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RESIDENTIAL INDOOR AIR QUALITY, STRUCTURAL LEAKAGE AND OCCUPANT ACTIVITIES FOR 50 WISCONSIN HOMES

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Abstract

As part of an investigation into the influence of a residential weatherization program on indoor air quality and energy efficiency, a multi-pollutant survey of the air inside of 50 Wisconsin homes was conducted three times during the heating season of 1982-1983. Air infiltration, structural leakiness, and the presence and use patterns of indoor air pollutant sources during the same time period were also measured. Indoor air quality measurements included integrated sampling for nitrogen dioxide, respirable sized particulates, radon, formaldehyde, and carbon monoxide. Air infiltration rates were measured using a constant emission Sulfur Hexafluoride method; structural leakage area was determined using the fan pressurization ("blower door") technique. Household residents kept a stove and exhaust fan usage diary during each sampling period. Occupant activities related to the use of other pollutant sources or to intentional ventilation were also recorded.

Introduction

Variability in the levels of several indoor air pollutants measured in different households is related both to the presence and to the frequency of use of the pollutant source indoors. Gas stoves have been linked to elevated mean indoor nitrogen dioxide (NO_2) concentrations by several investigators (6, 11, 16, 18). However, there is considerable variability in these measurements between homes with gas stoves. Part of this variation might be attributable to differences in stove and exhaust fan usage (8, 13, 19, 23). In addition to these occupant specific characteristics of each home, are the differences in the structural and local climatic factors that influence the infiltration of outdoor air into the home, the dilution of pollutants released there, and their removal. Similar interactions between occupant activities and air infiltration in determining indoor air pollutant levels may exist for other combustion byproduct pollutants, such as carbon monoxide (CO) and respirable size particulate matter (3, 13, 20). For pollutants whose rate of release indoors is not directly controlled by the occupant, such as formaldehyde and radon, the source rate characterization and information regarding air exchange rates may be sufficient to explain between home differences in concentrations. However, the relationship between indoor radon levels and air infiltration rate may not be a simple one, since the entry of radon into the home from the soil may not be independent of those factors determining the flow of outdoor air into the home (4).

Methods

Study Design

Potential households were identified for this study based on their eligibility for energy assistance as part of a residential energy conservation program conducted by the Wisconsin Power and Light Company, and generally belonged to low-income or elderly individuals. Fifty homes were selected for participation in an indoor air quality assessment study, and occupants were recruited during a visit to the home by representatives of the utility and the university. As part of the utility's program, the homes are weatherized at no cost to the homeowner. Each home was sampled three times during the 1982 to 1983 heating season, to determine the levels of indoor air pollutants and air infiltration rates before the home weatherization, and the magnitude of variability between measurements made in the same home at different times.

All data entry and transcription activities were completely verified. The data entry programs were designed to perform validation checks of entered values against pre-specified acceptable value ranges.

Indoor Air Quality Measurements

Nitrogen dioxide (NO_2). Passive integrating samplers developed by Palmes et al. (15) were used for determining week-long average concentrations of NO_2 at four household locations: the kitchen, the bedroom, the room identified as being most frequently used (identified subsequently as the primary living area), and outside of the home. Criteria for monitor siting included placing these samplers at a height of 1.2 to 1.8 m, locating the kitchen monitor between 1.8 and 2.4 m from a gas stove or oven, and placing outdoor monitors on the shady side of the house at least 3 m away from driveways, garages or exhaust vents. An additional sampler was used in 50% of the homes as a co-located replicate.

Formaldehyde. Similar passive integrating devices, developed at Lawrence Berkeley Laboratory (5), were employed for monitoring formaldehyde (HCHO) concentrations over the corresponding time period. Two monitors were placed in each home, one in the main living area and the other alternated between a replicate sampler and placement in a bedroom on the same floor as the kitchen. These were suspended from the ceiling or a plant hanger near the center of the room, between 1.2 and 1.8 m from the floor.

