HEI HEALTH EFFECTS INSTITUTE

Nitrogen Dioxide and Respiratory Illness in Children

Part IV: Effects of Housing and Meteorologic Factors on Indoor Nitrogen Dioxide Concentrations

John D. Spengler, Margo Schwab, Aidan McDermott, William E. Lambert, and Jonathan M. Samet

Department of Environmental Health, Harvard School of Public Health, Boston, MA, Departments of Medicine and Family and Community Medicine, and the New Mexico Tumor Registry at the Cancer Research and Treatment Center, University of New Mexico Health Sciences Center, Albuquerque, NM

Includes the Commentary of the Institute's Health Review Committee

Research Report Number 58
December 1996

HEI HEALTH EFFECTS INSTITUTE

The Health Effects Institute, established in 1980, is an independent and unbiased source of information on the health effects of motor vehicle emissions. HEI studies all major pollutants, including regulated pollutants (such as carbon monoxide, ozone, nitrogen dioxide, and particulate matter), and unregulated pollutants (such as diesel engine exhaust, methanol, and aldehydes). To date, HEI has supported more than 150 projects at institutions in North America and Europe.

Typically, HEI receives half its funds from the U.S. Environmental Protection Agency and half from 28 manufacturers and marketers of motor vehicles and engines in the United States. Occasionally, funds from other public or private organizations either support special projects or provide resources for a portion of an HEI study. For this study, the Institute acknowledges the significant support of the Gas Research Institute. However, in all cases HEI exercises complete autonomy in setting its research priorities and in reaching its conclusions. An independent Board of Directors governs HEI. The Institute's Research and Review Committees serve complementary scientific purposes and draw distinguished scientists as members. The results of HEI-funded studies are made available as Research Reports, which contain both the Investigators' Report and the Review Committee's evaluation of the work's scientific quality and regulatory relevance.

HEI Statement

Synopsis of Research Report Number 58 Part IV

Measuring Indoor Nitrogen Dioxide Exposures: Effects of Housing and Meteorologic Factors

BACKGROUND

Nitrogen dioxide, a common indoor and outdoor air pollutant, is a by-product of high-temperature combustion. Motor vehicles and power plants are primarily responsible for the nitrogen dioxide in outdoor air. The U.S. Environmental Protection Agency has set the National Ambient Air Quality Standard for nitrogen dioxide as an annual average of 53 parts per billion (ppb) (100 $\mu g/m^3$). Although the annual average concentrations of nitrogen dioxide are well below 50 ppb in most regions of the United States, the standard is exceeded in areas of Southern California, and short-term peaks of 100 ppb and occasionally 200 ppb occur in urban areas in other parts of the country.

Indoor levels of nitrogen dioxide are often higher than outdoor levels, especially in homes with unvented heating and cooking appliances that utilize natural gas, kerosene, coal, or wood. Such exposures are of concern because some evidence indicates that nitrogen dioxide exposure may increase a person's risk of respiratory infection. However, because of methodologic problems, particularly the difficulty of assessing exposure, the evidence is not definitive. Measurements of indoor nitrogen dioxide exposure are important because they form the basis for epidemiologic studies that assess the health risks of outdoor nitrogen dioxide exposure and the subsequent air quality standards established. In the late 1980s, HEI supported a prospective investigation of more than 1,200 healthy infants living in homes with gas or electric cooking ranges in Albuquerque, NM. The main results on health outcomes and nitrogen dioxide exposures, as well as details on the quality assurance procedures, were published as Parts I, II, and III of this Research Report. A secondary goal of this study, which was necessary for addressing the main objective, was to obtain accurate assessments of nitrogen dioxide exposure in the study population. Part IV uses the nitrogen dioxide exposure data to characterize the influence of housing characteristics and meteorologic factors on indoor nitrogen dioxide levels.

APPROACH

Drs. John Spengler, Jonathan Samet, and their colleagues determined the impact of housing characteristics and the type and use of cooking ranges on nitrogen dioxide levels in infants' bedrooms in Albuquerque. Housing characteristics included the age, size, and type of construction of the house, the type of furnace, and the presence of a gas or kerosene space heater, fireplace, evaporative cooler, or attached garage. They also determined whether the cooking appliance was a gas range with a continuously burning pilot light, electronic ignition, or manually lit pilot light, or an electric range, whether the cooking range was used for space heating, and the minutes of stove use per season or year. The investigators focused most of their measurements on the winter season, when the use of many appliances that produce nitrogen dioxide is highest. They also studied seasonal and year-to-year variations.

