

Volatile Organic Compounds, Polycyclic Aromatic Hydrocarbons and Elements in the Air of Ten Urban Homes

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Abstract Ten homes were monitored at regular intervals from June 1994 through April 1995 as part of a Public Health Assessment in Southeast Chicago for exposure to volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), and elements. Simultaneous 24-h indoor and outdoor samples were collected. VOCs were analyzed using USEPA Method TO-14 with Selected Ion Monitoring Mass Spectrometry (GC/MS). PAHs were analyzed using USEPA Method TO-13 with GC/MS. Elements were collected on quartz fiber filters and analyzed by Inductively Coupled Argon Plasma (ICP) spectroscopy or Graphite Furnace Atomic Absorption (GFAA). Continuous measurements of CO₂ and temperature were recorded for each indoor sample. Twenty-four h total CO₂ emissions were determined from occupancy and estimated gas stove usage and were moderately correlated ($R^2=0.19$) with 24 h average indoor CO₂ concentrations. Modeled 24-h air exchange rates ranged from 0.04 to 3.76 air changes h⁻¹ (ACH), with mean of 0.52 ACH. Median particle penetration was 0.89. Emission rates were calculated for each pollutant sampled. Using a detailed housing survey and field sampling questionnaires, it was possible to evaluate associations between housing characteristics and source activities, and pollutant source rates. The data indicate that several predictor variables, including mothball storage, air freshener use, and cooking activities, are reasonable predictors for emission rates for specific pollutants in the homes studied.

Key words Indoor air quality; Volatile organic compounds; Polycyclic aromatic hydrocarbons; Infiltration; Penetration; Mass balance model; Emission rate; Emission factor.

Practical Implications

Exposure to indoor airborne pollutants is a function of many variables, including pollutant infiltration, exfiltration, deposition, resuspension, filtration, and generation. Because of this, measurements of indoor concentration only provide limited information in identifying the source of indoor exposures. This study shows how measurements of carbon dioxide and indoor activities can be used to express measured indoor concentration on the bases of a source strength or as an emission factor within the home due to home character-

istics or occupant activities. The data indicate that several predictor variables, including mothball storage, air freshener use, and cooking activities, are reasonable predictors for emission rates of specific pollutants in the homes.

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Introduction

Exposure to indoor airborne pollutants is a function of many variables, including pollutant infiltration, exfiltration, deposition, resuspension, filtration, and generation (NAS, 1981; Wadden and Scheff, 1982). Measurement of indoor concentrations will provide an observation of the end result of the combined influence of all these variables on indoor pollutant exposure, but concentration alone provides only limited information in identifying the source of indoor exposures.

An important factor influencing residential indoor exposure is the source rate or emission of pollutants within the home due to home characteristics or occupant activities. The identification of sources and a determination of the contribution of these sources to indoor air quality is an important step to evaluate indoor pollutant exposure. Estimation of pollutant emission rates in a residential environment, however, is complicated due to the presence of a large number of sources within the home, the variability of sources between homes, an inability to measure emission rates directly, and for some pollutants, the large impact of outdoor sources on the indoor environment. The objective of this study was to develop indoor pollutant emission rates for VOCs, PAHs and metals, and to evaluate the factors influencing emission rates.

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Study Design

The "Southeast Chicago" study area has been defined as an eight square mile region bounded on the north and south by 87th Street and Sibley Boulevard, respectively, and on the east and west by the Indiana state line and Western Avenue, respectively. The study area has been heavily industrialized for over 100 years and contains many known air toxic emission source types including coke plants, manufacturing facilities, municipal solid waste landfills, population-oriented sources (i.e. home furnaces, lawn mowers, etc.), and on-road vehicles (Summerhays, 1991).

For this study, measurements were taken in ten homes in Southeast Chicago over a 10-month period (June–April) in 1994–1995. Five homes in the Altgeld Garden area, two homes in the Torrence Avenue area, two homes in the Beverly area, and one home in Calumet City were selected. Study participants were selected based upon results of a survey questionnaire by Illinois Department of Public Health (IDPH) to determine willingness to participate. Homes with resident smokers were eliminated from the study.

Samples were collected in six homes (Home 1, 4, and 6–9) quarterly during each season, and Home 2 was sampled monthly over the 10-month study (June–April). Home 3 was sampled monthly from June to August, then sampled quarterly thereafter, and home 5 was sampled monthly from September to the end of the study. Home 3 was originally selected to be sampled monthly throughout the study, however, due to the introduction of a smoker into home 3, home 5 was used as a substitute for the remainder of the study. One sample was collected from home 10.

Twenty-four-hour indoor air samples were collected from midnight to midnight, concurrent with U.S. EPA ambient air sample collection. Sampling equipment was placed in the residences the day before and removed the day following the 24-h sampling event. Samples were collected in the kitchens of the homes as close as possible to the breathing zone.

A questionnaire, developed by IDPH for this study, was administered to study participants after each sampling event. The questionnaire was designed to measure variables that may influence pollutant penetration, dispersion, and source strength. Potential influencing variables that were measured included household activity levels, household chemical sources, and factors that could affect ventilation. Specific variables included foods cooked, cleaners used during sampling, visitors during sampling, noticeable odors by occupant, chemicals used by occupant, window open status, and air-conditioning use.

Simultaneous outdoor air pollution samples were

collected and analyzed by the U.S. Environmental Protection Agency. Ambient samples were collected at four sites: 1) Carver High School, 13100 South Doty Avenue; 2) Orville T. Bright School, 10740 South Calhoun; 3) Washington High School, 3535 E. 114th St.; and 4) Calumet City Trailer, Paxton Avenue and State Street. The indoor and ambient air sampling events were coordinated and performed concurrently throughout the study period.

Objectives

The overall objective of this study was to model indoor emission rates for the toxic pollutants selected. Five major steps were required to achieve this goal.

1. Validate the use of 24-h CO₂ measurements as indicators of indoor ventilation.
2. Calculate air infiltration (air changes per hour) using indoor CO₂ measurements and a one-compartment steady-state mass balance model.
3. Estimate penetration of particulate matter into the indoor environment using a one-compartment steady-state mass balance model.
4. Calculate emission rates for toxic pollutants for each sampling event.
5. Identify significant positive associations between pollutant emission rates and potential predictor variables, and estimate emission factors for the significant associations.

Methodology

Indoor Air Monitoring and Sample Analyses

Volatile Organic Compounds

The VOCs were collected with SUMMA canisters equipped with a low flow controller and programmable timing device. Approximately 3.5 ml/min of air was sampled over the 24-h sampling period for a total volume of 5 liters. Pre- and post-flow calibration measurements were performed using a mass flow calibrator during equipment placement and removal activities. Canisters were flushed with ultra-pure nitrogen and evacuated before sampling. The flow control devices were also flushed with nitrogen before sampling. The canisters were analyzed in accordance with the U.S. EPA Compendium Method TO-14 by Gas Chromatography with Selected Ion Monitoring Mass Spectrometry (GC/MS).

The indoor methylene chloride concentrations were unusually high when compared to results of other studies (Wallace, 1987). The elevated methylene chloride concentration may reflect the presence of methylene chloride sources in every study home or the presence of a sampling or analytical artifact. However,

based upon the available information, the reported methylene chloride concentrations were likely associated with an analytical artifact.