Radon. Long-term average concentrations of radon (Rn) gas were determined using the passive Track-Etch(R) type SF radon detector (1). These were placed in the primary living area of each home, and 25% of the monitors were used as replicates.

Respirable particulates. Harvard/EPRI portable samplers (21) with Bendix cyclones were used for sampling respirable suspended particulates for approximately 24 hr time periods. Teflon filters were pre- and post-weighed with an electrobalance by Hazleton Raltech Laboratories to determine the mass of collected particulate matter. Sampler flow rates were measured before and after each sample was collected for estimation of the air volume sampled. For a subsample of homes, those with cigarette smokers were matched with a non-smoking household, based on selected home characteristics that might also influence indoor levels of polycyclic arometric hydrocarbons (PAHs). The factors controlled for in these tests included the use of other combustion sources (wood stove or fireplace, or gas stove), and of a kitchen exhaust fan. In these homes the particulate filter was followed by an XAD-II resin tube for collection of PAHs (22). These tubes were cleaned by the Hazleton Lab and stored in methylene chloride. After sampling, tubes and filters were refrigerated prior to methylene chloride extraction and analysis by high performance liquid chromatography (HPLC) for benzo(a)pyrene (14).

Carbon monoxide. A sample of indoor air was collected for the air infiltration testing described below. From this sample, an integrated average carbon monoxide (CO) concentration was measured using an Interscan Model 1146 CO-tector (Chatsworth, C.A., U.S.A.) carbon monoxide analyzer. This unit was calibrated with a known concentration of 25.1 ppm CO before each set of samples.

Infiltration and Structural Leakage Measurements

Infiltration rate. A constant emission tracer gas method was used for measuring air exchange rates during the active monitoring period. A cylinder of compressed sulfur hexafluoride was placed in the home approximately 24 hr before sampling began to allow the test structure to approach a steady state concentration (9). Flow rates from this source were measured before and after sampling using a micro bubble meter for measuring flow rates near 0.05 ml/min. The sampler consisted of a low cost pump, and a 555 timing circuit controlling a solenoid that directed flow into a 10 l gas sampling bag at an approximate sampling rate of one 0.2 sec sample every 20 seconds. This integrated average sample was analyzed using a Tracor 560 Gas Chromatograph with an electron capture detector to determine the average SF_6 concentration. Assuming that the outdoor concentration of SF_6 is negligible and that a single compartment model is appropriate, then a materials balance equation for the concentration C(t) of SF_6 is given by

$$V \frac{dC}{dt} = F - Q(t)\ C(t), \tag{1}$$

with F being the source flow rate (constant), Q(t) being the infiltration flow rate (m^3/hr), and V being the effective mixing volume of the test space (m^3). This can be solved as,

$$C = \frac{F}{Q} (1 - \epsilon^{-(Q/V)t}). \tag{2}$$

The first part of Equation 2 is the steady state concentration; the second part is the rate at which this concentration is reached. Solving for the infiltration flow rate (Q) and dividing by the volume of the test space yields the air exchange rate (hr^{-1}).

Leakage area. The fan pressurization/depressurization (blower door) technique (2, 10) was used to estimate the total effective leakage area (ELA) of the home. The 'blower door' apparatus (Energyworks, Inc., W. Newton, M.A., U.S.A.) consists of a large variable speed fan mounted on adjustable panels that are installed in the doorway, a digital tachometer to indicate fan speed, and a magnehelic pressure gauge to measure the induced indoor-outdoor pressure difference. This door was calibrated to yield the flow rate through the fan as a function of the fan RPM and the pressure difference. For each test, five equally spaced pressure differences between 12 Pa (0.05 in H_2O) and the maximum induced pressure difference were selected, and the fan RPM was recorded. Four tests were run in each home, two pressurization and two depressurization, except for homes with a wood burning stove or fireplace. External vents (kitchen, bathroom, heating and water heater flues) were sealed during the testing; their estimated passive effective leakage areas were added to the ELA estimated below (17).