RESULTS AND IMPLICATIONS

The results of this study confirm and extend those of previous studies of indoor nitrogen dioxide. Household characteristics that were associated with elevated levels of nitrogen dioxide in the infants' bedrooms were the presence of gas cooking appliances with continuously burning pilot lights, use of the gas stove or burners for space heating, the presence of wall or floor furnaces, and the size of the home (smaller homes have less volume to dilute the gas and fewer surfaces to adsorb it). Meteorologic factors that caused elevated nitrogen dioxide levels were decreasing temperature (which could increase the use of cooking and heating appliances) and increasing precipitation (which could decrease the exchange of indoor air with outdoor air). An important finding was the statistically significant year-to-year variability in average bedroom nitrogen dioxide concentrations. The variability could not be explained by changes in temperature, outdoor levels of nitrogen dioxide, or housing characteristics. This finding has implications for the design and interpretation of epidemiologic studies that use measurements of nitrogen dioxide concentration taken at one time to represent concentrations at different times and emphasizes the need to time repeated measures of nitrogen dioxide concentrations closely with measurements of health outcomes.

This Statement, prepared by the Health Effects Institute and approved by its Board of Directors, is a summary of a research project sponsored by HEI from 1987 through 1992. This study was conducted by Drs. Jonathan Samet, John Spengler, and their colleagues at the Harvard School of Public Health, Boston, MA and the University of New Mexico Health Sciences Center, Albuquerque, NM. Support for this study came from HEI, whose funding in this instance was derived from the U.S. Environmental Protection Agency, 28 motor vehicle manufacturers, and the Gas Research Institute. The following Research Report contains both the detailed Investigators' Report and a Commentary on the study prepared by the Institute's Health Review Committee.

Library of Congress Catalog Number for the HEI Research Report Series: WA 754 R432.
The paper in this publication meets the minimum standard requirements of the ANSI Standard Z39.48-1984 (Permanence of Paper) effective with Report Number 21, December 1988, and with Report Numbers 25, 26, 32, 51, and 65 Parts IV, VIII, and IX excepted. These excepted Reports are printed on acid-free coated paper.

TABLE OF CONTENTS

Research Report Number 58

Nitrogen Dioxide and Respiratory Illness in Children
Part IV: Effects of Housing and Meteorologic Factors on Indoor Nitrogen Dioxide Concentrations

John D. Spengler, Margo Schwab, Aidan McDermott, William E. Lambert, and Jonathan M. Samet

Nitrogen Dioxide and Respiratory Illness in Children

Part IV: Effects of Housing and Meteorologic Factors on Indoor Nitrogen Dioxide Concentrations

John D. Spengler, Margo Schwab, Aidan McDermott, William E. Lambert, and Jonathan M. Samet

ABSTRACT

In a prospective study of infants' exposure to nitrogen dioxide (NO_2)* and respiratory illness, NO_2 concentrations were measured in more than 1,400 homes in Albuquerque, NM, from January 1988 through June 1991 (Health Effects Institute Research Report Number 58, Parts I, II, and III). This report characterizes the variability in indoor NO_2 concentrations across seasons and years, and identifies factors associated with variation in concentrations between homes and across seasons. In regression analyses of winter data, NO_2 levels in the infants' bedrooms were predominately determined by the presence of gas cooking ranges with continuously burning pilot lights, the presence of wall or floor furnaces, the use of the stove for space heating, and the square footage of the living space. These findings are consistent with previously published analyses of data from homes in other U.S. cities. Relatively small differences in seasonal bedroom NO_2 levels were observed across years. The correlation coefficient (r) of bedroom NO_2 levels obtained in the same homes was 0.66 over two winters and 0.48 over two summers. For homes that had gas cooking ranges with continuously burning pilot lights, the bedroom NO_2 concentrations differed, on average, less than 5 parts per billion (ppb) across winters. These differences were hypothesized to be caused by differences in the use of indoor NO_2 sources, ventilation, and ambient (outdoor) NO_2 levels. We were, however, unable to demonstrate an association between year-to-year differences in seasonal indoor NO_2 concentrations and reported use of cooking range, furnace, or heater, or ambient NO_2 levels, or temperature.

INTRODUCTION

Nitrogen dioxide is a commonly occurring pollutant in indoor air and in the outdoor air of urban areas. It is produced during high-temperature combustion; nitrogen in air combines with oxygen to form oxides, some of which are converted to NO_2 (Atkinson 1988). Sources of NO_2 in outdoor air include motor vehicles, power plants, and industry. Important sources of this pollutant in the indoor setting include unvented cooking and heating appliances that utilize natural gas or kerosene. Surveys of urban residents indicate that the NO_2 exposure received inside homes is the largest contributor to total personal exposure, because indoor sources can raise concentrations in residences well above those found outdoors (Spengler et al. 1983) and people spend a large amount of time inside their homes (Szalai 1972; Jenkins et al. 1992).