Polycyclic Aromatic Hydrocarbons

PAHs were collected with high flow pumps at a target flow rate of 25 liters per min for 24 h through a PAH collection tube, for a total volume of approximately 36 cubic meters. The PAH samples were collected at approximately 1.5 meters above the floor. Pre- and post-flow calibration measurements of air flow were made during equipment placement and removal activities, respectively, using a calibrated rotameter.

The PAHs were collected in a tube which contained a quartz fiber filter in front of 5 grams of XAD-2 sorbent and a polyurethane foam plug (PuF). The samples were analyzed by GC/MS.

Elements

Elements were collected with high flow pumps at a target flow rate of 25 liters per min for 24 h through a quartz fiber filter, for a total volume of approximately 36 cubic meters. The elements samples were collected at approximately 1.5 meters above the floor. Pre- and post-flow calibration measurements of air flow were made during equipment placement and removal activities using a calibrated rotameter.

Particulate matter was collected with a 37-mm filter cassette containing a quartz fiber filter with a cellulose support pad. Filters were digested using hot acid and analyzed by Inductively Coupled Argon Plasma (ICP) spectroscopy. Lead, arsenic, and selenium were analyzed using Graphite Furnace Atomic Absorption Spectroscopy.

Ventilation Efficiency Monitoring System (VEMS)

Indoor carbon dioxide (CO₂), temperature, and relative humidity measurements were recorded with each sampling event, after the initial sampling round on June 14, 1994. CO₂ (ppm) was measured with a Telaire™ CO₂ sensor (Model 1050), which uses a non-dispersive infrared carbon dioxide sensor. Temperature (°F) was measured with the Telaire™ temperature sensor (Model 1058T), and relative humidity (1–100%) was measured with the Telaire™ relative humidity sensor (Model 1058RH). CO₂, temperature, and relative humidity measurements were recorded with the Recordaire™ data logger. The 24-h average concentrations of CO₂, temperature, and relative humidity that coincided with the sampling event were derived from the continuous monitoring record. Nine VEMS sets were used during the study and were calibrated on a quarterly basis.

Ambient Air Monitoring

Samples were collected at each of the four monitoring stations approximately every 12 days. Field duplicates were obtained for QA/QC purposes. There was one duplicate at one site 10% of the time for VOCs and elements, and one duplicate at all sites 10% of the time for PAHs.

Volatile Organic Compounds

The samples were collected using the Anderson Volatile Organic Compound Canister Sampler (VOCCS). The canisters were cleaned and evacuated to approximately 30" Hg vacuum. An air sample was drawn into the canisters with a Viton Diaphragm pump. The flow rate was controlled by a mass flow controller. The initial and post-sample flow rates were checked during equipment preparation and removal, respectively. A programmable digital timer was used to activate the pumps and sample between 12:00 a.m. and 12:00 a.m. local time. A maximum/minimum thermometer was set up and the interior temperature was recorded during equipment preparation. After sampling, the final elapsed time meter reading was recorded along with the interior maximum and minimum temperatures.

Blank canisters were filled with humidified zero air and placed in the sampler at Washington High School. Duplicate samples were collected ten percent of the time at Washington High School. The samples were analyzed in accordance with the USEPA Compendium Method TO-14 by Gas Chromatography with Selected Ion Monitoring Mass Spectrometry (GC/MS).

Polycyclic Aromatic Hydrocarbons

PAH samples were collected using the Anderson Model GPSI Polyurethane Foam (PuF) Sampler. A dual chambered aluminum sampling module contained a 102 mm quartz fiber filter and a glass cartridge with a combination of XAD-2 and PuF. The initial and post sample flow rates were checked during equipment preparation and removal, respectively, using a magnehelic gauge. Blanks were collected at Washington High School. Duplicate samples were collected 10% of the time at all sites. The filters and XAD-2/PuF combination cartridges were analyzed in accordance with the U.S. EPA Compendium Method TO-13.

Initially, the glass cartridge contained a PuF filter only. Based upon a USEPA Method and Quality Assurance Branch (MQAB) review, the combination XAD-2 and PuF filter was substituted for the PuF filter only approximately half way through the study.

Elements

Elements were collected using the Anderson Model GWML-2000H Hi Volume sampler with a flow range of 1.17 to 1.83 cubic meters per minute. The initial and post sample flow rates were checked during equipment preparation and removal. A programmable digital timer was used to activate the pumps and sample between 12:00 a.m. and 12:00 a.m. local time. Field blanks were collected at Washington High School. Duplicate samples were collected ten percent of the time at Washington High School. Filters were digested using hot acid and analyzed by Inductively Coupled

Argon Plasma (ICP) spectroscopy or Graphite Furnace Atomic Absorption Spectroscopy.

Modeling

Mathematical modeling is typically used to characterize chemical or physical processes that affect indoor pollutant concentrations and to predict indoor concentrations or exposure under different circumstances (Nagda et al., 1993). For this study, a one-compartment mass balance model was used to transform measurements of concentration to ventilation and emission rates. This mass balance model is given by Equation 1:

Table 1 Summary of VOC concentrations (ng m^{-3})

Compound	Indoor								Outdoor median
	Number of samples	Number >LOD	Mean	Std. Dev.	Minimum	Median	90th percentile	Maximum	
Ubiquitous									
Propylene	48	48	11,100	11,900	2,610	7,080	23,600	60,100	852
Chloromethane	48	48	2,000	900	970	1,690	3,540	4,330	3,015
Methylene Chloride ^a	48	48	140,000	235,000	760	60,500	510,000	1,190,000	486
1,1,1-Trichloroethane	48	48	24,900	52,700	980	5,880	68,100	293,000	1,037
Benzene	48	48	4,100	4,810	1,280	2,870	6,120	33,900	1,246
Toluene	48	48	15,300	10,300	2,370	12,000	29,400	44,700	2,693
Tetrachloroethylene	48	48	2,610	2,150	540	2,170	4,740	13,100	475
Ethylbenzene	48	48	9,710	26,500	910	3,210	13,000	174,000	630
m,p-Xylene	48	48	34,900	68,900	5,720	13,500	56,000	418,000	1,715
o-xylene	48	48	11,200	29,300	1,130	3,550	16,200	186,000	695
Chloroform	48	47	1,800	2,050	nd	970	4,040	10,600	49
Carbon Tetrachloride	48	45	516	190	nd	500	690	1,260	755
Styrene	48	44	1,100	1,400	nd	850	2,130	9,480	170
Trichloroethylene	48	43	489	480	520	380	1,130	nd	107
n-Octane	48	43	3,270	4,080	nd	1,400	11,300	16,600	187
1,3-Butadiene	48	39	419	550	nd	260	1,170	2,540	44
p-Dichlorobenzene	48	39	2,970	13,800	nd	600	2,040	95,500	60
Chloroethane	48	36	745	850	nd	470	2,010	3,580	nd
Often found									
o-Dichlorobenzene	48	14	64	0.12	nd	nd	240	540	nd
Occasionally found									
1,2-Dichloroethane	48	9	99	0.27	nd	nd	400	1,250	nd
Dibromochloromethane	48	6	20	0.06	nd	nd	90	260	na
m-Dichlorobenzene	48	5	21	0.07	nd	nd	60	360	nd
Bromomethane	48	4	19	0.07	nd	nd	nd	310	78
trans 1,2-Dichloroethylene	48	4	8	0.03	nd	nd	nd	160	na
cis-1,2-Dichloroethylene	48	4	10	0.03	nd	nd	nd	160	nd
Bromodichloromethane	48	4	188	1.01	nd	nd	nd	6,890	na
Vinyl Chloride	48	3	9	0.04	nd	nd	nd	200	na
1,1-Dichloroethane	48	3	8	0.04	nd	nd	nd	280	nd
Bromochloromethane	48	2	4	0.02	nd	nd	nd	160	na
Chloroprene	48	1	4	0.03	nd	nd	nd	180	na
Chlorobenzene	48	1	10	0.07	nd	nd	nd	460	nd
Bromoform	48	1	4	0.30	nd	nd	nd	210	na
1,1,2,2-Tetrachloroethane	48	1	7	0.05	nd	nd	nd	340	nd
Never found									
1,2-Dichloropropane	48	0	nd	nd	nd	nd	nd	nd	na
cis-1,2-Dichloropropene	48	0	nd	nd	nd	nd	nd	nd	na
trans-1,3-Dichloropropene	48	0	nd	nd	nd	nd	nd	nd	na
1,1,2-Trichloroethane	48	0	nd	nd	nd	nd	nd	nd	na