Logarithms of induced flows and their corresponding pressure differences were plotted, and a least-squares regression line was fit with the form:

$$Q = K\ (\Delta P)^N, \tag{3}$$

where Q is the flow rate (m^3/hr), K is constant ($m^3/hr\text{-}Pa^n$), ΔP is the pressure difference (Pa), and N is the flow exponent in the range 0.5 to 1. This line was extrapolated to a reference pressure difference of 4 Pa, which is typical of the weather induced pressure differences that drive infiltration rates (12). Air flow through leakage sites in the building shell was assumed to be proportional to the square root of the pressure difference (orifice flow) (7), so that

$$ELA = Q_4 \; [(2/\rho)\Delta P]^{-\frac{1}{2}} \tag{4}$$

where Q_4 is the estimated flow at 4 Pa, and ρ is the density of air (1.2 kg/m^3). Tests with excessively high flow exponents and homes where the absolute difference between the mean pressurization and depressurization ELA's was greater than 20% were checked for data points that might be attributable to irregularities during the testing.

LBL model. Infiltration rates were estimated by combining the average ELA calculated from the blower door test, with locally collected weather data, and a classification of the terrain and shielding characteristics of the area surrounding the home using a model developed at Lawrence Berkeley Laboratory (12). This model characterizes natural infiltration air flow (Q) as wind (Q_w) and temperature (or stack, Q_s) induced flows added in quadrature:

$$Q = (Q_w^{\,2} + Q_s^{\,2})^{\frac{1}{2}}. \tag{5}$$

Q_w is a function of both the wind speed and the obstructions to wind flow present regionally (terrain class) and nearby the home (shielding class); Q_s is related to the horizontal leakage characteristics and ceiling height of the home, and to differences in air density due to the difference between indoor and outdoor temperature and the acceleration of gravity.

Outdoor temperature and wind speed data was collected from the nearest weather station for each community. Indoor temperature and relative humidity were recorded for the 24 hr sampling periods on a Weathertronics model 5020 hygrothermograph (West Sacramento, C.A., U.S.A.). The accuracy of the temperature was reported to be ±1% over the full scale, and the readings were checked at the beginning and end of each test using a precision grade laboratory thermometer. The hygrothermographs were placed in the primary living area on a small cart (height 0.76 m) away from direct sunlight, outside doors, and heating vents.

Household characteristics. A survey of physical parameters of the home was conducted in conjunction with the blower door testing. This included the preparation of a detailed diagram of each home, and recording of other values (e.g., height and shape of ceilings) needed for calculating the volume of conditioned areas in the home. A home characteristics questionnaire was completed early in the study to (1) identify the presence and estimate normal use patterns for potential pollutant sources in the home, (2) record the building characteristics, materials, and furnishings possibly related to the release of pollutants into the home or to the increase of ventilation rates, and (3) identify and describe the most frequently used room in the home for monitor placement.

Activity patterns. After each 24 hr sampling period, a follow-up questionnaire was administered to determine occupant activities that might influence pollutant generation or mitigation, including the number and location of cigarettes smoked, windows left open, cleaning activities, consumer product used (e.g., spray products), and to check for changes in home characteristics since the last sampling was completed. A stove, oven and vent use diary was left in the home for the week-long NO_2 sampling period. It was placed on a magnetic clip with a small digital clock attached; household residents were given instructions to record the times that these kitchen appliances were used.

Preliminary Results

Indoor air quality monitoring results for samples collected in the primary living area are summarized in Table 1. The distributions for several of these measurements are skewed, so that their means should be interpreted with care; medians are also presented in Table 1. Both the magnitude and the variability in NO_2 concentrations were higher in homes with gas stoves (mean 71.89, std. dev. 70.99 $\mu g/m^3$) than in homes with electric stoves (mean 13.12, std. dev. 6.83 $\mu g/m^3$). Similarly, the levels and variability of respirable particulate matter was higher in homes with cigarette smokers (mean 81.91, std. dev. 65.21), than in those where no one smoked in the same room as the sampler (mean 20.87, std. dev. 13.63). The relationships between these pollutants and their sources were explored in a series of preliminary stepwise multiple linear regression analyses, after outlying cases (possibly attributable to inadequate furnace or water heater venting) were removed.