Exposures of the population to indoor and outdoor NO_2 have been the focus of monitoring studies in Northeastern cities (Spengler et al. 1983; Leaderer et al. 1986; Goldstein et al. 1988; Ryan et al. 1988a,b, 1990), the Midwest (Quackenboss et al. 1986), and southern California (Wilson et al. 1986; Spengler et al. 1990; Schwab et al. 1994). These descriptive studies provided some understanding of the determinants of NO_2 concentrations in residences. Analyses of these databases (Drye et al. 1989) have demonstrated that indoor NO_2 concentrations are primarily determined by the presence and strength of indoor NO_2 sources, the rate of exchange of indoor air with outdoor air, and the infiltration of NO_2 from outdoor air. However, few studies of indoor NO_2 levels have been conducted in the southwestern United States (Lebowitz et al. 1985; Marbury et al. 1988), where housing characteristics, occupant behaviors, and climate may differ from those studied previously and may result in different patterns of residential exposure.

* A list of abbreviations appears at the end of the Investigators' Report.

This Investigators' Report is one part of Health Effects Institute Research Report Number 58, Part IV, which also includes a Commentary by the Health Review Committee, and an HEI Statement about the research project. Parts I and II (Health Outcomes by Samet and colleagues, and Assessment of Exposure to Nitrogen Dioxide by Lambert and coworkers) were published by the Health Effects Institute in June of 1993. Part III (Quality Assurance in an Epidemiologic Study by Lambert and associates) was published in July of 1994. Part V (Frequency of Infants' Exposure to "Peak" Concentrations of NO_2 in Homes with Gas Cooking Stoves by Samet and coworkers) is forthcoming. Correspondence concerning the Part IV Investigators' Report may be addressed to Dr. John D. Spengler, Department of Environmental Health, Harvard School of Public Health, 665 Huntington Avenue, Boston, MA 02115.

This study was supported by funds from the U.S. Environmental Protection Agency, the motor vehicle industry, and the Gas Research Institute.

In this report, we examine potential determinants of indoor NO_2 concentrations in more than 1,400 homes in Albuquerque, NM. The analyses use measurements collected from January 1988 through June 1991 for a prospective cohort study of the relation between NO_2 exposure and respiratory infections in infants (Samet et al. 1992, 1993; Lambert et al. 1993). In contrast to the majority of the previous studies of indoor NO_2 levels (Goldstein et al. 1979; Dockery et al. 1981; Spengler et al. 1983, 1990; Clausing et al. 1986; Leaderer et al. 1986; Noy et al. 1986; Quackenboss et al. 1986; Wilson et al. 1986; Ryan et al. 1988a,b, 1990), in the Albuquerque study repeated measurements were made across several successive seasons as the subjects were followed during the first 18 months of life. This extensive data set provides more accurate estimations of seasonal mean concentrations than most previous studies (Lambert et al. 1992). This report examines predictors of indoor concentrations of NO_2 including housing characteristics, occupant behaviors, and meteorologic factors.

SPECIFIC AIMS

The goal of these analyses was to characterize the influence of housing characteristics (e.g., appliances, construction, and volume), occupant behaviors (e.g., cooking range, furnace, and heater use), and meteorologic factors (e.g., temperature and precipitation) on NO_2 concentrations in a sample of homes in Albuquerque. The specific objectives of the analyses were:

1. To identify the major determinants of seasonal average indoor NO_2 concentrations;
2. To characterize seasonal variability in indoor NO_2 concentrations and to identify housing, occupant, and meteorologic factors associated with this seasonal variability; and
3. To characterize the year-to-year variability in indoor NO_2 concentrations and to identify housing, occupant, and meteorologic factors associated with this annual variability.

METHODS

SELECTION OF HOUSEHOLDS AND TIME FRAME OF MONITORING

The overall design of the cohort study and criteria for the selection of subjects have been described previously (Samet et al. 1992, 1993). From January 1988 through June 1991, approximately 35 subjects were enrolled per month. The sample of households was selected with stratification by type of cooking range: 25% electric and 75% gas. A total of 1,315 infant subjects were enrolled, and 823 subjects (63%) completed the full 18 months of follow-up. Because 185 subjects changed residences at least once during follow-up, NO_2 measurements were available from 1,416 houses (Lambert et al. 1993). The NO_2 monitoring for the entire sample covered four calendar years. The analyses presented in this report are based on data collected from April 1988 to April 1991; before and after this period, sample sizes were too small for meaningful statistical analyses. Data from the winter seasons (November 1 through March 15) of 1988/89 and 1989/90 were used to estimate the effects on NO_2 concentrations of indoor sources and of variables determining dilution of NO_2, air exchange, and removal of NO_2.

