxic air contaminants, such as 1,1,1-trichloroethane have decreased.

<sup>1</sup> Corresponding author:

Address: Lawrence Berkeley National Laboratory, MS 70-108B, Berkeley, CA 94720, USA.

Tel.: +1-510-486-5301. Fax: +1-510-486-7303. E-mail: ATHodgson@lbl.gov

## **Introduction**

Consideration of indoor exposures to air pollutants is critical to accurate assessments of the health risks associated with these chemicals because people spend a large fraction of their time indoors where concentrations of many airborne pollutants often tend to exceed ambient levels.

A California statewide activity pattern survey conducted in 1987-88 showed that individuals spent, on average, 87% of their time indoors (Jenkins *et al.*, 1992). This was broken down into 65% of the time spent in a residence and 21% of the time spent in other indoor locations. The National Human Activity Pattern Survey conducted in 1992-94 produced similar results (Klepeis *et al.*, 2001). Again, the mean percentage of time spent indoors was 87%. This was broken down into 69% of time spent in a residence and 18% of the time spent in other indoor locations.

It is widely recognized that airborne concentrations of many toxic volatile organic compounds (VOCs) in residences, office buildings and some other indoor environments are higher than concentrations in outdoor air (*e.g.*, Pellizzari *et al.*, 1986; Wallace, 1987; Daisey *et al.*, 1994). This occurs in part because there are numerous indoor sources of VOCs and because the relatively low rates of outdoor air ventilation typically used in residences and offices prevent the rapid dispersal of airborne contaminants. The many consumer products that are used in residences and offices contain and emit numerous VOCs. Such products include cleaners, air fresheners, and insect repellents. Combustion processes, in particular smoking, are indoor sources of complex mixtures of VOCs. Attached garages are a potential source of gasoline vapors due to evaporative and exhaust emissions. Materials and products used in new construction, remodeling, and redecorating are other major contributors to indoor VOC concentrations in residences and offices.

In the U.S. and elsewhere, the decade since 1990 has witnessed increased concern about the environmental consequences and adverse health effects of air pollution. Most significantly, the U.S. 1990 Clean Air Act (CAA) Amendments established Federal and State programs to regulate the emissions of a large number of air pollutants that can cause cancer, reproductive harm, other serious illnesses as well as environmental damage. These are classified as hazardous air

pollutants (HAPs). A list of 189 HAPs was included in the 1990 CAA, and the U.S. Environmental Protection Agency (EPA) was given authority to add new chemicals to the list or to remove chemicals (U.S. EPA, 1994). Source categories also were defined. Both large and small area sources are regulated and now must reduce their emissions of HAPs through curtailment and the use of control technologies. Cleaner fuels and engines have been mandated to reduce emissions of HAPs from mobile sources. In 1998, the EPA promulgated national VOC emissions standards for certain categories of consumer products as authorized under a section of the 1990 CAA. It is possible that concentrations of some HAPs to which people are exposed in buildings have been reduced due to reductions in outdoor air pollution and reformulation of materials and products.

Indoor VOC data from about 1978 through 1990 were summarized in several reviews. In the late 1980's, Shah and Singh (1988) updated and analyzed a VOC database for the U.S. Most of the available measurements of VOCs in ambient air and in residential and commercial buildings were gathered, with data accepted in all forms. The final database included 66 VOCs measured indoors. Average, median and upper and lower quartile concentrations were presented for 35 indoor VOCs. Brown *et al.* (1994) reviewed the literature and summarized the data on the concentrations of VOCs measured indoors in different categories of buildings (*i.e.*, residences, offices, schools and hospitals). These included measurements reported in 50 studies, primarily in North America and northern Europe. Data were obtained for 90 VOCs occurring in residences. Considerably fewer data were available for the other building types. Holcomb and Seabrook (1995) compiled the data from 30 studies of houses and public places in North America and the United Kingdom, all conducted prior to 1990. Average concentrations were presented by environment for 18 of the 85 identified VOCs.

In this paper, we have compiled and summarized the data on the central tendency and upper limit indoor VOC concentrations measured from 1990 through the present. We have focused exclusively on measurements made in North America. Much of the available data are from studies of residences. Data from existing (*i.e.*, not newly constructed) residences, new residences

and primarily large office buildings are separately treated. VOC concentrations in other environments such as small offices, schools, retail stores and health care facilities generally have not been characterized and are not included. We also have not attempted to summarize indoor/outdoor concentration ratios. Our primary objective is to generate a database of typical and maximum VOC concentrations that can be used by others as a comparative basis for evaluating measured concentrations.

In a companion paper (Hodgson and Levin, In preparation), we assess the VOC concentrations in residences and office buildings summarized herein with respect to odor thresholds, derived sensory irritation levels for the general population and non-cancer chronic health risks. Our objective there is to identify VOCs that are most likely to result in comfort and/or health concerns and, therefore, that should be included in investigations of indoor air quality.

## **Methods**

For this review, VOCs were broadly defined as chemical compounds based on carbon chains or rings with vapor pressures greater than ~0.01 millimeters of mercury at room temperature. Carbon monoxide, carbon dioxide, carbonic acid, metallic carbides, carbonate salts, and C<sub>1</sub>-C<sub>3</sub> hydrocarbons were excluded.

Papers were gathered from the scientific journal literature with several exceptions. Papers were sought that reported measurements made in North American residences, both new and existing, and office buildings from 1990 through the present. Only cross-sectional studies that investigated five or more buildings were considered. Investigations of unusual environments or pollutant sources were excluded. One important probability-based study of residences was obtained as an agency report (Sheldon *et al.*, 1991). A probability-based study of office buildings was obtained from the proceedings of an international conference (Girman *et al.*, 1999). Finally, several very recent studies were obtained from the proceedings of Indoor Air 2002, the 9<sup>th</sup> International Conference on Indoor Air Quality and Climate (Foster *et al.*, 2002;

Kurtz *et al.*, 2002). In total, we identified 13 papers presenting the results of 12 studies of existing residences, two papers presenting results for new residences, and three papers presenting results for office buildings. Basic information regarding these studies (*i.e.*, study type, location, collection dates, and number of building units) is summarized by building type in Tables 1-3.

For existing residences, there were five probability-based studies. One of these (Sheldon *et al.*, 1992) provided complete population statistics including geometric means (GMs) and frequency distributions. More commonly, the existing residence studies presented central tendencies as median values or arithmetic averages. Upper concentration ranges were most frequently given as a maximum value and sometimes as 90<sup>th</sup> and/or 95<sup>th</sup> percentile values. For three existing residence studies (Heavner *et al.*, 1995 and 1996; Mukerjee *et al.*, 1997) in which the data were segmented (*i.e.*, smoking and non-smoking residences or spring and summer seasons), GM concentrations weighted by the numbers of housing units in each segment were calculated for the entire study as described by Brown *et al.* (1994).

Only two studies of new residences encompassing 20 single-family houses were identified. The measurements were made within the first six months after the houses were completed. For one study (Hodgson *et al.*, 2000), GM concentrations and ranges were presented for manufactured and site-built houses. GMs were summarized as weighted averages. For the other study (Lindstrom *et al.*, 1995), all of the individual concentration measurements for pre- and post-occupancy phases were presented. These data were combined and summarized as GMs. The office building data were used as reported. For one study (Girman *et al.*, 1999), the median and 95<sup>th</sup> percentile values were extracted from a Log-scale plot.

Limited data editing was performed. Environmental tobacco smoke specific compounds (*e.g.*, 3-ethenylpyridine and nicotine) reported by two studies (Heavner *et al.*, 1995 and 1996) were excluded. Mukerjee *et al.* (1997) reported data for 70 volatile and very volatile, predominantly hydrocarbon compounds. Twenty-five of these were included; many very volatile compounds, compounds with low occurrence, and branched alkane hydrocarbon isomers generally were excluded. Van Winkle *et al.* (2001) reported data for 37 volatile and very volatile

compounds. Only the 17 ubiquitous and often-found VOCs were included. Acrolein data reported by Lindstrom *et al.* (1995) were excluded as the method used likely underestimated the mass of this compound (Tejada, 1986).

All reported data were entered into a relational database (Microsoft Access). Concentrations given as mass per unit volume, *i.e.*,  $\mu\text{g m}^{-3}$  (the majority of studies) were converted to molar volume concentrations (ppb) assuming a normal indoor temperature of 25° C (298° K) and one atmosphere pressure (101 kPa). This conversion facilitates the inter-comparison of compounds with respect to health effects. Data summaries for individual studies were prepared as described above. In the tables, the compounds are grouped into 16 chemical classes and then, within each class, listed by decreasing volatility as indicated by boiling point.

