LBL-# 4598

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

APPLIED SCIENCE DIVISION

Presented at the Total Exposure Assessment Methodology:
A New Horizon Symposium, Las Vegas, NV,
November 28–30, 1989, and to be published
in the Proceedings

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January 1990

APPLIED SCIENCE
DIVISION

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

LBL-28321

Presented at the Air and Waste Management
Association International Symposium on "Total
Exposure Assessment Methodology: A New Horizon,"
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This work was supported by the Director, Office of Energy Research, Office of Health and Environmental Research, Human Health and Assessments Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 and by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Buildings Systems Division of the U.S. Department of Energy under contract DE-AC03-76SF00098.

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Volatile organic compounds (VOC) in office buildings originate from multiple sources, such as outdoor air, building materials, occupants, office supplies, and office equipment. Many of the VOC found in office buildings are also present in environmental tobacco smoke (ETS), e.g., benzene, toluene, formaldehyde. Measurements made to date in office buildings have been interpreted by some to imply that the contributions of ETS to VOC exposures in office buildings are small. We have made a first order estimate of the contributions of ETS to VOC concentrations based on the VOC content of ETS and a time-dependent mass-balance model. Four different ventilation-infiltration scenarios were modeled for a typical office building.

The results indicate that ETS can contribute significantly to total indoor levels of VOC in office buildings, even under moderate ventilation conditions. Ranges of concentrations for three of the four modeled scenarios substantially overlapped measured ranges of the compounds in office buildings. Average daytime concentrations of benzene from ETS, for example, for three of the four modeled scenarios, ranged from 2.7 to 6.2 $\mu g\ m^{-3}$, compared to reported measurements of 1.4 to 8.1 $\mu g\ m^{-3}$ for four office buildings. Under a "worst reasonable" case scenario, the average modeled ETS-contributed concentration of benzene was 33.9 $\mu g\ m^{-3}$ for a 40-hour work week.

INTRODUCTION

Environmental tobacco smoke, a mixture of sidestream and exhaled mainstream smoke, consists of particles and gases and contains over 3800 identified compounds.[1] The extent to which non-smoking office workers are exposed to ETS and various ETS components from smokers in the same building has been a point of controversy in recent years. The volatile organic compounds (VOC) in ETS have been the focus of at least two recent field studies. Proctor[2] measured VOC in the offices of smokers and non-smokers in a 16-story air-conditioned building in Great Britain. Each office was sampled on five separate occasions, on different days of the week and times of the day. Only ethylbenzene, limonene and n-octane were significantly higher, on average, in the offices of smokers compared to non-smokers. However, since approximately 80% of the air in the building was recirculated,[3] it cannot be inferred from this study that the contribution of ETS to VOC exposures of non-smokers was negligible. Bayer and Black[4] measured nicotine and VOC in smokers' and non-smokers' offices in three buildings. Nicotine concentrations were higher in the offices of smokers than non-smokers. However, there were no clear differences in VOC concentrations between smokers' and non-smokers' offices. Again, no inferences about VOC from ETS can be drawn from the study, as the authors have pointed out.

It is difficult to estimate exposures of non-smokers to VOC from ETS using the field study approach because many of the VOC originate from sources other than ETS, and because ventilation systems frequently circulate ETS components throughout the building so that spatial variations in ETS components are reduced. Thus, for example, the concentrations of benzene in offices of both smokers and non-smokers result from the combined contributions of outdoor air (largely motor vehicle emissions), ETS, and other indoor sources such as building materials. Resolving the contributions of the major VOC sources to indoor concentrations is only possible either through receptor-source apportionment modeling or through estimates of the contribution of each source, including ETS, based on emission rates and a mass-balance model.

The purpose of this investigation was to provide a first-order estimate of the range of contributions of ETS to VOC concentrations in office buildings under various ventilation conditions through the use of a mass-balance model and to evaluate the significance of such contributions relative to VOC concentrations measured in office buildings.