NITROGEN DIOXIDE MONITORING

The protocol for measuring NO_2 was based on the results of the pilot studies for this project (Harlos et al. 1987; Marbury et al. 1988; Samet and Spengler 1989). Two-week integrated samples of NO_2 were collected by placing passive diffusion samplers called "Palmes tubes" (Palmes et al. 1976) inside each subject's home and at 11 outdoor locations throughout the city. The details of sampler tube placement, laboratory analysis, and quality assurance practices are described in Part III of this Research Report (Lambert et al. 1994). In homes with gas ranges, consecutive two-week samples were obtained in the bedrooms of the subjects from the time of their enrollment until they reached 18 months of age. During alternate months in the winter, two-week samples were taken from the activity room (i.e., living room or family room) and the kitchen. In homes with electric ranges, samples were obtained in the subjects' bedrooms every other two-week cycle throughout follow-up; no samples were collected in other rooms. A small number of four-week samples were also collected at the beginning of the study. This analysis focuses on the measurements made in the infants' bedrooms because these measurements provide the most complete coverage for longitudinal analyses.

Home visits were conducted at the time of subject enrollment and when a change of residence occurred. Technicians placed the first set of NO_2 sampler tubes in the home according to standardized criteria, and instructed the parents in their use. The parents (usually the mothers) made subsequent exchanges of the samplers and were prompted to do so during biweekly telephone calls from field technicians.

ASSESSMENT OF HOUSING CHARACTERISTICS AND COOKING RANGE USE

At enrollment, technicians assessed housing characteristics by interview and direct observation. Information was collected on construction characteristics, appliances, and size of the residence. During follow-up, information was also obtained at two-week intervals on the number of minutes that the stove top or oven had been used during the previous 24 hours. At the midpoint of follow-up (when the subject was 9 months of age) and upon completion of participation, the parents were asked about use of the stove for space heating, and changes in cooking and space heating appliances.

DATA ANALYSIS

The data were initially edited for outlying values and exposure durations. Data editing involved several steps. Samples with missing or erroneous information on exposure duration (4% of the available samples) were removed. All samples with concentrations less than or equal to the limit of detection of 1 ppb reported for Palmes tubes (Boleij et al. 1986) were recoded as 1 ppb (4%). Those samples from tubes opened to exposure for durations of less than one week or more than six weeks or from tubes opened twice (e.g., sampler tubes were closed during a vacation and reopened upon return) were removed (2%). The median duration of exposure of the remaining tubes was 15 days.

For each household, each day of observation was assigned a NO_2 value based on the availability of data. For example, if a tube was open for 15 days, all 15 days during that monitoring cycle were assigned the average concentration associated with that integrated sample. In the event that two sampler tubes were exposed on the same day (e.g., the day on which sampler tubes were changed), the NO_2 level measured for the preceding interval was assigned to that day. For homes with electric ranges, the four-week samples collected during the early months of the study were used to fill in the gaps when two-week samples were not available. Days on which NO_2 measurements were not made were assigned a missing value.

Previous studies have shown that the type of cooking range is usually the strongest determinant of indoor NO_2 levels (Goldstein et al. 1979; Spengler et al. 1983, 1990; Leaderer et al. 1986; Quackenboss et al. 1986; Wilson et al. 1986; Ryan et al. 1988a,b, 1990). Thus, using range type, we stratified the sample into three groups: homes with electric ranges, homes with gas ranges with continuously burning pilot lights, and homes with gas ranges with electronic ignition or manually lit pilot lights. Because the analyses presented in this report focused on the house rather than the child, each time a subject changed residence during the study period (5% of the subjects), the data were treated as a separate observation or household.

Because seasonal variation in NO_2 concentrations has been found in other locations (Spengler et al. 1983; Wilson et al. 1986; Ryan et al. 1988a,b), we stratified the data set into winter and summer periods. A review of climatologic data for 1988 through 1992 (National Oceanic and Atmospheric Administration 1988–1992) indicated that "winter" could be reasonably defined as cooler months (November 1 through March 15) when daily mean temperatures averaged 35°F to 40°F and "summer" as warmer months (May 1 through September 30) when temperatures averaged 65°F to 80°F. When these definitions were applied to the 30-year climatologic record for Albuquerque (National Oceanic and Atmospheric Administration 1990), 80% of the average year's heating-degree days were in the winter and 15% in the summer. (A heating-degree day is defined as one during which the maximum temperature is lower than 65°F, and a heating-degree-day unit is calculated as the absolute difference between the daily maximum temperature and 65°F.) The transition periods between winter and summer seasons were excluded from the analyses. Individual NO_2 measurements were assigned to the season associated with 75% or more of the particular sampling period. Therefore, a typical two-week sampling period whose beginning and ending days straddled a season boundary was assigned to the season in which 10 or more days were represented, or it was censored from the data set.