## Results

Table 4 lists the 106 VOCs for which concentration data were obtained along with their Chemical Abstract Service (CAS) numbers, chemical class, molecular weights, boiling points,  $\mu\text{g}/\text{m}^3$  to ppb conversion factors, and toxic air pollutant list status. The EPA classifies 35 of these as HAPs. Five additional compounds are classified by the California EPA as Toxic Air Contaminants (CARB, 2003).

Central tendency data for existing residences were reported for 57 VOCs. These data are summarized in Table 5, which lists reported GM, median, and average concentrations. For compounds with data from two or more studies, a best estimate of central tendency is calculated as the unweighted GM of reported GM and median concentrations, with the GM selected to represent a study if both statistics were reported. All of the central tendency measures for 36 of the VOCs (63%) were less than 1 ppb. These included the HAPs, n-hexane, 1,3-butadiene, styrene, isopropylbenzene (cumene), naphthalene, vinyl chloride, chloroform, carbon tetrachloride, trichloroethene, and 1,4-dioxane.

Upper concentration ranges for existing residences were reported for 48 VOCs. These data are summarized in Table 6, which lists the reported 90<sup>th</sup> and 95<sup>th</sup> percentiles and maximum

concentrations. For compounds with data from three or more studies, ranges are shown and maximum values are summarized as unweighted GMs. All of their upper concentration measures for seven of the VOCs including the HAPs, naphthalene, vinyl chloride, carbon tetrachloride, chlorobenzene, and bromomethane, were less than 1 ppb. VOCs with maximum concentrations of 50 ppb or more included acetic acid, formaldehyde, toluene, m/p-xylene, 1,4-dichlorobenzene, dichloromethane, 1,1,1-trichloroethane, and 2-propanone.

Geometric mean and maximum concentration data from the two studies of new single-family houses are presented in Table 7. Data were reported for 69 VOCs. VOC concentrations reported by both studies are summarized as unweighted GMs. For 25 compounds (36%), their GM concentrations were less than 1 ppb. These included all nine halogenated compounds. VOCs with maximum concentrations of 50 ppb or more in the new houses included acetic acid, formaldehyde, acetaldehyde, hexanal, toluene, ethylene glycol, 1,2-propanediol, 2-propanone, and  $\alpha$ -pinene.

Central tendency (GMs or medians) and maximum concentration data from the three studies of office buildings are presented in Table 8. Data were reported for 67 VOCs. VOC concentrations reported by multiple studies were summarized as unweighted GMs. For 31 compounds (46%), their central tendency values were less than 1 ppb. These included the HAPs, n-hexane, ethylbenzene, o-xylene, styrene, 1,4-dichlorobenzene, dichloromethane, and tetrachloroethene. For nine of the VOCs, including the HAPs, 1,2,4-trichlorobenzene, carbon tetrachloride, and chlorobenzene, the maximum concentrations also were less than 1 ppb. VOCs with maximum concentrations of 50 ppb or more in the office buildings included ethanol, 2-propanol, n-octane, toluene, dichloromethane, 1,1,1-trichloroethane, and 2-propanone.

## **Discussion**

### ***Data Limitations***

Published data are available for only a fraction of the VOCs that are known or suspected to occur in indoor air. The uncharacterized VOCs likely include a number of compounds important with

respect to human health, sensory irritation and odor that have not been measured because they are inadequately collected or analyzed by conventional methods (Wolkoff *et al.*, 1997; Wolkoff and Nielsen, 2001).

Several important indoor environments are inadequately represented. In particular, there were almost no published data available for small office buildings where the majority of office workers are located, schools, retail stores, other non-office commercial environments, and institutionalized housing.

The estimates of central tendency and upper limit concentrations may not be representative. Some of the studies were conducted in the early 1990's and may not represent current levels. Only a fraction of these studies were probability based. For some VOCs, only a small number of building units was represented. Most of the residential studies obtained only short-term samples and no study sampled a given environment more than a few times. Such strategies are dictated by practical considerations but may result in substantial misrepresentations of long-term indoor exposure concentrations and inadequate characterization of peak concentrations. In addition, personal breathing zone exposures which typically were not measured can be substantially higher than indoor area concentrations (Rhodes, 1990). The predominance of personal exposures was further demonstrated by the U.S. EPA TEAM studies (Wallace, 2001). Finally, very few studies measured building ventilation rates, which directly influence VOC concentrations and which may vary substantially with time within buildings.

### ***Comparisons Among Building Types***

Concentrations of VOCs emitted by interior building materials are expected to be higher initially in newly constructed buildings. Table 9 compares central tendency and maximum VOC concentrations for new residences with values for existing residences. Central tendency concentrations of several aldehydes (acetaldehyde, propionaldehyde, and benzaldehyde), normal alkane hydrocarbons and terpene hydrocarbons ( $\alpha$ -pinene and d-limonene) were more three times (i.e., one-half order of magnitude) higher in the new houses than in the existing houses.



Maximum concentrations of propionaldehyde, pentanal, acetic acid and 1,2-dichlorobenzene were more than three times higher in the new houses. Acetaldehyde, pentanal, and terpenes are emitted by composite wood products used for cabinetry and subfloors (Hodgson *et al.*, 2002). Wood products probably also are a large source of acetic acid. Chloroform concentrations were lower in the new houses. This is expected, as these houses were unoccupied except for the final phase of one study (Lindstrom *et al.*, 1995) with little domestic water use, a primary source of this compound. Some of the other lower values of chlorinated hydrocarbons in new houses also may be attributable to the difference in occupancy.

The sources of some VOCs may differ between residences and office buildings. Table 10 compares central tendency and maximum VOC concentrations for office buildings with values for existing residences. Central tendency concentrations of n-dodecane, 1,1,1-trichloroethane, trichloroethene and tetrachloroethene were more than three times higher in the office buildings. Dodecane is a component of an isoparaffinic solvent that was used in once prevalent wet-process photocopiers (Hodgson *et al.*, 1991). The chlorinated solvents may be used in various office and janitorial products. The office buildings had lower central tendency concentrations of pentanal,  $\alpha$ -pinene, d-limonene, 1,4-dichlorobenzene, and dichloromethane. A lower prevalence of wood products in office buildings versus residences probably accounts for the lower pentanal and terpene concentrations. 1,4-Dichlorobenzene was once widely used in residences as a moth control agent. Maximum concentrations of the seven aromatic hydrocarbons were more than three times lower in office buildings.

### ***Historical Trends***

Changes in the production and use of environmentally harmful and toxic chemicals resulting from increased global awareness and the enactment in the U.S. of the 1990 CAA are expected to impact indoor concentrations and exposures to targeted HAPs in two ways. General reductions in the emissions, production, and use of HAPs should decrease the ambient concentrations of these compounds in ventilation and infiltration air entering buildings. Changes in industry

processes to use less toxic compounds in consumer products and other materials used indoors should directly reduce indoor concentrations of the targeted HAPs. These latter changes, in particular, can result in substantial decreases in overall population exposures as shown by Lai *et al.* (2000). They developed the concept of inhalation transfer factors (ITFs) for outdoor and indoor pollutant emissions that accounts for dispersion in ambient air and ventilation dilution in well mixed buildings. Using ITFs, emissions of pollutants indoors were shown to result, on average, in three orders of magnitude higher exposures than equivalent emissions occurring outdoors in an urban air basin.

Potential historical changes in VOC concentrations were explored by comparing central tendency VOC concentrations from this review with results from the U.S. EPA TEAM studies. The TEAM studies measured concentrations of toxic VOCs in outdoor air, indoor air, personal exposure air and breath samples for communities in several states (*i.e.*, NC, LA, TX, NJ and CA) from 1980 through 1984. Indoor samples were collected overnight at each residence and were analyzed for up to 30 VOCs. The indoor, residential median and maximum VOC concentrations were presented by Pellizzari *et al.* (1986). Because the measurements were probability based, limited to the U.S., and employed a consistent methodology, they provide a good benchmark for exploring potential historical changes in HAP concentrations. In Figure 1, the median and GM concentrations from the current review summarized as unweighted GMs are compared with the TEAM study's central tendency concentrations for 17 VOCs from nine studies also summarized as unweighted GMs. The 1,1,1-trichloroethane concentration in the current review is more than three times lower than the TEAM study value. Other compounds that are approximately one-half order of magnitude lower in the current review are benzene, 1,2-dichloroethane and tetrachloroethene.