LOD: Limit of Detection

nd: Below analytical detection limit

na: Not analyzed

^a Elevated methylene chloride concentrations indicate possible analytical artifact

Table 2 Summary of PAH concentrations (ng m⁻³)

Compound	Indoor								Outdoor median
	Number of samples	Number >LOD	Mean	Std. Dev.	Minimum	Median	90th percentile	Maximum	
Ubiquitous									
Naphthalene	45	40	851	952	nd	470	2150	5000	nd ^a
Fluorene	45	36	59.0	113	nd	26	113	600	6.4 ^a
Often found									
Fluoranthene	45	33	6.64	6.42	nd	7	14	26	7.0
Pyrene	45	29	6.91	10.6	nd	2	14	47	3.8
Acenaphthene	45	26	79.9	214	nd	6	170	1040	2.5
Phenanthrene	45	21	60.0	143	nd	nd	120	820	21.7
Acenaphthylene	45	20	12.8	27.7	nd	nd	50	122	1.5
Occasionally found									
Anthracene	45	11	2.05	6.82	nd	nd	4	40	2.3
Chrysene	45	5	0.20	0.66	nd	nd	1	3	0.66
Benzo(a)anthracene	45	3	0.56	2.54	nd	nd	nd	14	0.26
Benzo(a)pyrene	45	2	0.09	0.47	nd	nd	nd	3	0.15
Benzo(e)pyrene	45	1	0.40	2.68	nd	nd	nd	18	0.39
Benzo(b)fluoranthene	45	1	0.067	0.45	nd	nd	nd	3	na
Benzo(k)fluoranthene	45	1	0.067	0.45	nd	nd	nd	3	na
Never found									
Benzo(g,h,i)perylene	45	0	nd	nd	nd	nd	nd	nd	0.48
Dibenzo(a,h)anthracene	45	0	nd	nd	nd	nd	nd	nd	0.083
Indeno(1,2,3-cd)pyrene	45	0	nd	nd	nd	nd	nd	nd	0.275

LOD: Limit of Detection

nd: Below analytical detection limit

na: Not analyzed separately

^a Outdoor median concentrations low because PAH sampler contained polyurethane foam only for first 6 months of project

$$V \frac{dC_i}{dt} = kq_0C_o(1-F_0) + kq_1C_i(1-F_1) + kq_2C_o - k(q_0 + q_1 + q_2)C_i + S - R \quad (1)$$

where C is the concentration indoors (C_i) and outdoors (C_o); t is time; q is volumetric flow rate for make-up air (q_0), recirculation (q_1) and infiltration (q_2); F is filter efficiency for make-up (F_0) and recirculation air (F_1); V is room volume; S is indoor source emission rate (hr^{-1}); R is indoor sink removal rate; and k is a mixing factor which varies from 0 to 1 (Wadden and Scheff, 1982).

A steady state solution for Equation 1 can be derived by calculating the change in C_i with t, holding all other factors constant and with boundary values $C_i=C_s$ at $t=0$, and subsequently letting t approach infinity. This results in Equation 2,

$$C_{i,ss} = \frac{k[q_0(1-F_0) + q_2]C_o + S}{k(q_0 + q_1F_1 + q_2) + E} \quad (2)$$

where $C_{i,ss}$ is the steady-state indoor concentration and E is a proportionality constant for the particular pollutant of interest, such that $R=EC_i$.

A modified form of the steady-state model that incorporates an estimate of pollutant penetration, deposition loss, and a single ventilation term for infiltration into the study homes can be represented by equation 3.

$$C_{i,ss} = \frac{(Kq)PC_o + S}{(kq + E)} \quad (3)$$

where P is the penetration factor (the fraction of particulate matter that penetrates the building shell) and E represents the surface area to volume ratio of the home (σ) times the room volume times the particulate matter deposition velocity, u_d (Koutrakis and Briggs, 1992). Assumptions for Equation 3 include no resuspension of indoor pollutants and a constant emission rate over the measurement or modeling interval.

Results

Indoor Air Quality

Results from the indoor air sampling are presented here. Results from the ambient air sampling, and climatic factor observations have been presented (Rizzo and Scheff, 1998). Quality assurance was performed on the indoor data by the Illinois Department of Public Health. VOC, PAH, and elemental concentrations that were qualified as quantified (>10 times the mean blank concentration) and estimated (between 3 and 10 times the mean blank concentration) were included in the data analyses. VOC, PAH, and elemental concen-

trations identified as analyzed but not detected were assigned a zero value. All compounds not analyzed were designated as missing values. PAH and elemental results were blank corrected using the mean values determined from respective blank filter analyses.

Similar to the US Environmental Protection Agency TEAM study, concentration results are presented ranked in order of frequency of occurrence (Wallace, 1987). Four frequency groups are specified: 1) ubiquitous (>75% of results above analytical detection limit); 2) often found (25–75% of results above analytical detection limit); 3) occasionally found (<25% of results above analytical detection limits); and 4) never found (no results above analytical detection limits).

Indoor VOC concentrations are summarized in Table 1. Twenty-four of these compounds were also included in the ambient air study. Indoor PAH concentrations are summarized in Table 2. Fourteen of these compounds were also included in the ambient air study. Indoor elemental concentrations are summarized in Table 3. Nineteen of these elements were also included in the ambient air study. A summary of temperature, carbon dioxide, and relative humidity by indoor location is included in Table 4. The 24-h means for temperature, CO₂, and relative humidity were derived from a continuous monitoring period that started during equipment installation and ended during equipment removal from the home, approximately 48 h.