For homes with gas stoves, time spent cooking (oven or stove) contributed an average of 2.2 $\mu g/m^3$ NO_2 per hour of cooking to the week long average NO_2 concentration. Conversely, exhaust fan use appeared to reduce these non-kitchen levels by 4.6 $\mu g/m^3$ NO_2 per hour of use. However, as shown in Table 2, combined stove and oven use averaged near 10 hours per week while the mean for vent use was only about ½ hour per week. This model was only able to explain approximately 45% of the variance about the mean for NO_2 levels measured in the primary living area. Other variables included an estimated air leakage at 50 Pa (obtained from the blower door model equation), and the presence of an attached garage. For homes with electric stoves, only 18% of the variation was explained by a model that included exhaust fan use, ELA, and the presence of a gas water heater. A similar model for particulate matter explained 27% of the variability by using the amount smoked in the sampled room together with the amount of time an air cleaner was operated during the sampling period. Both of these models should be viewed as only preliminary indications of the types of analyses yet to be performed on the data sets being collected by this study. Additional efforts are required to evaluate the types of models to be used for these measurements (e.g. log-normal distributions or non-linear relationships).

A summary of infiltration measurements and estimates is given in Table 2 for each monitoring period. Reasons for the differences between the LBL model and SF_6 air infiltration rates are being further investigated, as well as other infiltration models based on blower door measurements.

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References

(1) Alter, H.W., and Fleischer, R.L. Passive integrating radon monitor for environmental monitoring. Health Physics, 1981, 40, 693-702.

(2) Blomsterberg, A.K., and Harrje, D.T. Approaches to evaluation of air infiltration energy losses in buildings. ASHRAE Trans., 1979, 85(1), 797-815.

(3) Dockery, D.W., and Spengler, J.D. Indoor-outdoor relationships of respirable particles. Atmos. Environ., 1981, 15, 335-343.

(4) Doyle, S.M., Nazaroff, W.W., and Nero, A.V. Time-averaged indoor radon concentrations and infiltration rates sampled in four U.S. cities. Lawrence Berkeley Laboratory report, LBL-16595, 1983.

(5) Geisling, K.L., Tashima, M.K., Girman, J.R., Miksch, R.R., and Rappaport, S.M. A passive sampling device for determining formaldehyde in indoor air. Environment International, 1982, 8, 153-158.

(6) Goldstein, B.D., Melia, R.J.W., Chinn, S., Florey, C. du V., Clark, D., and John, H.H. The relation between respiratory illness in primary schoolchildren and the use of gas for cooking: II. Factors affecting nitrogen dioxide levels in the home. Int. J. Epidemiol., 1979, 8, 339-345.

(7) Grimsrud, D.T., Sherman, M.H., and Sonderegger, R.C. Calculating infiltration: Implications for a construction quality standard. Lawrence Berkeley Laboratory report, LBL-9416, 1982.

(8) Hollowell, C.D. Indoor air quality. Lawrence Berkeley Laboratory report, LBL-12887, 1981.

(9) Hunt, C.M. Air infiltration: A review of some existing measurement techniques and data. In Hunt, C.M., King, J.C., and Trachsel, H.R. (Eds.), Building Air Change Rate and Infiltration Measurements. Philadelphia: American Society for Testing and Materials, Special Technical Publication 719, 1980, pp. 1-24.

(10) Kronvall, J. Testing of houses for air leakage using a pressure method. ASHRAE Trans., 1978, 84(1), 72-79.

(11) Melia, R.J.W., Florey, C. du V., Darby, S.C., Palmes, E.D., and Goldstein, B.D. Differences in NO_2 levels in kitchens with gas or electric cookers. Atmos. Environ., 1978, 12, 1379-1381.