These changes likely are due to increased regulations. The 1990 London Amendment to the Montreal Protocol established timelines for global phase out of the production and consumption of CFCs, halons, 1,1,1-trichloroethane, and carbon tetrachloride. By 1995, the production and consumption of 1,1,1-trichloroethane in the U.S. were down by more than 80% relative to 1989

with substantially larger decreases in subsequent years (Oberthur, 2001). The U.S. EPA estimated that nationwide tetrachloroethene emissions dropped 67% from 1990 to 1996 (U.S. EPA, 2001). Measurements of benzene at urban monitoring sites throughout the U.S. showed an average 40% reduction in benzene levels from 1994 to 1999 coincident with the phase-in of “tier 1” emissions standards for cars and increased regulation of oil refineries and chemical processes (*ibid.*). Other aromatic hydrocarbons associated with benzene may exhibit similar reductions.

## **Conclusions**

There are few health-based guidelines for VOC concentrations in non-industrial indoor environments. Thus, summaries of indoor VOC concentrations typically measured in houses and offices provide one means for evaluating measured VOC concentrations. Although the available data were limited in a number of aspects, the summary of these data fills an important gap by covering the decade since the substantial 1990 revision of the Clean Air Act in the U.S. A comparison of the concentrations reviewed here with data from the previous decade suggests that average indoor concentrations of some toxic indoor air contaminants, such as benzene, 1,1,1-trichloroethane and tetrachloroethene, have decreased. Despite these trends, indoor exposures to most common VOCs undoubtedly still dominate human exposures to these compounds.

## **Acknowledgements**

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. The authors thank Tosh Hotchi of LBNL for creating the Access database and assistance with data analysis.

## References

- Adgate JL, Bollenbeck M, Eberly LE, Stroebel C, Pellizzari ED and Sexton K. 2002. Residential VOC concentrations in a probability-based sample of households with children. In *Indoor Air 2002, Proc. 9<sup>th</sup> Int. Conf. Indoor Air Quality and Climate*, Vol. 1, pp. 203-208. H Levin (Ed.). Santa Cruz, CA: Indoor Air 2002.
- Brown SK, Sim MR, Abramson MJ and Gray CN. 1994. Concentrations of volatile organic compounds in indoor air – a review. *Indoor Air* 4: 123-134.
- CARB. 2003. *Toxic air contaminant identification list*. Air Quality Measures Branch, California Air Resources Board, Sacramento, CA. Web site <http://www.arb.ca.gov/toxics/id.htm>.
- Clayton CA, Pellizzari ED, Whitmore RW, Perritt RL and Quackenboss JJ. 1999. National Human Exposure Assessment Survey (NHEXAS): distributions and associations of lead, arsenic and volatile organic compounds in EPA Region 5. *J. Expos. Anal. Environ. Epidemiol.* 9: 381-392.
- Daisey, JM, Hodgson AT, Fisk WJ, Mendell MJ and Ten Brinke J. 1994. Volatile organic compounds in twelve California office buildings: classes, concentrations and sources. *Atmos. Environ.* 28: 3557-3562.
- Foster SJ, Kurtz JP and Woodland AK. 2002. Background indoor air risks in selected residences in Denver Colorado. In *Indoor Air 2002, Proc. 9<sup>th</sup> Int. Conf. Indoor Air Quality and Climate*, Vol. 1, pp. 932-937. H Levin (Ed.). Santa Cruz, CA: Indoor Air 2002.
- Girman JR, Hadwen GE, Burton LE, Womble SE and JF McCarthy. 1999. Individual volatile organic compound prevalence and concentrations in 56 buildings of the Building Assessment Survey and Evaluation (BASE) study. In *Indoor Air 99, Proc. 8<sup>th</sup> Int. Conf. Indoor Air Quality and Climate*, Vol. 2, pp. 460-465. G Raw, C Aizlewood, and P Warren (Eds.). London: Construction Research Communications Ltd.
- Gordon SM, Callahan PJ, Nishioka MG, *et al.* 1999. Residential environmental measurements in the National Human Exposure Assessment Survey (NHEXAS) pilot study in Arizona: preliminary results for pesticides and VOCs. *J. Expos. Anal. Environ. Epidemiol.* 9: 456-470.
- Heavner DL, Morgan WT and Ogden MW. 1995. Determination of volatile organic compounds and ETS apportionment in 49 homes. *Environ. Int.* 21: 3-21.
- Heavner DL, Morgan WT and Ogden MW. 1996. Determination of volatile organic compounds and respirable suspended particulate matter in New Jersey and Pennsylvania homes and workplaces. *Environ. Int.* 22: 159-183.
- Hodgson AT, Daisey JM and Grot RA. 1991. Sources and source strengths of volatile organic compounds in a new office building. *J. Air Waste Manage. Assoc.* 41: 1461-1468.
- Hodgson AT, Rudd AF, Beal D and Chandra S. 2000. Volatile organic compound concentrations and emission rates in new manufactured and site-built houses. *Indoor Air* 10: 178-192.
- Hodgson AT, Beal D and McIlvaine JER. 2002. Sources of formaldehyde, other aldehydes and terpenes in a new manufactured house. *Indoor Air* 12: 1-8.
- Hodgson AT and Levin H. In preparation. Volatile organic compounds in indoor air: concentrations of interest with respect to noncancer effects.

- Holcomb, LC and Seabrook BS. 1995. Indoor concentrations of volatile organic compounds: implications for comfort, health and regulation. *Indoor Environment* 4: 7-26.
- Jenkins PL, Phillips TJ, Mulberg EJ and Hui SP. 1992. Activity patterns of Californians: use of and proximity to indoor pollutant sources. *Atmos. Environ.* 26A: 2141-2148.
- Klepeis NE, Nelson WC, Ott WR, *et al.* 2001. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *J. Expos. Anal. Environ. Epidemiol.* 11: 231-252.
- Kurtz JP and Folkes DJ. 2002. Background concentrations of selected chlorinated hydrocarbons in residential indoor air. In *Indoor Air 2002, Proc. 9<sup>th</sup> Int. Conf. Indoor Air Quality and Climate*, Vol. 1, pp. 920-925. H Levin (Ed.). Santa Cruz, CA: Indoor Air 2002.
- Lai ACK, Thatcher TL and Nazaroff WW. 2000. Inhalation transfer factors for air pollution health-risk assessments. *J. Air Waste Manage. Assoc.* 50: 1688-1699.
- Lindstrom AB, Proffitt D and Fortune CR. 1995. Effects of modified residential construction on indoor air quality. *Indoor Air* 5: 258-269.
- Mukerjee S, Ellenson WD, Lewis RG, *et al.* 1997. An environmental scoping study in the lower Rio Grande Valley of Texas – III. Residential microenvironmental monitoring for air, house dust, and soil. *Environ. Int.* 23: 657-673.
- Oberthur, S. 2001. Production and consumption of ozone-depleting substances 1986-1999. Publication. Eschborn, Germany: GTZ/Proklima.
- Otson R, Fellin P and Tran Q. 1994. VOCs in representative Canadian residences. *Atmos. Environ.* 28: 3563-3569.
- Pellizzari ED, Hartwell TD, Perritt RL, *et al.* 1986. Comparison of indoor and outdoor residential levels of volatile organic chemicals in five U.S. geographical areas. *Environ. Int.* 12: 619-623.
- Rhodes CE, Kamens RM and Wiener RW. 1991. The significance and characteristics of the personal activity cloud on exposure assessment measurement for indoor contaminants. *Indoor Air* 1: 123-145.
- Shah JJ and Singh HB. 1988. Distribution of volatile organic chemicals in outdoor and indoor air. *Environ. Sci. Technol.* 22: 1381-1388.
- Shields HC, Fleischer DM and Weschler CJ. 1996. Comparisons among VOCs measured in three types of U.S. commercial buildings with different occupant densities. *Indoor Air* 6: 2-17.
- Sheldon LS, Clayton A, Jones B, *et al.* 1991. Indoor Pollutant Concentrations and Exposures. Final report. Sacramento, CA: California Air Resources Board.
- Tejada SB. 1986. Evaluation of silica gel cartridges coated in situ with acidified 2,4-dinitrophenylhydrazine for sampling aldehydes and ketones in air. *Int. J. Environ. Anal. Chem.* 26: 167-185.
- U.S. EPA. 1994. *EPA health effects notebook for hazardous air pollutants—draft*. Air Risk Information Support Center, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Washington, DC. EPA-452/D-95-00. U.S. EPA Air Toxics web site: <http://www.epa.gov/ttn/atw/>.