Table 3 Summary of elemental concentrations ($\mu\text{g m}^{-3}$)

Compound	Indoor								Outdoor median
	Number of samples	Number >LOD	Mean	Std. Dev.	Minimum	Median	90th percentile	Maximum	
Ubiquitous									
Lead (Pb)	48	48	0.019	0.020	0.0015	0.011	0.054	0.088	0.032
Aluminum (Al)	48	48	0.149	0.157	nd	0.099	0.485	0.739	0.44
Calcium (Ca)	48	48	0.796	0.754	nd	0.481	2.18	2.71	4.1
Iron (Fe)	48	48	0.359	0.316	nd	0.263	0.774	1.46	1.60
Magnesium (Mg)	48	48	0.191	0.184	0.0071	0.137	0.521	0.746	1.38
Sodium (Na)	48	48	0.391	0.392	nd	0.302	0.878	2.13	0.57
Zinc (Zn)	48	48	0.059	0.05	nd	0.045	0.137	0.176	0.106
Copper (Cu)	48	44	0.005	0.009	nd	0.0009	0.015	0.044	0.045
Manganese (Mn)	48	44	0.016	0.016	nd	0.012	0.042	0.06	0.111
Often found									
Potassium (K)	48	35	0.185	0.154	nd	0.184	0.360	0.564	0.253
Nickel (Ni)	48	35	0.002	0.002	nd	0.003	0.006	0.008	0.0034
Selenium (Se)	48	31	0.001	0.002	nd	0.0003	0.003	0.007	0.002
Occasionally/never found									
Chromium (Cr)	48	11	0.001	0.003	nd	nd	0.006	0.008	0.0068
Arsenic (As)	48	10	0.0005	0.001	nd	nd	0.002	0.004	0.0015
Cadmium (Cd)	48	7	0.0009	0.002	nd	nd	0.004	0.012	nd
Vanadium (V)	48	4	0.0002	0.0006	nd	nd	nd	0.003	0.0028
Tin (Sn)	48	3	0.002	0.007	nd	nd	nd	0.03	nd
Cobalt (Co)	48	2	0.0001	0.0005	nd	nd	nd	0.003	nd
Molybdenum (Mo)	48	1	0.0002	0.001	nd	nd	nd	0.008	nd
Antimony (Sb)	48	0	nd	nd	nd	nd	nd	0	nd

LOD: Limit of Detection
 nd: Below analytical detection limit

Table 4 Summary of temperature, carbon dioxide, and relative humidity by indoor location

House number	Number of observations	Temperature (F)			Carbon dioxide (ppm)			Relative humidity (%)		
		24 h mean	24 h min.	24 h max.	24 h mean	24 h min.	24 h max	24 h mean	24 h min.	24 h max
1	3	78	74	83	663	600	725	33.2	23.7	40.0
2	8	70	67	81	533	369	681	42.6	25.0	58.0
3	5	80	74	91	512	400	600	39.5	32.5	47.5
4	3	72	70	74	572	500	625	39.5	32.5	47.5
5	7	90	83	102	673	475	950	20.4	13.0	39.0
6	2	73	68	78	470	390	550	25.2	13.0	37.5
7	3	80	71	88	463	425	540	25.7	16.0	36.0
8	3	73	70	79	833	750	900	41.0	36.0	47.5
9	3	67	65	70	675	400	850	43.0	35.0	49.0

Table 5 Summary of housing characteristics survey variables

Variable name	Number	Description
AGE	10	Home age in years
ADULTS	10	Number of adults in home (>21 years)
CHILDREN	4	Number of children in home (<21 years)
FAHEAT	6	Forced air heating system
SHEAT	2	Steam heating system
EHEAT	2	Electric heating system
AIRCLEAN	4	Air cleaner in home (including furnace)
NVCOOL	7	Natural ventilation used for cooling home
CAC	2	Central air conditioning used to cool home
WAC	4	Window air conditioning used to cool home
FIREPLC	1	Wood fireplace present in home
PAINT	7	Paint stored/used in home
THINNER	2	Thinner stored/used in home
OVENCLR	6	Oven cleaner stored/used in home
HAIRSPY	5	Aerosol hair spray stored/used in home
SPOTRMVR	4	Spot remover stored/used in home
GLUE	4	Glue stored/used in home
DRAINCLR	3	Drain cleaner stored/used in home
SPRAYWAX	2	Spray wax stored/used in home
MTHBALL	2	Mothballs stored/used in home
PSBASE	3	Basement storage of chemicals
PSGAR	3	Garage storage of chemicals
PSKIT	5	Kitchen storage of chemicals
PSUTILRM	3	Utility room storage/use of chemicals
PSCLST	2	Closet storage of chemicals
PSBATH	5	Bathroom storage of chemicals
PSOTHER	2	Other storage place for chemicals
REMODEL	3	Remodeling in the last 6 months
DRYCLN	4	Dry-cleaning performed infrequently
WORKSLVT	1	Resident works with solvents
WASHWK	3	Work clothes washed at home
WASHBASE	3	Washer/Dryer located in basement
WASHKIT	3	Washer/dryer located in kitchen
WASHUTRM	4	Washer/dryer located in utility room
WASHVENT	3	Dryer vent located inside home
AIRFRESH	5	Air fresheners used in home
SLVTHBBY	1	Resident has hobby involving solvents
BASEMENT	5	Basement present at home
BSMTFSDH	4	Basement finished
BASFDSP	5	Floor drains/sumps present in basement
BASECRKS	2	Cracks in basement floors/walls
PROJECT	4	Project housing sample site
PRIVATE	6	Private residence sampling site
GARAGE	4	Non-attached garage at sampling home
HISPANIC	2	Hispanic
WHITE	3	White
BLACK	5	Black
CARPET	2	Carpet beneath sampling train
NUMEMPLY	7	Number of people employed in home
OLD	1	Occupants present in home >65 years
ADULT	9	Occupants present in home 21-65 years
YOUTH	1	Occupants present in home 12-21 years
CHILD	3	Occupants present in home <12 years

^a Number of positive responses (Total N=10)

^b Not applicable

Table 6 Summary of sampling questionnaire survey variables

Variable name	Number	Description
FOODS	33	Foods cooked during sampling period
STIRFRY	2	Stir fry foods cooked
FRIED	17	Fried foods cooked
BAKED	9	Baked foods cooked
BOILED	16	Boiled foods cooked
MICRO	5	Microwave foods cooked
BROILED	2	Broiled foods cooked
CLEANERS	11	Cleaners used during sampling period
CARSHAMP	1	Carpet shampoos during sampling period
MOIL	2	Murphy's oil used during sampling period
DETDISH	4	Dishwashing detergent used during sampling
DETLAUN	4	Laundry detergent used during sampling
NH3	1	Ammonia used during sampling period
WINDEX	1	Windex used during sampling period
BLEACH	1	Bleach used during sampling period
MRCLEAN	1	Mr. Clean used during sampling period
PSOL	1	Pinesol used during sampling period
AJAX	1	Ajax used during sampling period
VISITORS	3	Visitors during sampling period
VSMOKER	2	Visitors during sampling period smoked
CHEMUSED	16	Chemicals used during sampling period
UPAINT	3	Painted portion of home during sampling
UPER	9	Perfume/cologne used during sampling
UBUGSP	1	Bug spray used during sampling period
UDEOD	1	Deodorant used during sampling period
UELMWG	1	Elmers wood glue used during sampling
USANDAL	4	Sandalwood scent used during sampling
UAF	4	Used electric or spray air freshener
OOBS	9	Other observations noted during sampling
ALONE	1	Residents not home during sampling period
FIRE	1	Area fire reported by resident
MINERAL	3	Mineral spirits stored adjacent to samplers
PAINTED	2	Painted portion of home interior
KERO	6	Kerosene lamp detected in home
WINDOWS	21	Windows open during sampling period
UAC	3	Air conditioning used during sampling

study initiation. Table 5 is a summary of the variable name, description of variable, categorical definition, and number of responses greater than zero recorded.

A second questionnaire designed to measure variables that may influence pollutant penetration, dispersion, and source strength in the study homes was administered to study participants after each sampling event. Specific variables surveyed included: foods cooked, cleaners used during sampling, visitors during sampling, noticeable odors by occupant, chemicals used by occupant, window open status, and air conditioning use. Based upon a positive response to one

Environmental Surveys

Survey questionnaires to characterize the general residence and potential sources of contamination in the home were administered to study participants prior to

or more of these variable categories, additional inquiry was performed at the discretion of the field technician. Table 6 is a summary of the variable name, description of variable, categorical definition, and number of responses greater than zero recorded.