METHODS

Indoor concentrations of selected VOC from ETS were estimated using a time-dependent mass-balance equation:

$$C = C_o\,(e^{-Qt}) + \frac{S\,(1-e^{-Qt})}{QV} \qquad (1)$$

where C = the concentration ($\mu g\ m^{-3}$) of any given VOC at time t (h), C_o = the initial concentration of any VOC, Q = the air exchange rate for the building (h^{-1}), i.e., the outside air supply rate divided by the building volume, S = the source emission rate ($\mu g\ h^{-1}$) for the building and V = the air volume of the building (m^3). The mass-balance equation was solved for each hour of the week. Concentration in the previous hour was used as the value for C_o when calculating each hourly concentration.

A number of assumptions were made in applying the model. Equation (1) is based on the first-order assumption of perfectly mixed air within the building. It was assumed that the building HVAC system was operated 10 hours per day for 5 days a week and that the system was turned off for 14 hours on weekday nights and for 48 hours over the weekend. When the HVAC system was off, it was assumed that the only ventilation was by infiltration through the building shell. This latter assumption is valid for moderate weather. In very cold or hot weather, building HVAC systems are generally operated continuously at some level to distribute heat or cool air throughout the building. Under these conditions, much of the air is recirculated. Equation (1) would still apply with appropriate values for air exchange rates during operating and off-hours.

It was assumed that there are no losses of VOC through sorption or chemical reaction on indoor surfaces. This is a reasonable assumption for the non-polar hydrocarbons such as benzene and toluene. Such compounds are likely to reach a quasi-equilibrium between sorption and desorption under a standard operating condition. This assumption, however, is probably not appropriate for more reactive compounds such as aldehydes, 1,3-butadiene and limonene. Consequently, the calculated concentrations for these compounds must be regarded as upper limits.

The model was applied to a representative office building whose size and occupancy were based on a survey of 15 intermediate-size office buildings.[5] (The authors designated the 15 buildings as large. However, comparison with data from other studies, also included in their report, suggests that these 15 buildings are more appropriately designated intermediate in size). The average characteristics of these buildings are summarized in Table I. The average characteristics of 70 small office buildings and the characteristics of a prototype large (high rise) office building have been included for comparison.[5] The large building prototype is used by the California Energy Commission for energy-use simulations.

It was assumed that smokers comprise 30% of the office workforce,[6,7] each of whom smokes an average of 2 cigarettes per hour.[8] These assumptions, while not exact or universal, are within the range of reported data. The smoking rate assumption of 2 cigarettes per hour may, in fact, be low. Sterling et al.[9] reported an average of 2.9 cigarettes per hour per person, based on a survey of smoking office workers. More recently, Moschandreas[10] measured an average of 2.4 cigarettes per hour per smoker, based on counts of cigarette butts in an office building.

Most of the VOC emission factors used in the model were taken from the chamber measurements of Jermini et al.[11] and are presented in Table II. These data were used because they are the most complete and because the samples were collected from chambers rather than from a sidestream smoke sampler. Emission factors reported for selected VOC by two other investigators are also included in Table II. For those VOC for which there is more than one determination, the emissions factors are generally in reasonable agreement. If emission factors for a compound were not reported by Jermini et al., data from the other investigators were used.[12,13] The emission factors for formaldehyde and acetaldehyde were taken from the data reported recently from Schlitt and Knoppel[12].