- U.S. EPA. 2001. Latest findings on National air quality: 2000 status and trends. Report EPA 454/K-01-002. Research Triangle Park, NC: U.S. Environmental Protection Agency.
- Van Winkle MR and Scheff PA. 2001. Volatile organic compounds, polycyclic aromatic hydrocarbons and elements in the air of ten urban homes. *Indoor Air* 11: 49-64.
- Wallace LA, Pellizzari ED, Hartwell TD, *et al.* 1986. Total Exposure Assessment Methodology (TEAM) study: personal exposures, indoor-outdoor relationships, and breath levels of volatile organic compounds in New Jersey. *Environ. Int.* 12: 369-387.
- Wallace LA. 1987. The Total Exposure Assessment Methodology (TEAM) Study: Summary and Analysis: Volume I. EPA/600/6-87/002a. Washington, DC: Office of Research and Development, US EPA.
- Wallace LA, Pellizzari ED, Hartwell TD, *et al.* 1988. The California TEAM study: breath concentrations and personal exposures to 26 volatile compounds in air and drinking water of 188 residents of Los Angeles, Antioch and Pittsburg, CA. *Atmos. Environ.* 22: 2141-2163.
- Wallace LA. 2001. Assessing human exposure to volatile organic compounds. In *Indoor Air Quality Handbook*, pp. 33.1-33.35. JD Spengler, JM Samet, and JF McCarthy (Eds.). New York, NY: McGraw-Hill.
- Wolkoff P, Clausen PA, Jensen B, Nielsen GD and Wilkins CK. 1997. Are we measuring the relevant indoor pollutants? *Indoor Air* 7: 92-106.
- Wolkoff P and Nielsen GD. 2001. Organic compounds in indoor air – their relevance for perceived indoor air quality. *Atmos. Environ.* 35: 4407-4417.
- Zhang J, He Q and Liroy PJ. 1994. Characteristics of aldehydes: concentrations, sources and exposures for indoor and outdoor residential microenvironments. *Environ. Sci. Technol.* 28: 146-152.
- Zhang J, Wilson W and Liroy PJ. 1994. Sources of organic acids in indoor air: a field study. 1994. *J. Expos. Anal. Environ. Epidemiol.* 4: 25-47.

**Table 1.** Residential studies included in review. Probability-based studies are listed first.

Reference (ID)	Parameter	Data
Sheldon <i>et al.</i> (s) 1992	Study type	Stratified probability sample
	Loc. & Date	Woodland, CA; Jun 1990
	No. units	128 Residences
	Data source	Tbls. 9-13, 9-14, 9-18
Otson <i>et al.</i> (o) 1994	Study type	Probability sample
	Loc. & Date	Canada; Date not specified
	No. units	757 Housing units
	Data source	Tbl. 1, p. 3564
Clayton <i>et al.</i> (c) 1999	Study type	Stratified, 4-stage probability sample
	Loc. & Date	IL, OH, MI, MN, WI; Jul 1995 - May 1997
	No. units	~170 Housing units, sampled up to 3 times
	Data source	Tbl. 7, p. 387
Gordon <i>et al.</i> (g) 1999	Study type	Stratified, 3-stage probability sample
	Loc. & Date	AZ; Date not specified
	No. units	~190 Housing units
	Data source	Tbls. 10 & 11, pp. 467-468
Adgate <i>et al.</i> (a) 2002	Study type	Stratified probability sample; units with children
	Loc. & Date	MN; May - Aug 1997
	No. units	~290 Housing units
	Data source	Tbl. 2 & Fig. 1, Vol. 1, pp. 205-206
Zhang <i>et al.</i> (za, zb) 1994a & b	Study type	Convenience sample
	Loc. & Date	NJ; Jun - Aug, 1992
	No. units	6
	Data source	Tbl. 1, p. 148; Tbl. 2, p. 32
Heavner <i>et al.</i> (ha) 1995	Study type	Convenience sample; units with married non-smoking females
	Loc. & Date	Columbus, OH; Feb 1991
	No. units	24 Non-smoking units, 25 smoking units
	Data source	Tbl. 1, p. 7
Heavner <i>et al.</i> (hb) 1996	Study type	Convenience sample; units with married non-smoking females
	Loc. & Date	Mt. Laurel, NJ; Nov 1992
	No. units	61 Non-smoking units, 32 smoking units
	Data source	Tbl. 4, p. 169
Mukerjee <i>et al.</i> (m) 1997	Study type	Convenience sample
	Loc. & Date	Brownsville, TX; 1993
	No. units	3 City units, 6 rural agricultural units
	Data source	Tbl. 8, pp. 668-669

**Table 1.** Continued.

Reference (ID)	Parameter	Data
Van Winkle <i>et al.</i> (v) 2001	Study type	Convenience sample of non-smoking units
	Loc. & Date	Chicago, IL; 1994 - 1995
	No. units	10 Units sampled monthly or quarterly
	Data source	Tbl. 1, pp. 52-53
Kurtz & Folkes (k) 2002	Study type	Convenience sample
	Loc. & Date	Denver, CO; 1998 - 2001
	No. units	120 Single-family residences in Redfield Rifle Scope site
	Data source	Tbl. 1, Vol. 1, p. 923
Foster <i>et al.</i> (f) 2002	Study type	Convenience sample
	Loc. & Date	Denver, CO; 1996 - 2001
	No. units	21 Single-family resid., 8 town house; 12 apart.bldg.
	Data source	Tbl. 2, Vol. 1, p. 935



**Table 2.** Studies of new residences included in review.

Reference (ID)	Parameter	Data
Lindstrom <i>et al.</i> (l) 1995	Study type	Convenience sample
	Loc. & Date	Denver, CO; Dec 1992 - May 1993
	No. units	6 Experimental & 3 conventional single-family houses
	Data source	Tbls. 6, 8, 9 & 11, pp. 262, 265 & 267
Hodgson <i>et al.</i> (ho) 2000	Study type	Convenience sample
	Loc. & Date	FL & east, southeast U.S.; 1997 - 1998
	No. units	4 Manufactured houses; 7 site-built single-family houses
	Data source	Tbls. 3 & 4, pp. 668-669

**Table 3.** Office building studies included in review.

Reference (ID)	Parameter	Data
Daisey <i>et al.</i> (d) 1994	Study type	Convenience
	Loc. & Date	San Francisco Bay Area, CA; Jun - Sep 1990
	No. units	12 Public buildings (3 natural vent., 3 mech. vent., 6 mech. vent. with AC)
	Data source	Tbl. 2, p. 3559
Shields <i>et al.</i> (sh) 1996	Study type	Convenience
	Loc. & Date	U.S.; Mar - Apr 1991
	No. units	11 Telco administrative offices
	Data source	Tbl. 3, p. 8
Girman <i>et al.</i> (gi) 1999	Study type	Stratified probability sample
	Loc. & Date	U.S., 1995 - 1998
	No. units	56 Public & private buildings
	Data source	Tbl. 1 & Fig. 1; Vol. 2, pp. 462 & 464

**Table 4.** VOCs reported in existing and new residences and in office buildings ordered by chemical class and increasing boiling point within class. Factors for  $\mu\text{g}/\text{m}^3$  to ppb concentration conversions are shown. Presence on U.S. EPA Hazardous Air Pollutant (H) and California EPA Toxic Air Contaminant (T) lists is indicated.

Compound	CAS No.	Chem. Class <sup>a</sup>	BP (°C)	MW	$\mu\text{g}/\text{m}^3$ to ppb	Toxic Cat.
Ethanol	64-17-5	Alc	78	46.1	0.530	
2-Propanol	67-63-0	Alc	82	60.1	0.407	
1-Butanol	71-36-3	Alc	118	74.1	0.330	T
Phenol	108-95-2	Alc	182	94.1	0.260	H,T
2-Ethyl-1-hexanol	104-76-7	Alc	183	130.2	0.188	
1-Octanol	111-87-5	Alc	195	130.2	0.188	
Butylated hydroxytoluene	128-37-0	Alc	265	220.4	0.111	
<i>t</i> -Butyl methyl ether	1634-04-4	Ethr	20	88.2	0.277	H,T
1,4-Dioxane	123-91-1	Ethr	101	88.1	0.278	H,T
Ethylene glycol	107-21-1	Gly	19	62.1	0.394	H,T
2-Butoxyethanol	111-76-2	Gly	171	118.2	0.207	H,T
1,2-Propanediol	57-55-6	Gly	188	76.1	0.321	
2-(2-Butoxyethoxy)ethanol	112-34-5	Gly	231	162.2	0.151	H,T
2-Propanone	67-64-1	Ket	56	58.1	0.421	
2-Butanone	78-93-3	Ket	80	72.1	0.339	H,T
4-Methyl-2-pentanone	108-10-1	Ket	117	100.2	0.244	H,T
Cyclohexanone	108-94-1	Ket	156	98.2	0.249	
1-Phenylethanone	98-86-2	Ket	202	120.2	0.203	H,T
Formaldehyde	50-00-0	Ald	-19	30.0	0.815	H,T
Acetaldehyde	75-07-0	Ald	20	44.1	0.554	H,T
Propionaldehyde	127-38-6	Ald	48	58.1	0.421	
Acrolein	107-02-8	Ald	53	56.1	0.436	H,T
Butanal	123-72-8	Ald	75	72.1	0.339	
3-Methylbutanal	590-86-3	Ald	90	86.1	0.284	
Pentanal	110-62-3	Ald	103	86.1	0.284	
Hexanal	66-25-1	Ald	128	100.2	0.244	
Heptanal	111-71-7	Ald	153	114.2	0.214	
2-Furaldehyde	98-01-1	Ald	162	96.1	0.254	
Octanal	124-13-0	Ald	174	128.2	0.191	
Benzaldehyde	100-52-7	Ald	179	106.1	0.230	
Nonanal	124-19-6	Ald	195	142.2	0.172	
Ethyl acetate	141-78-6	Estr	77	88.1	0.278	
Butyl acetate	123-86-4	Estr	126	116.2	0.210	
TMPD-MIB <sup>b</sup>	25265-77-4	Estr	244	216.3	0.113	
TMPD-DIB <sup>c</sup>	6846-50-0	Estr	280	286.4	0.085	
Diethyl phthalate	84-66-2	Estr	298	222.2	0.110	