Infiltration

Estimates of infiltration were derived from the CO₂ measurements and generation rates. Carbon dioxide generation rates were derived from estimates of human sources and gas stove usage. Human sources were estimated from occupancy and the occupant's activity. Employed individuals and students time spent at home was estimated to be 60%. Unemployed individuals, infants/toddlers, and elderly time spent at home was estimated to be 75, 85, and 95%, respectively. Occupancy estimates were also adjusted based upon observations denoted in the sampling questionnaire.

Occupancy activity was assigned to one of three levels: 1) sleep; 2) active awake; and 3) passive awake to occupants. A metabolic activity was assigned to each level of activity based upon 2 m²/person, where 1 met unit=50 kcal/h · m²=metabolic rate of a person sitting at rest in a comfortable environment (Scheff and Wadden, 1982). The relationship between met units and activity levels are as follows: sleep (0.7 mets), active awake (2.5 mets for adults and 2.95 mets for children), and passive awake (1 met). Met units for children and infant/toddlers were reduced by 50 and 75%, respectively, to account for decreased CO₂ output. Individual CO₂ emission rates were then calculated and summed for each home, using a 0.53 ft³ CO₂/met · h · person conversion factor (ASHRAE, 1989).

Carbon dioxide generation rates for gas stove emissions were calculated assuming a heat input rate of 2500 kcal/burner · h and an emission factor of 200,000 µg CO₂/kcal (Wadden and Scheff, 1982). The average CO₂ emission factor was 8.3 g CO₂/burner min. Gas stove burner minutes were estimated from cooking activities reported on the sampling survey.

Infiltration was estimated using a one compartment mass balance model. The model defines the relationship between outdoor air flow rate, generation of CO₂ indoors, indoor CO₂ concentrations, and outdoor CO₂ concentrations. Assigning a zero value to E, an equation to determine air exchange rate can be derived from Equation 2:

$$kq = \frac{S}{C_i - C_o} \tag{4}$$

where S is the estimated CO₂ generation rate in home, C_i is the measured 24-h mean indoor CO₂ concentration, C_o is the typical outdoor CO₂ concentration (i.e. 356 ppm), and kq is the effective outdoor air flow rate (volume per time) where q describes the flow rate and k defines the mixing factor. With V as the volume of the home, kq/V is the effective air exchange rate (h⁻¹). Table 7 summarizes CO₂ emissions for occupancy, CO₂ emissions for gas-stove use, indoor CO₂ concentrations, and calculated air exchange rates for each study home.

Penetration

The penetration of outdoor particulate matter into the homes was determined for specific elements using the mass balance model. Analysis of the Indoor/Outdoor concentration relationships indicated that seven elements had significant regression slopes. These elements were Pb, Se, Al, Fe, Mg, Mn, and Zn. In general, these elements all have significant outdoor sources. The remaining elements were determined to have significant indoor sources (did not show significant indoor/outdoor relationships) and were not used to estimate penetration.

The penetration factor describes the amount that the infiltration of particles is reduced due to the filtering effect of the building shell. Under steady-state conditions, if there is no generation or resuspension of particles, penetration can be calculated from deposition loss rate, the infiltration rate, and I/O concentration

Table 7 CO₂ emissions from occupancy and gas stove use, concentrations and air exchange rates

Home number	Observed range of values			
	Occupancy CO ₂ production (g/day)	Gas stove CO ₂ production (g/day)	CO ₂ concentrations (ppm)	Air exchange rates, kq/V (h ⁻¹)
1	1390-1410	0-415	600-725	0.15-0.19
2	364-470	0-166	369-681	0.07-1.83
3	590-652	0-540	400-600	0.28-1.94
4	1460-1580	0-373	500-590	0.22-0.44
5	1370-1600	0-705	475-950	0.26-0.84
6	1380-1460	332-373	390-550	0.67-3.76
7	611-911	0-290	425-540	0.35-0.96
8	1460-1550	0-415	750-900	0.08-0.14
9	729-769	No gas stove	400-850	0.04-0.51

Table 8 Regression slopes and penetration efficiencies for the elements measured

Element	Regression slope	Standard error	Penetration mean ^{a,b}
Arsenic	0.27*	0.11	0.82
Lead	0.27***	0.03	1.02
Selenium	0.38**	0.12	1.43
Antimony	0	0	0
Aluminum	0.19**	0.05	1.15
Calcium	0.05*	0.02	0.85
Cadmium	0.04	0.32	3.93
Cobalt	-0.10	0.20	0
Chromium	0.08	0.05	0.16
Copper	-0.05	0.07	0.28
Iron	0.10**	0.02	0.48
Potassium	0	0	2.52
Magnesium	0.05**	0.02	0.47
Manganese	0.06**	0.02	0.46
Sodium	0.10	0.2	9.01
Nickel	0.05	0.12	3.19
Tin	0	0	0
Vanadium	-0.02	0.02	0.09
Zinc	0.13**	0.04	1.14

* P≤0.05

** P≤0.01

*** P≤0.001

^a Penetration calculated as described in Equation 7^b Mean penetration calculated from elements with significant (P<0.01) regression slopes equals 0.89

modified mass balance equation can be derived to estimate penetration:

$$P = \left(\frac{C_i}{C_o} \right) \frac{(\sigma u_d + kq/V)}{(kq/V)} \quad (5)$$

where C_i is the indoor concentration, C_o is the outdoor concentration, σ is the surface area to volume ratio, u_d is the deposition velocity, and kq/V is the air exchange rate. Estimates of positive penetration efficiency ranged from 0.09–9.01. Penetration efficiencies greater than one are physically unrealistic and result from significant indoor sources. To eliminate the potential influence of elements with indoor sources, only the seven elements (Pb, Se, Al, Fe, Mg, Mn, and Zn) with significant ($P \leq 0.01$) I/O correlation (i.e., indicative of outdoor dominated source) were included in the final calculation of overall penetration. Table 8 summarizes the regression slopes, standard errors, and mean penetration estimates for each element. The mean penetration efficiency of these seven elements is 0.89.

Emission Rates

Assuming steady-state conditions and by using the calculated infiltration and penetration values, a mass balance relationship can be defined to determine the indoor pollutant emission rate. A modified mass balance relationship, derived from Equation 3 is

ratio (Thatcher and Layton, 1995). Assuming a deposition velocity, u_d , equal to 0.0005 cm/s (Sinclair and Psota-Kelty, 1988) and a surface area to volume ratio (σ) equal to 2 m⁻¹ (Koutrakis and Briggs, 1992), a