Source emission rates ($\mu g\ h^{-1}$) were calculated from the emission factors (μg cigarette^{-1}), the average smoking rate per smoker, the number of occupants per square meter of floor area, assuming that 30% of the occupants are smokers, and the total floor area of the building. The latter was usually taken as 23.8 m^2, the average measured for 15 intermediate-sized buildings.[5]

Four different ventilation-infiltration scenarios, presented in Table III, were modeled. Each scenario has characteristic values for the air changes per hour during HVAC operating (daytime) and non-operating (nighttime) hours, designated a_D and a_N, respectively. The first set of values (a_D=0.13 h^{-1}, a_N=0.10 h^{-1}) was selected to represent low air-exchange operation of a "tight" building and a "worst reasonable" case scenario. These air exchange rates were measured in a small office building (6,420 m^2 floor area) in Huron, South Dakota by Grot and Persily [14] for their study of eight federal buildings. These values were the lowest among the eight buildings and the lowest of those measured for this particular building. Air infiltration rates as low as 0.1 to 0.2 have also been reported for other buildings[15,16] for small values of indoor-outdoor temperature differences. To estimate the concentrations of VOC contributed by ETS under this "worst reasonable" case scenario, we further assumed a high occupancy of 17.1 m^2 per person, an elevated smoking rate of 2.4 cigarettes per cigarette per smoker and an effective zone height of only 2.2 meters. This occupancy is used by the California Energy Commission in its 1985 definition of a high-rise office building for energy-use simulations.[5] The effective zone height is based on a ceiling height of 2.6 meters times a factor of 0.85 to correct for the volume of interior space occupied by furnishings.

In the second scenario, titled ASHRAE, an operating-hours ventilation rate of a_D=0.47 h^{-1} was used. This ventilation rate is based on the ASHRAE 62-1989 Standard[17] of 20 cfm (34 m^3 h^{-1}) of outside air per occupant. It is noteworthy that ASHRAE 62-1989 is a design (as distinct from an operating) guideline. In practice, minimum air change rates are sometimes lower[14-16,18] but are usually higher. The non-operating hours air exchange rate for this scenario is the average value of infiltration measurements reported by Grot and Persily for 8 federal buildings.[14] The effective zone heights for this scenario and scenarios 3 and 4, are assumed to be 3.0 meters.

The "leaky building" scenario (a_D=0.62 h^{-1}, a_N=0.52 h^{-1}) represents a "leaky" building with a low daytime air-exchange rate. This pair of air-exchange rates was measured for an eight-story building (17,300 m^2 floor area) in Norfolk, Virginia.[14] The operating hours ventilation rate used for the fourth scenario, "PNW buildings" (a_D = 1.27 h^{-1}), is the geometric mean of measurements made in 38 office buildings in the Pacific Northwest by Turk et al.[18] The non-operating hours infiltration value is again the average value of the infiltration measurements reported by Grot and Persily.[14]

RESULTS AND DISCUSSION

Figure 1 presents the hourly concentration profiles of ETS-contributed benzene in indoor air under the four different ventilation-infiltration scenarios for an entire week. The variations in the concentrations of other VOC are not shown but would be proportional to their emission factors shown in Table II.

As expected, concentrations of ETS-contributed benzene are not very sensitive to the infiltration rate (0.1 h^{-1} and up) during non-operating hours, but are very sensitive to the ventilation rate during operating hours. The peak concentrations of ETS-contributed benzene occur during operating hours when smokers are present. These peak concentrations vary from 47.0 $\mu g\ m^{-3}$ (Friday) under the "worst reasonable" case scenario to a low of 2.8 $\mu g\ m^{-3}$ (Monday) under the most optimal ventilation conditions (a_D=1.27 ach, a_N=0.41 ach) modeled. The peak concentrations for the "worst reasonable" case do not reach a steady-state value during the workday (Figure 1). Thus, concentrations measured using samples collected over short intervals, even in mid-day or late afternoon, would not generally be representative of the average exposure of a worker. For the "worst reasonable case" scenario, the concentrations of benzene do not fall below about 10 $\mu g\ m^{-3}$ during weekday nights. For the other scenarios, concentrations return to near zero at night.