**Table 4.** Continued.

Compound	CAS No.	Chem. Class <sup>a</sup>	BP (°C)	MW	µg/m <sup>3</sup> to ppb	Toxic Cat.
Formic acid	64-18-6	Acid	100	46.0	0.532	
Acetic acid	64-19-7	Acid	118	60.0	0.408	
Hexanoic acid	142-62-1	Acid	206	166.2	0.147	
n-Pentane	109-66-0	Alka	36	72.2	0.339	
2-Methylpentane	107-83-5	Alka	60	86.2	0.284	
3-Methylpentane	96-14-0	Alka	64	86.2	0.284	
n-Hexane	110-54-3	Alka	69	86.2	0.284	H,T
3-Methylhexane	589-34-4	Alka	91	100.2	0.244	
n-Heptane	142-82-5	Alka	98	100.2	0.244	
2,2,5-Trimethylhexane	3522-94-9	Alka	124	128.3	0.191	
n-Octane	111-65-9	Alka	126	114.2	0.214	
n-Nonane	111-84-2	Alka	151	128.3	0.191	
n-Decane	124-18-5	Alka	174	142.3	0.172	
n-Undecane	1120-21-4	Alka	196	156.3	0.156	
n-Dodecane	112-40-3	Alka	216	170.3	0.144	
n-Tridecane	629-50-5	Alka	236	184.4	0.133	
n-Tetradecane	629-59-4	Alka	252	198.4	0.123	
n-Pentadecane	629-62-9	Alka	270	212.4	0.115	
n-Hexadecane	544-76-3	Alka	287	226.4	0.108	
Methylcyclopentane	96-37-7	Cycl	72	84.2	0.290	
Cyclohexane	110-82-7	Cycl	81	84.2	0.290	T
Methylcyclohexane	108-87-2	Cycl	100	98.2	0.249	
Propylcyclohexane	1678-92-8	Cycl	155	126.2	0.194	
Butylcyclohexane	1678-93-9	Cycl	178	140.3	0.174	
1,3-Butadiene	106-99-0	Alke	-5	54.1	0.452	H,T
Isoprene	78-79-5	Terp	34	68.1	0.359	
α-Pinene	7785-70-8	Terp	155	136.2	0.180	
Camphene	5794-04-7	Terp	160	136.2	0.180	
3-Carene	13466-78-9	Terp	165	136.2	0.180	
β-Pinene	18172-67-3	Terp	166	136.2	0.180	
d-Limonene	5989-27-5	Terp	177	136.2	0.180	
p-Cymene	99-87-6	Terp	177	134.2	0.182	
Benzene	71-43-2	Arom	80	78.1	0.313	H,T
Toluene	108-88-3	Arom	111	92.1	0.265	H,T
Ethylbenzene	100-41-4	Arom	136	106.2	0.230	H,T
m/p-Xylene		Arom	139	106.2	0.230	
o-Xylene	95-47-6	Arom	143	106.2	0.230	H,T
Styrene	100-42-5	Arom	145	104.2	0.235	H,T

**Table 4.** Continued.

Compound	CAS No.	Chem. Class <sup>a</sup>	BP (°C)	MW	µg/m <sup>3</sup> to ppb	Toxic Cat.
Isopropylbenzene (cumene)	98-82-8	Arom	153	120.2	0.203	H,T
3/4-Ethyltoluene		Arom	159	120.2	0.203	
Propylbenzene	103-65-1	Arom	159	120.2	0.203	
4-Ethyltoluene	622-96-8	Arom	162	120.2	0.203	
2-Ethyltoluene	611-14-3	Arom	164	120.2	0.203	
1,3,5-Trimethylbenzene	108-67-8	Arom	165	120.2	0.203	
1,2,4-Trimethylbenzene	95-63-6	Arom	169	120.2	0.203	T
1,2,3-Trimethylbenzene	526-73-8	Arom	175	120.2	0.203	
Butylbenzene	104-51-8	Arom	183	134.2	0.182	
Naphthalene	91-20-3	Arom	218	128.2	0.191	H,T
4-Phenylcyclohexene	4994-16-5	Arom	252	158.2	0.155	
Chlorobenzene	108-90-7	ClAro	132	112.6	0.217	H,T
1,4-Dichlorobenzene	106-46-7	ClAro	174	147.0	0.166	H,T
1,2-Dichlorobenzene	95-50-1	ClAro	180	147.0	0.166	
1,2,4-Trichlorobenzene	120-82-1	ClAro	213	181.4	0.135	H,T
Vinyl chloride	75-01-4	Halo	-13	62.5	0.391	H,T
Bromomethane	74-83-9	Halo	4	94.9	0.258	H,T
Trichlorofluoromethane	75-69-4	Halo	24	137.4	0.178	T
Dichloromethane	75-09-2	Halo	40	84.9	0.288	H,T
Trichlorotrifluoroethane	76-13-1	Halo	48	187.4	0.130	T
Chloroform	67-66-3	Halo	62	119.4	0.205	H,T
1,1,1-Trichloroethane	71-55-6	Halo	74	133.4	0.183	H,T
Carbon tetrachloride	56-23-5	Halo	77	153.8	0.159	H,T
1,2-Dichloroethane	107-06-2	Halo	83	99.0	0.247	H,T
Trichloroethene	79-01-6	Halo	87	131.4	0.186	H,T
Tetrachloroethene	127-18-4	Halo	121	165.8	0.147	H,T
Carbon disulfide	75-15-0	Misc	46	76.1	0.321	H,T
Acrylonitrile	107-13-1	Misc	77	53.1	0.460	H,T
Pyridine	110-86-1	Misc	115	79.1	0.309	
d4 Siloxane <sup>d</sup>	556-67-2	Misc	175	296.6	0.082	
d5 Siloxane <sup>e</sup>	541-02-6	Misc	210	370.8	0.066	
Benzothiazole	95-16-9	Misc	231	135.2	0.181	

a. Alc = alcohol; Ethr = ether; Gly = glycol ether; Ket = ketone; Ald = aldehyde; Estr = acetates and other esters; Acid = carboxylic acid; Alka = alkane HC; Alke = alkene HC; Cycl = cyclic HC; Terp = terpene HC; Arom = aromatic HC; ClAro = chlorinated aromatic HC; Halo = halogenated aliphatic HC; Misc = miscellaneous category

b. 2,2,4-Trimethyl-1,3-pentanediol monoisobutyrate (combined isomers 1 & 3)

c. 2,2,4-Trimethyl-1,3-pentanediol diisobutyrate

d. Octamethylcyclotetrasiloxane

e. Decamethylcyclopentasiloxane

**Table 5.** Geometric mean (GM), median and mean VOC concentrations in existing residences. For multiple studies, concentrations are summarized as unweighted GMs. Best estimates are calculated as unweighted GMs of reported GM and median concentrations. Numbers of residential units comprising best estimates are shown..