Table 9 Summary of VOC source rates, µg/h

Compound	n	Mean	Std. Dev.	Min.	Median	90th %	Max.
Propylene	37	1,280	2,050	nd ^b	524	2,540	9,810
Chloromethane	37	168	371	nd	53.5	415	2,140
1,3-Butadiene	37	65.5	157	nd	12.5	217	828
Bromomethane	37	1.97	7.24	0	0	0	34.8
Chloroethane	37	95.2	141	0	38.0	346	591
Methylene Chloride ^a	37	39,900	104,000	nd	10,700	70,400	609,000
1,1-Dichloroethane	37	0.14	0.87	0	0	0	5.30
Chloroform	37	293	407	nd	94.8	867	1,910
1,2-Dichloroethane	37	12.5	57.3	nd	0	27.3	342
1,1,1-Trichloroethane	37	3,470	8,890	nd	528	11,300	39,900
Benzene	37	357	1,260	nd	87.2	485	5,370
Carbon Tetrachloride	37	36.9	107	nd	3.66	99.8	597
Trichloroethylene	37	47.6	115	nd	16.1	222	399
Toluene	37	1,320	2,100	nd	638	4,670	7,010
n-Octane	37	271	500	nd	159	673	2,670
Tetrachloroethylene	37	225	366	nd	147	632	1,320
Ethylbenzene	37	530	600	nd	351	1,400	2,830
m,p-Xylene	37	2,690	2,920	nd	1,770	8,270	13,100
Styrene	37	110	176	nd	61.5	188	812
1,1,2,2-Tetrachloroethylene	37	0.25	5.04	nd	0	0	28.5
o-Xylene	37	555	609	4.32	258	1,680	2,010
m-Dichlorobenzene	37	4.48	17.1	nd	0	0	41.3
p-Dichlorobenzene	37	248	787	nd	53.8	317	4,420
o-Dichlorobenzene	37	2.37	31.0	nd	0	26.0	143

^a Elevated methylene chloride source rate may reflect possible analytical artifact^b Not detected

Table 10 Summary of PAH source rates, $\mu\text{g}/\text{h}$

Compound	n	Mean	Std. Dev.	Min.	Median	90th %	Max.
Naphthalene	35	245	512	nd ^a	115	460	2,540
Acenaphthylene	35	4.36	16.1	nd	nd	22.4	79.0
Acenaphthene	35	36.7	96.3	nd	0.26	165	379
Fluorene	35	22.8	522	nd	5.71	92.5	240
Phenanthrene	35	20.0	66.2	nd	nd	126	324
Anthracene	35	nd	3.38	nd	nd	1.85	14.5
Fluoranthene	35	nd	3.54	nd	0.14	2.92	11.0
Pyrene	35	1.55	7.63	nd	nd	6.10	37.0
Benzo(a)anthracene	35	0.20	2.60	nd	nd	nd	13.8
Chrysene	35	nd	0.60	nd	nd	nd	1.25
Benzo(a)pyrene	35	nd	0.64	nd	nd	0	2.92
Benzo(e)pyrene	35	0.30	3.50	nd	nd	nd	20.3
Benzo(g,h,i)perylene	35	nd	0.37	nd	nd	nd	nd
Indeno(1,2,3-cd)pyrene	35	nd	0.28	nd	nd	nd	0

^a Not detected

Table 11 Summary of elemental source rates, $\mu\text{g}/\text{h}$

Compound	n	Mean	Std. Dev.	Min.	Median	90th %	Max.
Arsenic	36	nd	0.76	nd	nd	0	2.95
Lead	36	nd	15.1	nd	nd	2.10	16.9
Selenium	36	nd	0.66	nd	nd	nd	0.86
Antimony	36	nd	0.31	nd	nd	0	0
Aluminum	36	nd	191	nd	nd	nd	22.1
Calcium	36	nd	2,640	nd	nd	nd	258
Cadmium	36	0.26	1.56	nd	0	1.64	8.29
Cobalt	36	0.01	0.38	nd	0	0	1.94
Chromium	36	nd	2.14	nd	nd	0	1.17
Copper	36	nd	16.2	nd	nd	nd	4.90
Iron	36	nd	689	nd	nd	nd	nd
Potassium	36	nd	949	nd	nd	90.1	265
Magnesium	36	nd	1,100	nd	nd	nd	10.9
Manganese	36	nd	55.5	nd	nd	nd	1.20
Sodium	36	28.0	222	nd	17.9	241	889
Nickel	36	0.14	1.25	nd	nd	1.48	2.79
Tin	36	nd	4.35	nd	0	0	0
Vanadium	36	nd	0.96	nd	nd	nd	0.33
Zinc	36	nd	50.7	nd	nd	3.63	33.95

$$S = (C_i - PC_o) \left(\frac{kq}{V} + \sigma u_d \right) (V) \quad (6)$$

where deposition velocity, u_d , is assumed to be applicable only to elements; penetration, P , is only applicable to elements; house volume, V , is house specific; infiltration, kq/V , is date and home specific, and S is the emission rate. VOC and PAH compound penetration efficiencies were assumed to be one and the average penetration efficiency (0.89) was applied to elements. A deposition velocity of zero was assumed for both PAHs and VOCs. All emission rates are based upon 24-h measurements of indoor/outdoor pollutant and CO_2 concentrations.

Emission rates were calculated for each individual indoor concentration measured. Tables 9, 10 and 11

summarize the emission rates for the VOCs, PAHs, and elements, respectively. All VOC median emission rates were positive suggesting significant indoor sources of the compounds measured. Excluding methylene chloride, the VOCs with the five highest median emission rates were (1) *m,p*-xylene, (2) toluene, (3) 1,1,1-trichloroethane, (4) propylene, and (5) ethylbenzene. In contrast, only four PAHs had positive median emission rates (naphthalene, fluorene, acenaphthene, and fluoranthene). Of the elements measured, only sodium had a positive median emission rate. This suggests that the dominant source of most components of indoor particulate matter is outdoor air.

Emission Factors

Emission rates have the dimensions of mass released per unit of time. Emission rates can be grouped or

Table 12 Significant VOC emission factors, µg/h/unit of activity

House characteristic	Compound	Emission factor ^c
Washer/drier vented indoors (N=17)	m,p-Xylene	1,950
	Toluene	1,630
	Propylene	1,370
	Benzene	930
	Ethylbenzene	457
	Chloromethane	225
	Chloroethane	95.6
	Carbon tetrachloride	70
	1,1,2,2-Tetrachloroethane	2.64
Air freshener use (N=2)	Propylene	3,700
	Chloromethane	885
	Styrene	319
	o-Dichlorobenzene	67.5
Child ^a (N=12)	Propylene	1,370
	Chloromethane	256
	Chloroform	178
	Toluene	1,770
	n-Octane	429
	Ethylbenzene	586
	m,p-Xylene	2,440
Glue (N=12)	Chloroform	145
	Ethylbenzene	302
	m,p-Xylene	897
Kitchen storage of chemicals (N=15)	Chloromethane	95
	n-Octane	155
	Ethylbenzene	403
	o-Xylene	220
Closet storage of chemicals ^b (N=6)	Bromomethane	9.76
	Toluene	1,510
	m,p-Xylene	2,080
Utility room storage of chemicals (N=13)	Bromomethane	5.59
	1,1,1-Trichloroethane	988
Carpet beneath sampling train (N=10)	1,1,1-Trichloroethylene	3,710
	Tetrachloroethylene	135
Hair spray storage (N=19)	1,1,1-Trichloroethane	522
Mothball storage (N=10)	1,1,1-Trichloroethane	2,790
Dry-clean periodically (N=13)	1,1,1-Trichloroethane	1,419
Washer/drier in utility room (N=16)	1,1,1-Trichloroethane	353

^a Based on 3 homes with children

^b Based on 6 observations in one home

^c All emission factors significant at $p < 0.05$

characterized with respect to an observed house characteristic or sampling questionnaire variable to develop emission factors. An emission factor (EF) is used to relate the mass of contaminant released with a unit of activity associated with the release of the pollutant.