Table IV compares the estimated 40-hour mean concentrations of selected VOC contributed by ETS to ranges of concentrations measured in a small number of office buildings. These measurements are for daytime (operating) hours. The estimated concentrations for scenarios 2, 3 and 4 all fall within the ranges of measured values. Even for the "worst reasonable" case, the modeled concentrations for five of the eight compounds shown in Table IV are close to the maximum measured concentrations. The measured values, of course, include contributions from all sources. Nonetheless, the results clearly indicate that ETS can be a substantial source of VOC in office buildings even under the ASHRAE ventilation standard.

Under the "worst reasonable" case scenario, the predicted value for formaldehyde of 178 $\mu g\ m^{-3}$, is greater than the 120 $\mu g\text{-}m^{-3}$ Canadian residential indoor air guideline value[22] and about two and a half times greater than the indoor air guideline recommended by the California Department of Health Services.[23] This predicted concentration is considerably greater than the maximum measured by Turk et al.[18] for 38 office buildings (See Table IV). The model, however, does not take into account losses of formaldehyde to interior surfaces, which may be substantial. The average deposition rate measured for formaldehyde in a chamber was 0.4 $\pm$ 0.24 h^{-1},[23] but deposition rates for formaldehyde in office buildings have not been reported, to our knowledge. Inclusion of a deposition rate of this magnitude in the model would result in substantially lower predicted indoor concentrations for formaldehyde. Inclusion of deposition rates in the model would also give lower estimated concentrations for for acrolein, acetaldehyde and 1,3-butadiene, particularly under low to moderate ventilation rates.

In principle, it should be possible to estimate the contribution of ETS to total measured VOC concentrations based on indoor air measurements of gas-phase nicotine or some other unique tracer of ETS and the ratio of nicotine (or tracer) to VOC in ETS. Such an estimate might require corrections for losses of nicotine to surfaces. Unfortunately, there are few field studies in office buildings in which both VOC and nicotine have been measured. In the two studies of which we are aware, either the sampling intervals for VOC and nicotine did not match[4] or only concentration means and ranges were reported.[2]

From equation (1), it can be seen that the modeled average concentrations are directly proportional to the source emission rates, S, inversely proportional to the building volume, V, and rapidly decrease with increasing air exchange rates, Q. The source emission rates, in turn, depend directly on: the emission factors, the number of cigarettes per hour per smoker, the fraction of smokers, and the number of workers per square meter of floor space. Each of the variables affecting the emission rates is likely to be within a factor of two of the values used here. The effective ceiling height is the only source of variation in the building volume. Ceiling heights typically range from about 2.6 m to 3.7 m.[25] Thus, even with a correction for the volume occupied by furnishings, this factor will be within about $\pm$ 25% of the value used here. Ventilation rates, however, can vary over more than an order of magnitude. Consequently, ventilation rates have the most significant effect on the modeled concentrations.

Two other processes, not taken into account in this analysis, can also affect the accuracy of the concentrations predicted by the model. If there are deposition losses for any VOC, this will substantially reduce the indoor concentration. Finally, we have assumed complete and uniform mixing in the building. When this condition is not met, there will be regions of the building with both higher and lower concentrations than those modeled here.

In summary, the results of a mass-balance model have indicated that the contributions of ETS to VOC concentrations in office buildings can be substantial for average ventilation conditions, even when the ventilation rates meet the ASHRAE standard. At very low, but realistic, ventilation rates, the contribution of ETS to VOC can be much higher.

ACKNOWLEDGMENTS

This work was supported by the Director, Office of Energy Research, Office of Health and Environmental Research, Human Health and Assessments Division of the U.S. Dept. of Energy under Contract No. DE-AC03-76SF00098 and by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Buildings Systems Division of the U.S. Department of Energy under contract DE-AC03-76SF00098.

The authors gratefully acknowledge the many helpful comments and suggestions of W. J. Fisk, A.V. Nero, J.R. Girman and G. W. Traynor during the preparation of this manuscript.

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Table I. Some size and occupancy characteristics of office buildings[a.]