Compound	Chem. Class	Concentration (ppb)			Best Est.	No. Units	Study ID <sup>a</sup>
		Value or GM	(No. Studies) Median	Mean			
1,4-Dioxane	Ethr	0.03		0.39	0.03	128	s
2-Propanone	Ket		15	30	15	93	hb
Formaldehyde	Ald		17	55	17	190	g,za
Acetaldehyde	Ald			3.0			za
Propionaldehyde	Ald			1.2			za
Acrolein	Ald	1.8			1.8	128	s
Butanal	Ald			0.66			za
3-Methylbutanal	Ald			0.41			za
Pentanal	Ald			0.91			za
2-Furaldehyde	Ald			0.27			za
Benzaldehyde	Ald			0.38			za
Formic acid	Acid			8.8			za
Acetic acid	Acid			24			za
2-Methylpentane	Alka		0.56		0.56	9	m
3-Methylpentane	Alka		0.33		0.33	9	m
n-Hexane	Alka		0.51	0.28	0.51	9	m,o
n-Heptane	Alka		0.26		0.26	9	m
n-Octane	Alka		0.24 (2)	0.70	0.24	19	m,v
n-Nonane	Alka		0.25 (3)	0.78 (2)	0.25	151	ha,hb,m
n-Decane	Alka		0.44 (2)	0.97 (2)	0.44	142	ha,hb
n-Undecane	Alka		0.28 (2)	1.3 (2)	0.28	142	ha,hb
n-Dodecane	Alka		0.17 (2)	0.55 (2)	0.17	142	ha,hb
n-Tridecane	Alka		0.14 (2)	0.31 (2)	0.14	142	ha,hb
Cyclohexane	Cycl		0.18		0.18		m
Methylcyclohexane	Cycl		0.40		0.40		m
1,3-Butadiene	Alke		0.23 (4)	0.31 (2)	0.23	302	g,hb,m,v
Isoprene	Terp		0.54 (2)	6.5	0.54	102	hb,m
$\alpha$ -Pinene	Terp			4.1			o
d-Limonene	Terp			3.6			o
p-Cymene	Terp			0.18			o
Benzene	Arom	1.0 (2)	0.87 (7)	1.5 (7)	0.90	980	a,c,f,g,ha,hb,m,o,s,v
Toluene	Arom		3.3 (6)	6.7 (5)	3.3	641	a,g,ha,hb,m,o,v
Ethylbenzene	Arom		0.53 (4)	1.4 (4)	0.53	160	ha,hb,m,o,v,

**Table 5.** Continued.

Compound	Chem. Class	Concentration (ppb)			Best Est.	No. Units	Study ID <sup>a</sup>
		Value or GM	(No. Studies) Median	Mean			
m/p-Xylene	Arom	1.0	1.4 (3)	2.9 (3)	1.3	437	a,m,s,v
o-Xylene	Arom	0.44	0.53 (5)	1.1 (6)	0.51	579	a,ha,hb,m,o,s,v
Styrene	Arom	0.18	0.25 (5)	0.35 (6)	0.23	579	a,ha,hb,m,o,s,v
Isopropylbenzene	Arom		0.07 (2)	0.12 (2)	0.07	142	ha,hb
Propylbenzene	Arom		0.11 (2)	0.25 (2)	0.11	142	ha,hb
4-Ethyltoluene	Arom		0.55		0.55	9	m
2-Ethyltoluene	Arom		0.45		0.45	9	m
1,3,5-Trimethylbenz	Arom		0.25 (3)	0.51 (3)	0.25	151	ha,hb,m,o
1,2,4-Trimethylbenz	Arom		0.79	2.4	0.79	9	m,o
1,2,3-Trimethylbenz	Arom		0.20	0.42	0.20	142	ha,hb
Butylbenzene	Arom		0.03 (2)	0.06 (2)	0.03	142	ha,hb
Naphthalene	Arom		0.09	0.35 (2)	0.09	10	o,v
4-Phenylcyclohexene	Arom			0.02			hb
1,4-Dichlorobenzene	ClAro	0.18	0.08 (4)	1.3 (6)	0.09	570	a,ha,hb,o,s,v
1,2-Dichlorobenzene	ClAro			11			v
Vinyl chloride	Halo	0.01 (2)	<0.01		0.01	161	f,k
Dichloromethane	Halo	0.88 (2)	2.1 (2)	6.4 (4)	1.4	299	f,k,o,s,v
Chloroform	Halo	0.43	0.19 (5)	0.37 (5)	0.22	613	a,c,f,hb,m,o,v
1,1,1-Trichloroethane	Halo	0.26 (3)	0.36 (4)	2.4 (3)	0.35	598	a,f,k,m,s,v
Carbon tetrachloride	Halo	0.09	0.09 (2)	0.09 (2)	0.09	147	m,s,v
1,2-Dichloroethane	Halo	0.01 (2)	0.01	0.06 (3)	0.01	161	f,ha,hb,k,o
Trichloroethene	Halo	0.04 (3)	0.08 (8)	0.23 (7)	0.07	1100	a,c,f,g,ha,hb,k,m,o,s,v
Tetrachloroethene	Halo	0.13 (3)	0.15 (7)	0.41 (6)	0.14	910	a,c,f,ha,hb,k,m,s,v
Pyridine	Misc		0.17 (2)	0.54 (2)	0.17	142	ha,hb

a. IDs of all studies reporting values are indicated; study IDs defined in Table 1

**Table 6.** Upper percentile (90<sup>th</sup> and 95<sup>th</sup>) and maximum VOC concentrations in existing residences. Values are shown as ranges for compounds reported by three or more studies. Maximum concentrations for multiple studies are summarized as unweighted GMs.

Compound	Chem. Class	Concentration (ppb)			GM Max	Study ID <sup>a</sup>
		Value or Range (No. Studies)		Max		
		90%ile	95%ile	Max		
1,4-Dioxane	Ethr	0.18		39		s
2-Propanone	Ket			280		hb
Formaldehyde	Ald	37		100, 330	180	za,g
Acetaldehyde	Ald			16		za
Propionaldehyde	Ald			5.6		za
Acrolein	Ald	9.2		13		s
Butanal	Ald			2.4		za
3-Methylbutanal	Ald			1.2		za
Pentanal	Ald			2.0		za
2-Furaldehyde	Ald			1.5		za
Benzaldehyde	Ald			1.3		za
Formic acid	Acid			19		zb
Acetic acid	Acid			81		zb
n-Octane	Alka	2.4		3.6		v
n-Nonane	Alka			3.2, 14	6.7	ha,hb
n-Decane	Alka			7.9, 20	13	ha,hb
n-Undecane	Alka			9.2, 39	19	hb,ha
n-Dodecane	Alka			4.1, 18	8.7	hb,ha
n-Tridecane	Alka			2.1, 5.2	3.3	ha,hb
1,3-Butadiene	Alke	0.17, 0.53		0.27-5.5 (4)	1.7	g,hb,s,v
Isoprene	Terp			24		hb
Benzene	Arom	1.9-4.1 (4)	4.0	8.4-41 (7)	41	a,c,f,g,ha,hb,s,v
Toluene	Arom	7.8, 13		12-240 (5)	47	a,g,ha,hb,v
Ethylbenzene	Arom	3.0		5.9-40 (3)	11	ha,hb,v
m/p-Xylene	Arom	2.8, 13	5.0	28-120 (3)	67	a,s,v
o-Xylene	Arom	1.3, 3.7	1.6	7.9-43 (5)	14	a,ha,hb,s,v
Styrene	Arom	0.50, 0.89	0.56	1.7-33 (5)	5.5	a,ha,hb,s,v
Isopropylbenzene	Arom			0.66, 2.1	1.2	ha,hb
Propylbenzene	Arom			2.0, 6.1	3.5	ha,hb
1,3,5-Trimethylbenz	Arom			3.1, 14	6.5	ha,hb
1,2,3-Trimethylbenz	Arom			2.2, 7.9	4.2	ha,hb
Butylbenzene	Arom			0.3, 2.3	0.80	ha,hb
Naphthalene	Arom	0.41		0.95		v
4-Phenylcyclohexene	Arom			0.29		hb
Chlorobenzene	ClAro			0.11		s

**Table 6.** Continued.

Compound	Chem. Class	Concentration (ppb)			GM Max	Study ID <sup>a</sup>
		Value or Range (No. Studies)		Max		
		90%ile	95%ile			
1,4-Dichlorobenzene	ClAro	0.34, 4.7	0.57	16-50 (5)	26	a,ha,hb,s,v
1,2-Dichlorobenzene	ClAro	0.04		0.09		v
Vinyl chloride	Halo		0.04	0.13, 0.20	0.16	f,k
Bromomethane	Halo			0.72		s
Dichloromethane	Halo	46, 150	4.6	3.5-490 (4)	74	f,k,s,v
Chloroform	Halo	0.83, 1.3	1.2	1.2-4.3 (4)	2.6	a,c,f,hb,v
1,1,1-Trichloroethane	Halo	2.2, 12	1.4, 3.2	2.6-180 (5)	28	a,f,k,s,v
Carbon tetrachloride	Halo	0.11, 0.15		0.20, 0.41	0.29	s,v
1,2-Dichloroethane	Halo		0.04	0.10-2.4 (4)	0.26	f,ha,hb,k
Trichloroethene	Halo	0.21-0.42 (4)	0.13, 0.26	0.58-5.0 (7)	1.9	a,c,f,g,ha,hb, k,s,v
Tetrachloroethene	Halo	0.34-1.0 (3)	0.72, 1.0	0.76-65 (7)	7.0	a,c,f,ha,hb,k, s,v
Pyridine	Misc			1.5, 2.7	2.0	hb,ha
Acrylonitrile	Misc			12		s

a. IDs of all studies reporting values are indicated; study IDs defined in Table 1



**Table 7.** Geometric mean (GM) and maximum VOC concentrations in new single-family houses. Concentrations reported by both studies are summarized as unweighted GMs.