Several studies have documented increased indoor NO_2 levels during the winter when air exchange rates tend to be lower and use of heating appliances is more intensive (Spengler et al. 1983; Quackenboss et al. 1986; Wilson et al. 1986; Ryan et al. 1988a). In the Albuquerque study, bedroom concentrations in homes with gas ranges averaged 6 ppb higher in the winter (21 ppb) than the summer (15 ppb) (Lambert et al. 1993). In order to document the effect of indoor NO_2 sources, this analysis focuses on the measurements collected from samples during the cooler months of the year. The analyses presented in this report use the bedroom samples collected during the winters (November 1 through March 15) of 1989/90 and 1990/91.

RESULTS

SECTION 1: DETERMINANTS OF BEDROOM NITROGEN DIOXIDE CONCENTRATIONS

Overview

Factors contributing to the variation in NO_2 across homes were assessed using a three-step modeling approach. First, data collected during the winter of 1989/90 were used to test housing characteristics, particularly indoor NO_2 sources and ventilation factors, as predictors of average bedroom NO_2 levels. Linear regression was used to test the effect of each characteristic individually, and then multivariate linear models were constructed. Models were applied to both untransformed (arithmetic) and natural logarithm–transformed mean bedroom NO_2 levels to evaluate the impact of the skewed distribution of the outcome variable. In the second stage of analysis, we explored the effects on bedroom NO_2 levels of ambient temperature and precipitation. In the third stage of analysis, the multivariate model was validated by employing the models generated from data for the winter of 1989/90 to predict bedroom NO_2 levels in a separate set of households monitored during the previous winter of 1988/89.

Description of the Data Set

The data set used in this analysis consisted of measurements from 766 houses for the winter period of 1989/90, of which 77% had gas cooking ranges. For homes with gas ranges, the median number of NO_2 measurements available was 7 (interquartile range 4 to 8), which met quality control criteria; for homes with electric ranges, the median number of measurements available was 3 (interquartile range 2 to 3). In total, 398 homes with gas ranges and 125 homes with electric ranges were available from the winter of 1988/89 for validation of the predictive models. In the validation data set, the median number of NO_2 measurements available for homes with gas ranges was 7 (interquartile range 4 to 8) and the median number of measurements available for homes with electric ranges was 2 (interquartile range 2 to 3).

Housing and Occupant Characteristics Associated with Indoor Nitrogen Dioxide Concentrations

Table 1 shows the percentage distribution of the housing and occupant characteristics across homes monitored for NO_2 levels during the winter of 1989/90. Of the homes with gas ranges, 58% had pilot lights. The residence characteristics were fairly homogeneous with respect to factors other than the type of cooking range. Central forced-air furnaces were the main type of heating system for most homes. Floor or wall furnaces were used in 17% of the homes with gas ranges with continuously burning pilot lights, 8% of the homes with gas ranges without pilot lights, and 11% of the homes with electric ranges. Other types of heating systems such as solar or wood-burning, or no heating system, were reported for 17% of the homes with gas ranges without pilot lights and 10% of the homes with other range types.

The average house size was 1,213 sq ft (standard deviation [SD] = 517 sq ft) for homes with gas ranges with continuously burning pilot lights, 1,578 sq ft (SD = 737 sq ft) for homes with gas ranges without pilot lights, and 1,619 sq ft (SD = 776 sq ft) for homes with electric ranges. Homes built before 1970 averaged 1,157 sq ft (SD = 470 sq ft), whereas homes built after 1970 averaged 1,567 sq ft (SD = 765 sq ft). Among homes with gas cooking ranges with continuously burning pilot lights, 51% had attached garages versus 81% of the homes with gas ranges without pilot lights or 80% of the homes with electric ranges.

Homes with gas stoves with continuously burning pilot lights were less likely to have fireplaces (35%) than those with gas ranges without pilot lights (47%) or those with electric ranges (59%). Only 2% of households with gas ranges with continuously burning pilot lights reported owning unvented gas or kerosene space heaters. In 9% of homes with gas ranges, parents reported using their range for space heating. Most homes, irrespective of the type of stove, had evaporative air cooling units: 89% for homes with gas ranges with pilot lights, 94% for homes with gas ranges without pilot lights, and 87% for homes with electric ranges. Only 10% of homes with electric ranges and 5% of homes with gas ranges had refrigerated air conditioning units.

Univariate Relations

Table 2 shows the distributions of average NO_2 concentrations for the winter of 1989/90 by type of cooking range

Table 1. Selected Characteristics of Households Monitored for Bedroom Nitrogen Dioxide Levels by Type of Cooking Range[a]

Household Characteristic	Gas Range With Pilot Light[b] (%)	Gas Range Without Pilot Light[c] (%)	Electric Range[d] (%)
Wall or floor furnace	17	8	11
Older home (built before 1970)	34	47	25
Attached garage	51	81	80
Fireplace	35	47	59
Gas or kerosene space heater	2	4	5
Microwave oven	81	85	88
Evaporative cooler	89	94	87
Use range burners or oven for space heating	11	5	4

[a] Data are based on a sample of 766 homes from winter 1989/90.