	Number of Buildings	Average Occupancy m^2/person	Average Floor Area, m^2
Small	70	21.7	353
Intermediate	15	23.8	6,150
Prototype High-Rise[b.]	--	17.1	32,570

a. Akbari et al., 1989.

b. Prototype used by The California Energy Commission for energy usage simulations.

Table II. Emission factors for volatile organic compounds in environmental tobacco smoke

<u>µg/cigarette</u>

Compound	Reference 11[a.]	Reference 12[b.]	Reference 13
Benzene	431 ± 23		500
Toluene	848 ± 27		
o-Xylene	478 ± 0		
m-Xylene	200 ± 30		
Styrene	105 ± 9		
Acetone	1080 ± 18	1800 ± 280	
2-Butanone	722 ± 20	835 ± 135	
2-Pentanone	56 ± 5		
Methyl vinyl ketone	330 ± 61		
2,3-Butadione	687 ± 124		
Acrolein	860 ± 16	850 ± 42	560
Limonene	265 ± 35		
1,3-Butadiene			400
Formaldehyde		2250 ± 70	2000
Acetaldehyde		5400 ± 990	2400

a. Mean ± standard deviation (S.D.) for two chamber experiments

b. Mean ± S.D. for filter and non-filter cigarettes

Table III. Ventilation - infiltration scenarios modeled[a.]

	ACH[a.] during Operating Hours	ACH[a.] during Non-operating Hours	Effective zone height, m.	Occupancy, m^2/worker	Smoking Rate, cigarettes/h-smoker
Case 1 (Worst reasonable)	0.13	0.10	2.2	17.1	2.4
Case 2 (ASHRAE)	0.47	0.41	3.0	23.8	2.0
Case 3 (Leaky building)	0.62	0.52	3.0	23.8	2.0
Case 4 (PNW buildings)	1.27	0.41	3.0	23.8	2.0

a. Air changes per hour.

Table IV. Comparison of modeled 40-hour mean concentrations of ETS-contributed VOC to concentration ranges measured in office buildings

UG-M^{-3}

Compound	Ventilation Conditions[a.] Case 1	Case 2	Case 3	Case 4	Measured Ranges of Concentrations
Benzene	33.9	6.2	5.0	2.7	1.4 - 31[b.,c.]
Toluene	66.7	12.2	9.8	5.3	7 - 65[c.]
o-Xylene	37.7	6.9	5.6	3.0	2.9 - 34.8[b.,c.]
Styrene	8.3	1.5	1.2	0.7	1.0 - 79[b.,c.]
Acetone	85.1	15.6	12.6	6.8	17 - 50[d.]
2-Butanone	56.9	10.4	8.4	4.5	1 - 64[d.]
Limonene	20.8	3.8	3.1	1.7	0.4 - 8[c.]
Formaldehyde	177.1	32.5	26.2	14.1	< 25 - 69[e.]

a. Case 1 - Worst reasonable case, $a_D = 0.13\ h^{-1}$, $a_N = 0.10\ h^{-1}$; Case 2 - ASHRAE, $a_D = 0.47\ h^{-1}$, $a_N = 0.41\ h^{-1}$; Case 3 - Leaky Bldg., $a_D = 0.62\ h^{-1}$, $a_N = 0.52\ h^{-1}$; Case 3 - Average for 40 Pacific Northwest Bldgs., $a_D = 1.27\ h^{-1}$, $a_N = 0.41\ h^{-1}$

b. Reference 19; 3 office buildings, 12-hour daytime

c. Reference 2; one office building, measurement in offices of non-smokers

d. Reference 20 and 21; 3 office buildings, daytime

e. Reference 18; 38 office buildings in the Pacific Northwest; passive samplers exposed 75 to 100 hours, day-time only.