In this study, pollutant emission factors were determined by using either univariate statistics or with regression analysis. Using the univariate approach, specific pollutant emission rates were grouped by the presence or absence of a source activity (i.e. glue storage or no glue storage) and mean emission rates were calculated for each pollutant within these source categories. The difference between source and non-source emission rates is the emission factor for the predictor variable. For example, for benzene (pollutant) and glue

storage (predictor variable): $EF_{\text{benzene}} = S_{\text{Glue Storage, benzene}} - S_{\text{No Glue Storage, benzene}}$

The emission factor can also be determined using a regression analysis between specific pollutant emission rates (Y) and a source activity (X). For example, $S_{\text{specific pollutant}} = \beta_0 + \beta_1 A + E$, where β_0 is the regression intercept, and β_1 is the parameter estimate or emission factor for the predictor variable, A. Linear regression analysis was used to examine the relationship between variables with a range of responses to pollutant emissions.

Tables 12, 13 and 14 summarize significant emission factors for VOC, PAH and elements, respectively. These tables show the specific variable and the number of measurements that the emission factor is based on. For example, Table 12 shows that there were 17

Table 13 Significant PAH emission factors, $\mu\text{g}/\text{h}/\text{unit}$ of activity

House characteristic	Compound	Emission factor ^b
Mothballs-stored indoors (N=10)	Naphthalene	675
	Acenaphthene	130
	Fluorene	65.5
	Phenanthrene	78.3
Washer dryer vented indoors (N=17)	Fluoranthene	2.39
	Pyrene	1.57
	Indeno(1,2,3-cd)pyrene	0.18
Visitor smoked (N=1)	Fluorene	116
	Phenanthrene	193
	Anthracene	122
Fried foods cooked (N=13)	Anthracene	3.06
	Fluoranthene	3.49
	Benzo(g,h,i)perylene	0.32
Closet storage of chemicals ^a (N=6)	Benzo(a)anthracene	0.13
	Chrysene	0.40
	Indeno(1,2,3-cd)pyrene	0.20
Washer/drier in utility Room (N=16)	Naphthalene	410
	Acenaphthene	82.5
	Fluorene	41.8
	Phenanthrene	54.3
Dry clean periodically (N=13)	Naphthalene	481
	Acenaphthene	98.6
	Fluorene	51.2
Hair spray stored in home (N=18)	Acenaphthene	72.8
	Phenanthrene	47.5
Remodeling in last 6 months (N=14)	Chrysene	0.18
	Indeno(1,2,3-cd)pyrene	0.18
Electric heat ^b (N=3)	Naphthalene	796
	Acenaphthene	292
	Fluorene	153
	Phenanthrene	192
Spraywax Stored in Home (N=8)	Indeno(1,2,3-cd)pyrene	0.187
Bathroom storage of chemicals (N=15)	Naphthalene	424
	Acenaphthene	86.7

^a Based on six observations in one home

^b All emission factors significant at $p < 0.05$

samples of VOCs in homes with driers vented indoors, and that this activity resulted in an emission of 1,950 $\mu\text{g}/\text{h}$ of m,p-Xylene. Excluding methylene chloride, the significant emission factors for the kitchen-storage-of-chemicals variable included 220 $\mu\text{g}/\text{h}$ for o-xylene and 403 $\mu\text{g}/\text{h}$ for ethylbenzene. It is interesting to note that the storage of mothballs was associated with emissions of low molecular weight PAH compounds and that fried foods cooked was associated with PAH and elemental emissions. Table 13 also shows that significant emission factors were found for three PAH compounds resulting from one sample collected when a visitor smoked in a study home.

Discussion

Indoor and Outdoor Concentrations

Indoor VOC concentrations were highly variable. Similar to the TEAM study, the range of indoor VOC con-

centrations were within a factor of 10 to 1000. As indicated in Table 1, the indoor VOC concentrations, with the exception of methylene chloride, are generally comparable to the other studies. The outdoor PAH and VOCs concentrations are generally comparable to other studies in the Chicago area (Sweet and Vermette, 1992). The indoor and outdoor element concentrations appear to be in general agreement with results determined by other studies (Sweet et al., 1993; Sparks et al., 1990).

Factors Influencing Indoor Concentrations

The ten sample homes in the study were either single family homes (N=5) or town houses (N=5). Over half of the homes were over 35 years old. Only four of the homes had garages, however none were attached. None of the Altgeld Garden homes (N=5) had garages or basements. A majority of the homes reported using forced air heating, although only two homes had cen-

Table 14 Significant elemental emission factors, $\mu\text{g}/\text{h}/\text{unit}$ of activity

House characteristic	Compound	Emission factor ^b
Fried foods cooked (N=15)	Aluminum	134
	Calcium	1,660
	Iron	421
	Magnesium	621
	Zinc	36.6
Mothball storage (N=10)	Arsenic	0.65
	Selenium	0.54
Washer/drier vented indoors (N=17)	Cobalt	0.26
Closet Storage of Chemicals (N=6) ^b	Copper	13.3
Washer/Drier in Utility Room (N=16)	Magnesium	545
Glue Storage (N=12)	Copper	10.8
Hair spray Storage (N=19)	Magnesium	618
Spot-remover (N=16)	Copper	5.19

^a Based on six observations in one house

^b All emission factors significant at $P < 0.05$

tral air conditioning and four homes had window air conditioning units. There were correlations between the presence of a central air conditioning system and a forced air heating system ($r=0.41$) and between natural ventilation cooling (i.e., opening windows) and non-forced air heating systems ($r=0.33$). No significant trends were observed between home age and heating system. These correlations indicate the potential for measured variables to be acting as surrogates for other variables in the study or variables not measured. Pollutant source characteristics measured by the initial survey indicated that most homes stored paints, solvents, or other chemicals in the kitchen, basement, or closets. Half the homes indicated routine use of air fresheners, while only two homes stored or used mothballs. It should be noted again that no homes with smokers were included in the study.

Forty-two percent of the housing characteristics associated with increased indoor pollutant concentrations were either in the general categories of chemical storage or chemical storage area. VOCs had the largest number of positive concentration associations with predictor variables, followed by PAHs, and then elements. The predicted trend of increasing indoor VOC concentrations with the storage of chemicals and mothballs in the home, and storage of chemicals near the sampling stations was observed. The predicted trend of increasing PAH concentrations with mothball storage or use was also noted, which is consistent with the intent to supply a continuous source of naphthalene and other organics (i.e., p-dichlorobenzene) in the home.

Most of the PAH compounds with significant associations with survey variables had I/O ratios above 1, suggesting significant indoor sources. Elevated concen-

trations of phenanthrene ($P \leq 0.01$) and anthracene ($P \leq 0.001$) were observed in the presence of a visitor who smoked. Significantly ($P \leq 0.05$) higher concentrations of several VOC's including propylene, chloromethane, chloroethane, methylene chloride, n-octane, tetrachloroethylene, ethylbenzene, xylenes, and m-dichlorobenzene, were observed during use of air conditioning, however, 12.5 percent of the observations for air conditioning use were missing values, indicating a potential bias in this association. Elevated o-dichlorobenzene concentrations were observed with reported air freshener use, however, no significant association with p-dichlorobenzene was documented.

Infiltration

The continuous indoor monitoring of CO_2 in the homes during the sampling period was used with an estimate of CO_2 generation in the homes to calculate the sample specific infiltration. A linear regression between total CO_2 emissions and CO_2 concentrations revealed a correlation of $r^2=0.19$, suggesting the relationship between measured CO_2 concentrations and the estimated indoor CO_2 generation rate was satisfactory.