(12) Modera, M.P., Sherman, M.H., and Grimsrud, D.T. A predictive air infiltration model--Long-term field test validation. Lawrence Berkeley Laboratory report LBL-13509, 1981.

(13) National Academy of Sciences. Indoor Pollutants. Washington, D.C.: National Academy Press, 1981.

(14) Ogan, K., Katz, E., and Slavin, W. Determination of polycyclic aromatic hydrocarbons in aqueous samples by reversed-phase liquid chromatography. Analytical Chemistry, 1979, 51(8), 1315-1320.

(15) Palmes, E.D., Gunnison, A.F., DiMattio, J., and Tomczyck, C. Personal sampler for nitrogen dioxide. Amer. Ind. Hyg. Assoc. J., 1976, 37, 570-577.

(16) Palmes, E.D., Tomczyk, C., and DiMattio, J. Average concentrations in dwellings with gas or electric stoves. Atmos. Environ., 1977, 11, 869-872.

(17) Reinhold, C., and Sonderegger, R. Component leakage areas in residential buildings. Lawrence Berkeley Laboratory report LBL-16221, 1983.

(18) Spengler, J.D., Duffy, C.P., Letz, R., Tibbitts, T.W., and Ferris, B.G. Nitrogen dioxide inside and outside 137 homes and implications for ambient air quality standards and health effects research. Environ. Sci. and Technol., 1983, 17(3), 164-168.

(19) Spengler, J.D., Ferris, B.G., and Dockery, D.W. Sulfur dioxide and nitrogen dioxide levels inside and outside homes and the implications for health effects research. Environ. Sci. and Technol., 1979, 13, 1276-1280.

(20) Sterling, T.D., and Sterling, E. Carbon monoxide levels in kitchens and homes with gas cookers. J. Air Pollut. Control Assoc., 1979, 29(3), 238-241.

(21) Turner, W.A., Spengler, J.D., Dockery, D.W., and Colome, S.D. Design and performance of a reliable personal monitoring system for respirable particulates. J. Air Pollut. Control Assoc., 1979, 29(7), 747-749.

(22) Walcott, R.J., Paik, N., and Singh, J. Sampling and analysis of polynuclear aromatic hydrocarbons in the refinery environment. Paper presented at Amer. Hyg. Assoc. Conference, May, 1981.

(23) Working Group on Health Aspects Related to Indoor Air Quality (Bilthoven, 3-6 April 1979). Copenhagen: Regional Office for Europe, World Health Organization, Euro Reports and Studies, 1979, 21, 1-32.

Table 1. Summary Statistics for Indoor Air Monitoring.

Measurement	Mean	Standard Deviation	Median	N
NO_2 (μg/m^3)				
· Gas stove	71.89	70.99	54.89	80
· Electric	13.12	6.83	11.21	68
Formaldehyde (ppm)	0.031	0.016	0.028	145
Radon (pCi/l)	1.45	1.18	1.14	50
Respirable Suspended Particulate (μg/m^3)				
· Smoking	81.91	65.21	59.90	53
· No smoking	20.87	13.63	17.30	83
Benzo(a)Pyrene (μg/m^3)	1.61	2.17	0.49	28*

*21 of 49 samples were below the detectable limit of 0.2 ng of Benzo(a)pyrene.

Table 2. Summary of Ventilation and Occupant Activity Data.

Measurement	Mean	Standard Deviation	N
Infiltration (hr^{-1})			
· Dec.-Jan.	0.45	0.30	24
· Feb.-March	0.60	0.54	39
· April-May	0.53	0.53	42
LBL Model (hr^{-1})*			
· Dec.-Jan.	1.17	0.53	24
· Feb.-March	1.20	0.51	39
· April-May	1.06	0.49	42
ELA (cm^2)**	1302	527	49
Stove use (hr/wk)	6.93	4.99	142
Oven use (hr/wk)	2.98	3.58	142
Vent use (hr/wk)	0.32	1.00	142

*Corresponding to same time periods as infiltration tests.
**ELA = effective leakage area.