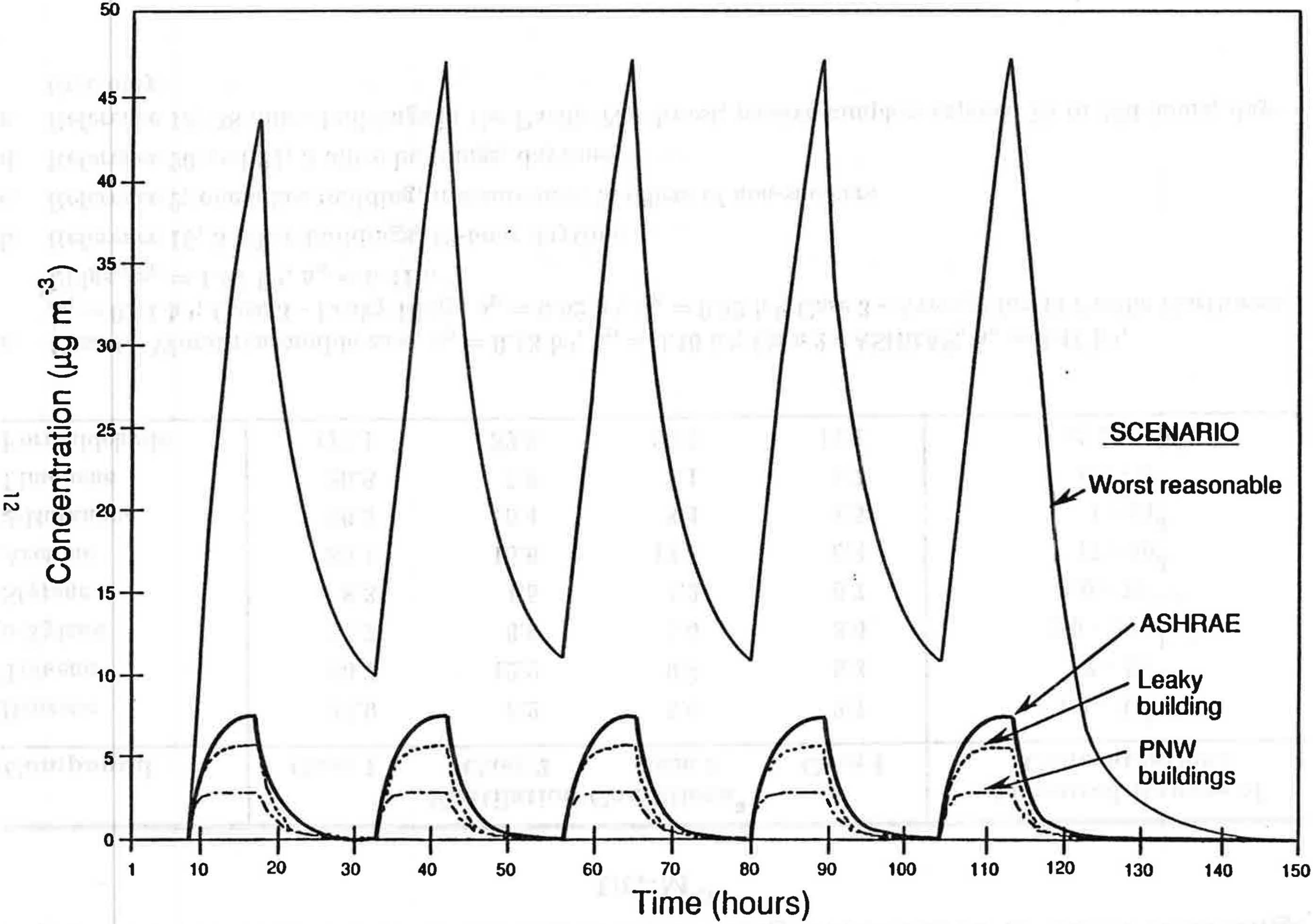

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FIGURE 1. Variation in the concentrations of benzene over a period of a work week in an intermediate-size office building for four ventilation-infiltration scenarios.