The calculated mean air exchange rate of 0.52 h^{-1} (standard deviation= 0.70) was in substantial agreement with air exchanges measured in other urban residential environments. In Colorado Springs, an average air exchange of 0.82 h^{-1} was reported in 23 homes (114 measurements) and in North Dakota, an average air exchange rate of 0.77 h^{-1} was reported for 17 homes (83 measurements) (Wadden and Scheff, 1982).

Penetration

An important factor in estimating the impact of outdoor elements on indoor element concentrations is penetration efficiency. Seven elements (Pb, Se, Al, Fe, Mg, Mn, and Zn) had significant ($P \leq 0.01$) Indoor/Outdoor correlation indicative of outdoor dominated sources. For these elements, the mean penetration efficiency is 0.89. A penetration efficiency of 0.89 suggests the building shell is only slightly effective at removing elements. It is interesting to note that of these seven elements, four elements (i.e., Al, Fe, Mg, and Zn) were determined to have significant indoor emissions when foods were cooked. If only penetrations from Pb, Se, and Mn are considered together as representative of elements without indoor sources, the mean penetration efficiency is 0.97. Koutrakis calculated penetrations between 0.84 and 0.89 (Koutrakis and Briggs, 1992). Dockery and Spengler (1981) calculated the penetration of fine sulfate particles equal to 0.65. More recently, Thatcher and Layton (1995) calculated penetration efficiencies of approximately 1.

Emission Factors

Many predictor variables had significant associations with pollutant emission rates, however, interpretation of these associations and examining the potential physicochemical mechanisms behind the associations is complex. For instance, the interpretation of the large number of associations between washer/drier-vented-indoors variable and pollutant emissions is difficult. Since the washer/drier-vented-indoors variable is correlated with the general categories of location and race, it is difficult to specifically designate this housing trait as the sole contributing source for the associated significant pollutant emission rates. Due to the large number of similarities between all the homes located in the Altgeld Gardens, it is not surprising that significantly different emission rates were observed between these homes and the remaining homes in the survey. Identification of specific housing traits or activities associated with increased pollutant emissions within this group is beyond the scope of the housing characteristic survey.

VOCs had the largest number of associations with the category of chemicals used, specifically when air freshener use was reported. Excluding methylene chloride, the VOC emission factors for reported air freshener use ranged from 67.5 $\mu\text{g}/\text{h}$ for o-dichlorobenzene to 3,700 $\mu\text{g}/\text{h}$ for propylene. The emission of VOCs with the reported use air fresheners has been documented previously. Pearson documented total VOC emission rates of 1.6×10^5 – 2.0×10^6 $\mu\text{g}/\text{m}^2/\text{h}$ from room deodorizers and Cohen observed elevated 1,1,1-trichloroethane and p-dichlorobenzene concentrations with air freshener use (Person et al., 1990; Cohen et al., 1989). In summary, the significant emission factors associated with reported air freshener use are limited by the sampling questionnaire format and sample size, but indicate interesting specific compound associations to be examined in future studies and reinforce the results of other studies that identified increased total VOC emissions with air freshener use.

We also noted the association of significant VOC emissions with the kitchen-storage-of-chemicals. All the indoor samples were collected in the kitchen, and it is not unrealistic that emission factors were associated with kitchen-storage-of-chemicals. The presence of emission factors for both ethylbenzene and o-xylene reflects a possible common solvent source located in the kitchen (i.e., miscellaneous cleaners beneath the kitchen sink).

In examining the associations between PAHs and predictor variables, the one event where smoking was reported (4 cigarettes) had significant associations with increased PAH emissions. PAH emission factors for this smoking event are reported in Table 13. Smoking

has been identified as the single largest source of PAHs in the indoor environment, and the PAHs with significant emission factors have been previously associated with smoking (Chuang et al., 1991). Many additional PAHs may also be associated with smoking activity in the home, and the identification of only three significant PAH emission factors likely reflects the small sample size ($N=1$). Additionally, due to the sampling questionnaire format, incidental smoking events may have been under-reported. The reported emission factors provide useful estimates of PAH emissions to be compared to future PAH studies and potentially used for exposure assessment.

Mothball storage was associated with significant emission factors for naphthalene, acenaphthene, phenanthrene, and fluorene. Naphthalene is a principle component of mothball crystals and elevated emissions associated with its presence are a function of this products use in the home. The significant emission factors associated with reported mothball storage are limited by this variable's 100% correlated status with race (Hispanic) and location (Torrence area).

Cooking activity was also associated with increased PAH emissions. The variable foods-cooked was found to have a significant association with increased emissions of anthracene, chrysene, benzo(a)pyrene, and benzo(g,h,i)perylene, regardless of cooking type (i.e., gas stove versus electric stove). When type of foods cooked was examined, fried foods was also found to have significant emission factors for anthracene, benzo(g,h,i)perylene, and fluoranthene. Only anthracene and benzo(g,h,i)perylene were also associated with both the categories of foods-cooked and fried-foods. Of these five PAHs associated with cooking activity, only anthracene had a significant association ($P \leq 0.05$) with estimated time spent cooking (0.05 $\mu\text{g}/\text{h}$ per cooking minute).

The USEPA Particle TEAM (PTEAM) study identified the two most important sources for elements were smoking and cooking. Element emission profiles associated with smoking and cooking were developed during the PTEAM studies. Elements associated with cooking included aluminum, iron, calcium, and chlorine (Wallace, 1996). Ozkaynak and others developed element emission rates from the PTEAM data and compared them to source and influencing factors (Ozkaynak et al., 1993). When cooking was identified as the source factor, Ozkaynak reported mean emission rates for Cu (36.2 $\mu\text{g}/\text{h}$), P (2.93 $\mu\text{g}/\text{h}$), Ca (869 $\mu\text{g}/\text{h}$), and Cl (318 $\mu\text{g}/\text{h}$). In the present study, Ca, Al, Fe, Mg, and Zn were elements with significant associations with cooking. As observed with PAHs, when type of foods cooked was examined closely, Al, Ca, Fe, Mg, and Zn

were found to have significant associations with the cooking of fried foods.

Conclusions

1. The mass balance model was a useful tool to assess sources and contributions to human exposures from indoor air pollutants.
2. Twenty-four-h average CO₂ measurements, indoor CO₂ generation, and a steady-state one-compartment mass balance model was used to determine ventilation in the homes studied. The mean air exchange rate of 0.52 h⁻¹ is consistent with studies of infiltration in residences located throughout the United States.
3. The penetration efficiency of 0.89 for the homes studied is comparable to other recent calculations of penetration efficiency. These findings suggest that small diameter particles penetrate the building shell with an efficiency approaching that of nonreactive gases.
4. A large variation in home-to-home and day-to-day source rates was observed for the measured pollutants.
5. Indoor VOC and PAH concentrations and emissions appear to be dominated by product use and occupant activities.
6. Indoor element concentrations are generally dominated by outdoor sources. The prominent source of indoor element emissions measured in this study was cooking activities.
7. Future studies involving the use of CO₂ as a meas-

urement of infiltration should include the measurement of occupant activities related to CO₂ generation.

8. Unknown sources account for a significant portion of the indoor emission rates for VOCs, PAHs, and elements. Additional studies should identify these unknown sources. Special attention should be focused on unknown indoor sources of PAHs and elements.

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