Compound	Chem. Class	Concentration (ppb)		Study ID <sup>a</sup>
		GM	Maximum	
1-Butanol	Alc	7.7	21	ho
Phenol	Alc	1.8	5.8	ho
2-Ethyl-1-hexanol	Alc	<1.5		ho
1-Octanol	Alc	<1.5		ho
BHT	Alc	<0.5		ho
Ethylene glycol	Gly	48	490	ho
2-Butoxyethanol	Gly	2.9	12	ho
1,2-Propanediol	Gly	4.8	360	ho
DEGBE	Gly	<1.5		ho
2-Propanone	Ket	28	210	1
2-Butanone	Ket	6.4	37	ho,l
4-Methyl-2-pentanone	Ket	<0.5		ho
Cyclohexanone	Ket	<0.5		ho
1-Phenylethanone	Ket	<1.5		ho
Formaldehyde	Ald	32	62	ho,l
Acetaldehyde	Ald	14	43	ho,l
Propionaldehyde	Ald	4.4	19	1
Butanal	Ald	0.30	2.0	1
Pentanal	Ald	2.5	9.8	1
Hexanal	Ald	15	36	ho,l
Heptanal	Ald	1.9	4.9	ho
2-Furaldehyde	Ald	<1.5		ho
Octanal	Ald	2.6	7.2	ho
Benzaldehyde	Ald	1.3	3.7	1
Nonanal	Ald	3.1	7.6	ho
Ethyl acetate	Estr	<0.5		ho
Butyl acetate	Estr	1.4	14	ho
TMPD-MIB <sup>b</sup>	Estr	5.6	25	ho
TMPD-DIB <sup>c</sup>	Estr	1.3	7.2	ho
Acetic acid	Acid	71	280	ho
Hexanoic acid	Acid	1.1	5.5	ho
n-Heptane	Alka	<1.5		ho
n-Nonane	Alka	<1.5		ho
n-Decane	Alka	3.9	22	ho
n-Undecane	Alka	2.3	9.1	ho
n-Dodecane	Alka	3.6	11	ho
n-Tridecane	Alka	5.2	21	ho
n-Tetradecane	Alka	<5.0		ho

**Table 7.** Continued.

Compound	Chem. Class	Concentration (ppb)		Study ID <sup>a</sup>
		GM	Maximum	
n-Pentadecane	Alka	<0.5		ho
n-Hexadecane	Alka	<0.5		ho
Methylcyclohexane	Cycl	<1.5		ho
Propylcyclohexane	Cycl	<0.5		ho
Butylcyclohexane	Cycl	<0.5		ho
$\alpha$ -Pinene	Terp	23	60	ho
Camphene	Terp	<1.5		ho
3-Carene	Terp	4.1	15	ho
$\beta$ -Pinene	Terp	8.0	26	ho
d-Limonene	Terp	4.3	12	ho
Benzene	Arom	0.47	6.1	1
Toluene	Arom	8.5	68	ho,l
Ethylbenzene	Arom	0.32	2.1	1
m/p-Xylene	Arom	2.1	11	ho,l
o-Xylene	Arom	0.64	4.4	1
Styrene	Arom	0.59	7.8	ho,l
1,3,5-Trimethylbenzene	Arom	<0.5		ho
1,2,4-Trimethylbenzene	Arom	<1.5		ho
Naphthalene	Arom	<1.5		ho
4-Phenylcyclohexene	Arom	<0.5		ho
Chlorobenzene	ClAro	0.17	0.32	1
1,2-Dichlorobenzene	ClAro	0.22	0.54	1
Trichlorofluoromethane	Halo	0.55	1.3	1
Dichloromethane	Halo	0.29	2.3	1
Trichlorotrifluoroethane	Halo	0.17	1.2	1
Chloroform	Halo	0.06	0.47	1
1,1,1-Trichloroethane	Halo	0.46	2.3	1
Trichloroethene	Halo	0.06	0.43	1
Tetrachloroethene	Halo	0.06	0.29	1
Benzothiazole	Misc	<0.5		ho

a. Study IDs defined in Table 2

b. 2,2,4-Trimethyl-1,3-pentanediol monisobutyrate (combined isomers 1 & 3)

c. 2,2,4-Trimethyl-1,3-pentanediol diisobutyrate

**Table 8.** Central tendency (GM or median) and maximum VOC concentrations in existing office buildings. Concentrations reported by multiple studies are summarized as unweighted GMs.

Compound	Chem. Class	Central Tendency		Maximum	
		Conc. (ppb)	Study ID <sup>a</sup>	Conc. (ppb)	Study ID <sup>a</sup>
Ethanol	Alc	19	d	130	d
2-Propanol	Alc	2.3	d	62	d
1-Butanol	Alc			5.0	gi
Phenol	Alc			2.5	gi
2-Ethyl-1-hexanol	Alc			9.0	gi
<i>t</i> -Butyl methyl ether	Ethr			8.3	gi
2-Butoxyethanol	Gly	0.65	d,gi,sh	14	d,gi,sh
2-Propanone	Ket	7.4	d,gi	33	d,gi
2-Butanone	Ket			6.1	gi
4-Methyl-2-pentanone	Ket			6.8	gi
1-Phenylethanone	Ket	1.0	d	2.8	d,gi
Pentanal	Ald	0.17	d	1.3	d,gi
Hexanal	Ald	0.47	d,gi	2.4	d,gi
Benzaldehyde	Ald	0.47	d	1.5	d
Nonanal	Ald	0.52	gi	1.4	gi
Ethyl acetate	Estr	0.34	d	7.4	d,gi
Butyl acetate	Estr	0.21	d	3.9	d,gi
TMPD-MIB <sup>b</sup>	Estr	0.06	sh	3.2	gi
TMPD-DIB <sup>c</sup>	Estr	0.20	sh	0.88	gi,sh
Diethyl phthalate	Estr	<0.01	sh	0.66	sh
n-Pentane	Alka	2.5	d	8.9	d
3-Methylpentane	Alka			4.5	gi
n-Hexane	Alka	0.62	d,gi	3.1	d,gi
3-Methylhexane	Alka	0.34	d	0.71	d
n-Heptane	Alka	0.40	d	0.72	d
2,2,5-Trimethylhexane	Alka	0.14	d	0.31	d
n-Octane	Alka	0.11	d,sh	13	d,gi
n-Nonane	Alka	0.36	d	5.6	d,gi
n-Decane	Alka	0.69	d,sh	5.8	d,gi
n-Undecane	Alka	0.65	d	10	d,gi
n-Dodecane	Alka	0.86	d,gi,sh	16	d,gi
n-Tetradecane	Alka	1.4	sh		
n-Pentadecane	Alka	1.5	sh		
n-Hexadecane	Alka	1.2	sh		
Methylcyclopentane	Cycl	0.45	d	1.2	d
Methylcyclohexane	Cycl	0.38	d	0.76	d
$\alpha$ -Pinene	Terp	0.04	sh	1.5	gi

**Table 8.** Continued.

Compound	Chem. Class	Central Tendency		Maximum	
		Conc. (ppb)	Study ID <sup>a</sup>	Conc. (ppb)	Study ID <sup>a</sup>
d-Limonene	Terp	1.2	d,gi,sh	12	d,gi
Benzene	Arom	1.0	d,gi	3.8	d,gi
Toluene	Arom	2.1	d,gi,sh	40	d,gi
Ethylbenzene	Arom	0.48	d,sh	2.6	d,gi
m/p-Xylene	Arom	1.4	d,gi,sh	10	d,gi
o-Xylene	Arom	0.66	d	3.5	d,gi
Styrene	Arom	0.40	d	1.2	d,gi
3/4-Ethyltoluene	Arom	0.75	d	1.7	d
4-Ethyltoluene	Arom			2.2	gi
2-Ethyltoluene	Arom	0.48	d	0.98	d
1,3,5-Trimethylbenzene	Arom	0.38	d	1.1	d,gi
1,2,4-Trimethylbenzene	Arom	0.88	d,sh	2.9	d,gi
1,2,3-Trimethylbenzene	Arom	0.29	d	1.1	d
Naphthalene	Arom			1.9	gi
4-Phenylcyclohexene	Arom			0.09	gi
Chlorobenzene	ClAro			0.15	gi
1,4-Dichlorobenzene	ClAro	0.03	sh	7.0	gi,sh
1,2-Dichlorobenzene	ClAro			2.2	gi
1,2,4-Trichlorobenzene	ClAro			0.16	gi
Trichlorofluoromethane	Halo	0.75	d	13	d,gi
Dichloromethane	Halo	0.40	d	65	d,gi
Trichlorotrifluoroethane	halo			3.0	gi
Chloroform	Halo			2.0	gi
1,1,1-Trichloroethane	Halo	1.6	d,gi	77	d,gi
Carbon tetrachloride	Halo			0.62	gi
Trichloroethene	Halo	1.8	d	4.8	d,gi
Tetrachloroethene	Halo	0.47	d,sh	3.8	d,gi
Carbon disulfide	Misc			5.8	gi
d4 Siloxane <sup>d</sup>	Misc	0.84	sh		
d5 Siloxane <sup>e</sup>	Misc	2.6	sh		