[b] Gas ranges with pilot lights were present in 349 homes.

[c] Gas ranges with electronic (spark) ignition were present in 240 homes.

[d] Electric ranges were present in 177 homes.

Table 2. Distribution of Average Bedroom Nitrogen Dioxide Concentrations (ppb) for Winter 1989/90 by Selected Household Characteristics and Type of Cooking Range

	Gas Range With Pilot Light			Gas Range Without Pilot Light			Electric Range		
	n	Mean (SD)	Median	*n*	Mean (SD)	Median	*n*	Mean (SD)	Median
Furnace type									
Floor or wall	52	44.7 (32.1)	35.6	18	23.4 (14.0)	19.4	17	12.5 (7.4)	10.2
Central	260	20.6 (10.6)	20.0	198	15.3 (13.0)	13.0	138	6.7 (4.3)	5.9
Year home built									
Before 1970	104	37.3 (28.2)	29.3	93	24.4 (22.9)	18.9	40	10.4 (5.3)	9.0
After 1970	202	18.9 (8.7)	17.6	106	9.4 (6.2)	7.4	120	6.0 (4.2)	4.9
Attached garage									
Yes	179	22.0 (14.5)	19.0	195	14.9 (10.4)	12.6	141	6.9 (5.0)	6.0
No	169	22.5 (31.7)	24.6	45	25.7 (30.4)	18.2	36	8.6 (4.3)	7.6
Fireplace									
Yes	123	24.1 (22.3)	19.0	112	13.1 (15.8)	9.0	105	6.3 (3.5)	6.0
No	225	29.4 (26.3)	23.4	128	22.2 (16.7)	17.1	72	8.5 (6.1)	7.0
Gas or kerosene space heater									
Yes	7	35.5 (20.3)	33.0	9	17.9 (9.7)	14.9	8	7.7 (4.7)	7.6
No	342	27.4 (25.1)	21.6	231	16.9 (16.8)	13.8	169	7.7 (4.7)	7.6
Microwave oven									
Yes	283	25.1 (21.7)	20.6	205	16.2 (16.0)	13.1	155	7.1 (4.9)	6.0
No	66	37.9 (34.4)	28.4	35	21.0 (19.7)	17.5	22	8.3 (4.2)	8.1
Evaporative cooler									
Yes	310	26.8 (24.2)	21.2	224	16.3 (15.0)	13.2	154	7.3 (4.9)	6.3
No	39	33.1 (30.4)	25.0	15	26.5 (32.1)	18.1	23	6.8 (4.3)	5.7

and other household characteristics. Table 3 shows the differences in the mean bedroom NO_2 concentrations and the statistical significance of the differences by range type and by selected household characteristics. Several trends are apparent across the different range types. Median concentrations are 49% to 78% higher for residences with floor or wall furnaces than for those with central forced-air heating, 66% to 155% higher for residences built before 1970 than for those built after 1970, 23% to 30% lower for residences with attached garages, 14% to 47% lower for residences with fireplaces, and 25% to 27% lower for residences with microwave ovens. Among homes with gas cooking ranges, the median concentration was 20% lower in homes with evaporative coolers; however, the median concentration in homes with electric ranges was 10% higher for those with evaporative coolers. These trends in mean winter bedroom NO_2 concentrations were generally statistically significant (Table 3).

Table 3. Average Difference in Mean Winter Bedroom Nitrogen Dioxide Concentrations (ppb) by Selected Household Characteristics and Type of Cooking Range

Household Characteristic	Gas Range With Pilot Light	Gas Range Without Pilot Light	Electric Range
Furnace type, floor or wall vs. central	24[a]	8[a]	6[a]
Year home built, before 1970 vs. after 1970	18[a]	15a	4[a]
Attached garage, present vs. absent	−1	−11[b]	−2[a]
Fireplace, present vs. absent	−5[b]	−9[a]	−2[a]
Gas or kerosene space heater, present vs. absent	8	1	0
Microwave oven, present vs. absent	−13[a]	−5	−1
Evaporative cooler, present vs. absent	−6	−10	1

[a] Difference in means based on Student's t test is statistically significant with a value of $p < 0.01$.

[b] Difference in means based on Student's t test is statistically significant with a value of $p < 0.05$.

Stratified analyses were performed to determine whether trends in bedroom NO_2 concentrations by range type remained consistent across categories including other indoor NO_2 sources and household characteristics (Table 4). Consistent and statistically significant differences were observed in all but a few of the strata.