a. Study IDs defined in Table 3

b. 2,2,4-Trimethyl-1,3-pentanediol monoisobutyrate (combined isomers 1 & 3)

c. 2,2,4-Trimethyl-1,3-pentanediol diisobutyrate

d. Octamethylcyclotetrasiloxane

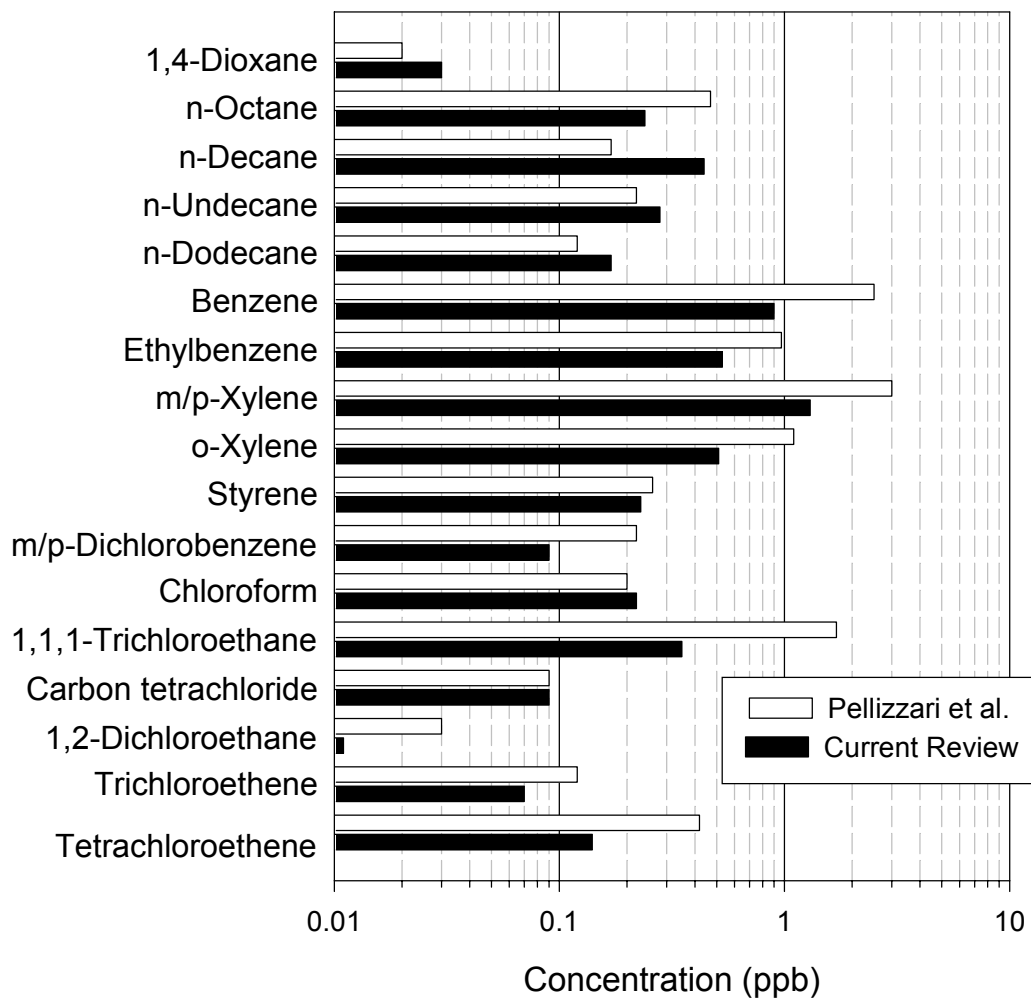
e. Decamethylcyclopentasiloxane

**Table 9.** Comparison of central tendency and maximum VOC concentrations between unoccupied new residences and occupied existing residences. Only VOCs with substantial differences are shown. Concentrations that are more than three times higher in new residences are indicated in bold. Concentrations that are more than three times lower in new residences are indicated in underlined italics.

Compound	Class	Concentration (ppb)			
		Central Tendency		Maximum	
		Existing	New	Existing	New
Formaldehyde	Ald	17	32	180	62
Acetaldehyde	Ald	3.0	<b>14</b>	16	43
Propionaldehyde	Ald	1.2	<b>4.4</b>	5.6	<b>19</b>
Pentanal	Ald	0.91	2.5	2.0	<b>9.8</b>
Benzaldehyde	Ald	0.38	<b>1.3</b>	1.3	3.7
Acetic acid	Acid	24	71	81	<b>280</b>
n-Decane	Alka	0.44	<b>3.9</b>	13	22
n-Undecane	Alka	0.28	<b>2.3</b>	19	9.1
n-Dodecane	Alka	0.17	<b>3.6</b>	8.7	11
n-Tridecane	Alka	0.14	<b>5.2</b>	3.3	<b>21</b>
$\alpha$ -Pinene	Terp	4.1	<b>60</b>		
d-Limonene	Terp	3.6	<b>12</b>		
Ethylbenzene	Arom	0.53	0.32	11	<u>2.1</u>
m/p-Xylene	Arom	1.3	2.1	67	<u>10</u>
o-Xylene	Arom	0.51	0.64	14	<u>4.4</u>
1,2-Dichlorobenzene	ClAro			0.09	<b>0.54</b>
Dichloromethane	Halo	1.4	<u>0.29</u>	74	<u>2.3</u>
Chloroform	Halo	0.22	<u>0.06</u>	2.6	<u>0.47</u>
1,1,1-Trichloroethane	Halo	0.35	0.46	28	<u>2.3</u>
Trichloroethene	Halo	0.07	0.06	1.9	<u>0.43</u>
Tetrachloroethene	Halo	0.14	0.06	7.0	<u>0.29</u>

**Table 10.** Comparison of central tendency and maximum VOC concentrations between office buildings and existing residences. Only compounds with substantial differences are shown. Concentrations that are more than a factor of three higher in office buildings are indicated in bold. Concentrations that are more than a factor of three lower in office buildings are indicated in underlined italics.

Compound	Class	Concentration (ppb)			
		Central Tendency Resid.	Office	Maximum Resid.	Office
2-Propanone	Ket	15	7.4	280	<u>33</u>
Pentanal	Ald	0.91	<u>0.17</u>	2.0	1.3
n-Octane	Alka	0.24	0.11	3.6	<b>13</b>
n-Dodecane	Alka	0.17	<b>0.86</b>	8.7	16
$\alpha$ -Pinene	Terp	4.1	<u>0.04</u>		
d-Limonene	Terp	3.6	<u>1.2</u>		
Benzene	Arom	0.90	1.0	18	<u>3.8</u>
Ethylbenzene	Arom	0.53	0.48	11	<u>2.6</u>
m/p-Xylene	Arom	1.3	1.4	67	<u>10</u>
o-Xylene	Arom	0.51	0.66	14	<u>3.5</u>
1,3,5-Trimethylbenzene	Arom	0.25	0.38	6.5	<u>1.1</u>
1,2,3-Trimethylbenzene	Arom	0.20	0.29	4.2	<u>1.1</u>
4-Phenylcyclohexene	Arom			0.29	<u>0.09</u>
1,4-Dichlorobenzene	ClAro	0.09	<u>0.03</u>	26	<u>7.0</u>
1,2-Dichlorobenzene	ClAro			0.09	<b>2.2</b>
Dichloromethane	Halo	1.4	<u>0.40</u>	74	65
1,1,1-Trichloroethane	Halo	0.35	<b>1.6</b>	28	77
Trichloroethene	Halo	0.07	<b>1.8</b>	1.9	4.8
Tetrachloroethene	Halo	0.14	<b>0.47</b>	7.0	3.8



**Figure 1.** Comparison of central tendency VOC concentrations in existing residences from current review with unweighted GM VOC concentrations from the 1980-84 U.S. EPA TEAM studies (Pellizzari *et al.*, 1986)