The dominance of gas-fueled ranges as a source of indoor NO_2 is clear in the cumulative distribution plots of average bedroom NO_2 concentration by type of cooking range (Figure 1). Homes in the upper end of the distributions tended

Table 4. Z Scores[a] of Differences in Mean Winter Bedroom Nitrogen Dioxide Concentrations by Selected Household Characteristics Within Strata of Cooking Range

Household Characteristic	Gas Range With vs. Without Pilot Light	Gas Range Without Pilot Light vs. Electric Range
Furnace type		
Floor or wall	3.84[b]	2.90[b]
Central	4.67[b]	8.65[b]
Year home built		
Before 1970	3.54[b]	5.56[b]
After 1970	11.06[b]	4.76[b]
Attached garage		
Present	5.40[b]	9.35[b]
Absent	−0.62[b]	3.73[b]
Fireplace		
Present	4.39[b]	4.44[b]
Absent	3.14[b]	8.34[b]
Gas or kerosene space heater		
Present	2.11[b]	2.81[b]
Absent	6.00[b]	7.91[b]
Microwave oven		
Present	5.21[b]	7.68[b]
Absent	3.14[b]	3.68[b]
Evaporative cooler		
Present	6.17[b]	8.35[b]
Absent	0.69	2.36[c]

[a] Because variances are known and sample sizes are large, Z is used as the test statistic.

[b] Difference in means based on a standard normal distribution and two-tailed test is statistically significant with a value of $p < 0.01$.

[c] Difference in means based on a standard normal distribution and two-tailed test is statistically significant with a value of $p < 0.05$.

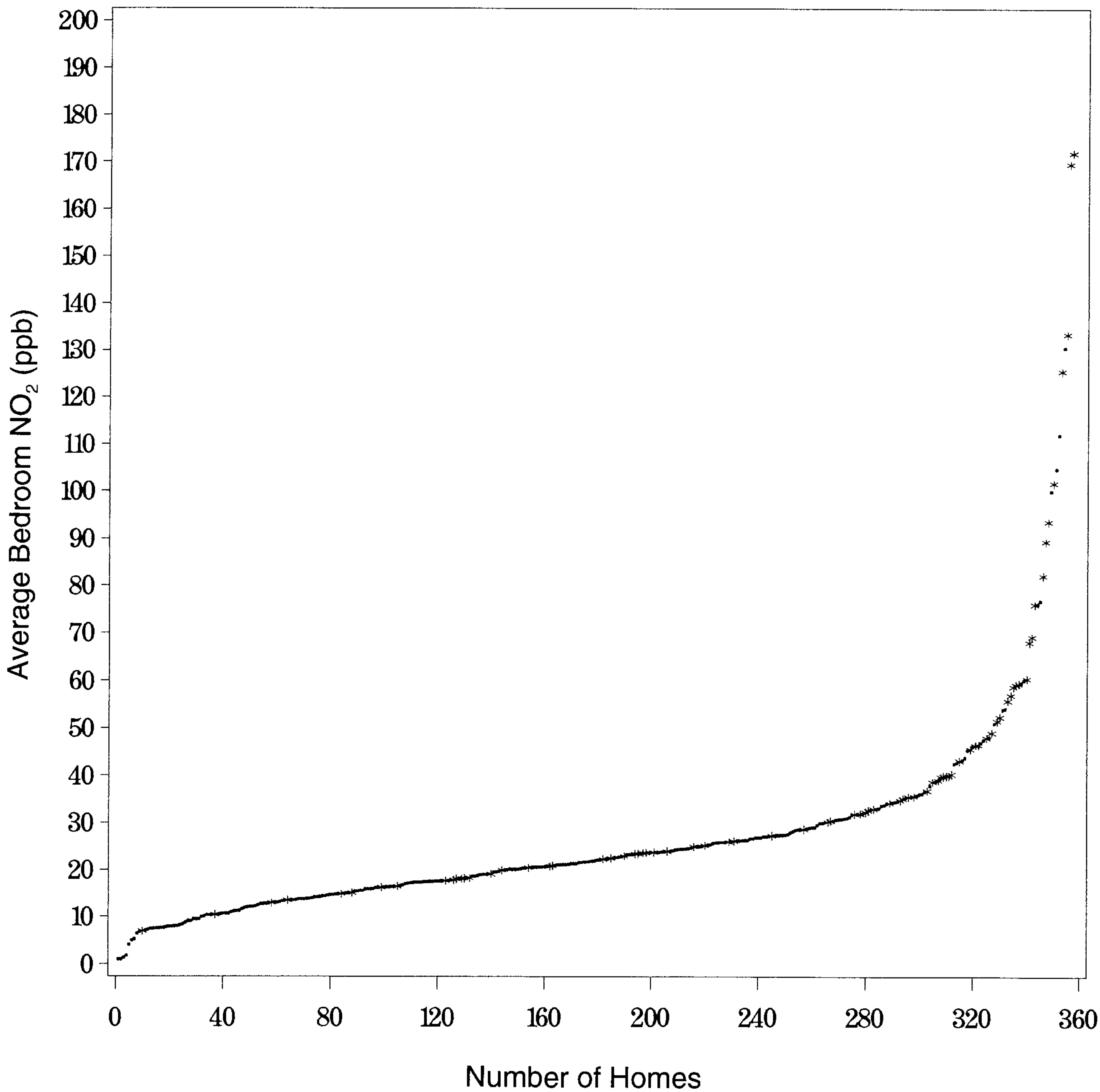

Figure 1A. Cumulative distribution of average winter bedroom NO_2 concentrations by type of cooking range: Gas range with continuously lit pilot light. * = homes with a floor or wall furnace, or a gas or kerosene space heater, or in which the cooking range was used for space heating; ● = all other homes.

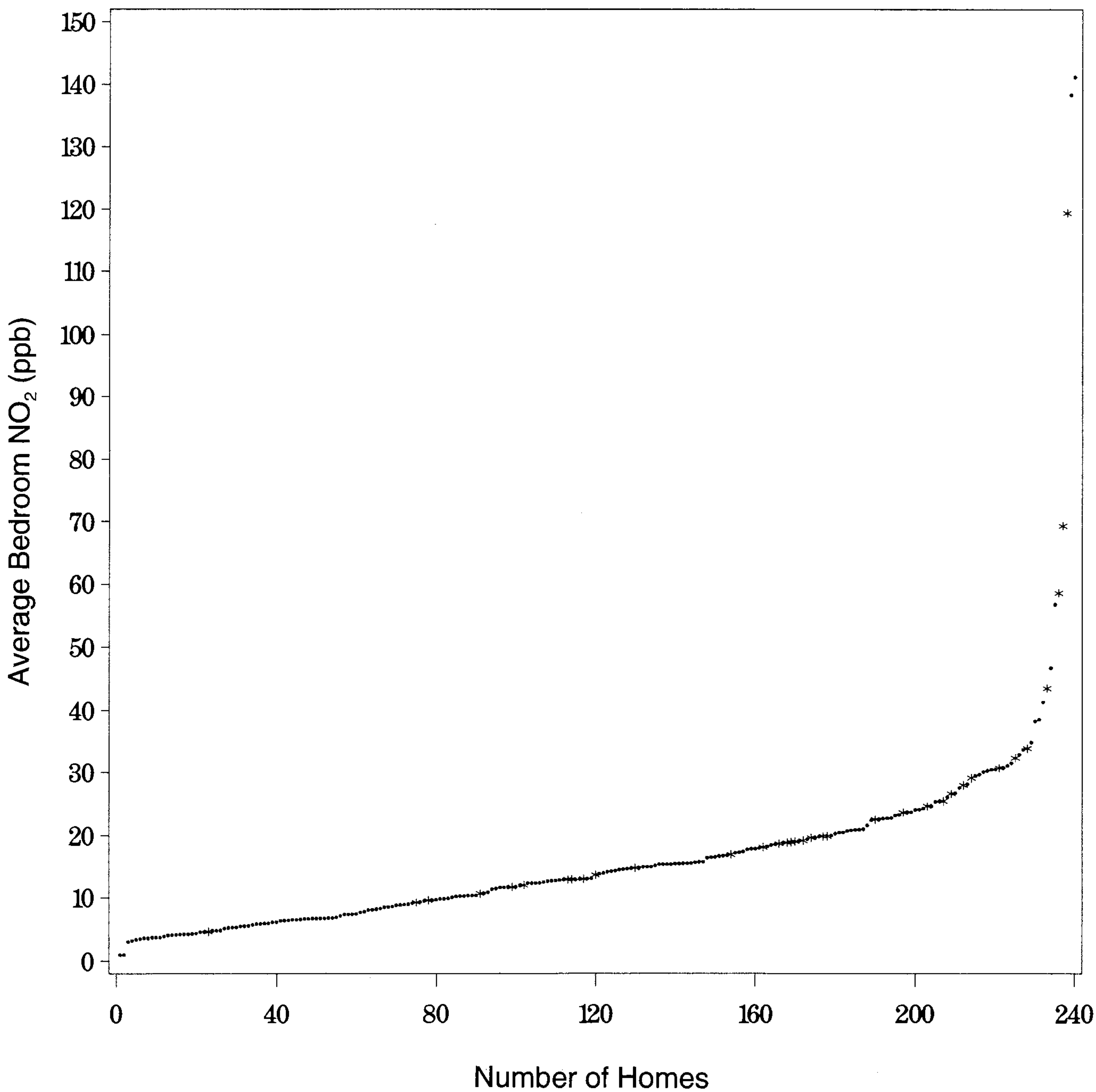

Figure 1B. Cumulative distribution of average winter bedroom NO_2 concentrations by type of cooking range: Gas range without continuously lit pilot light. * = homes with a floor or wall furnace, or a gas or kerosene space heater, or in which the cooking range was used for space heating; ● = all other homes.

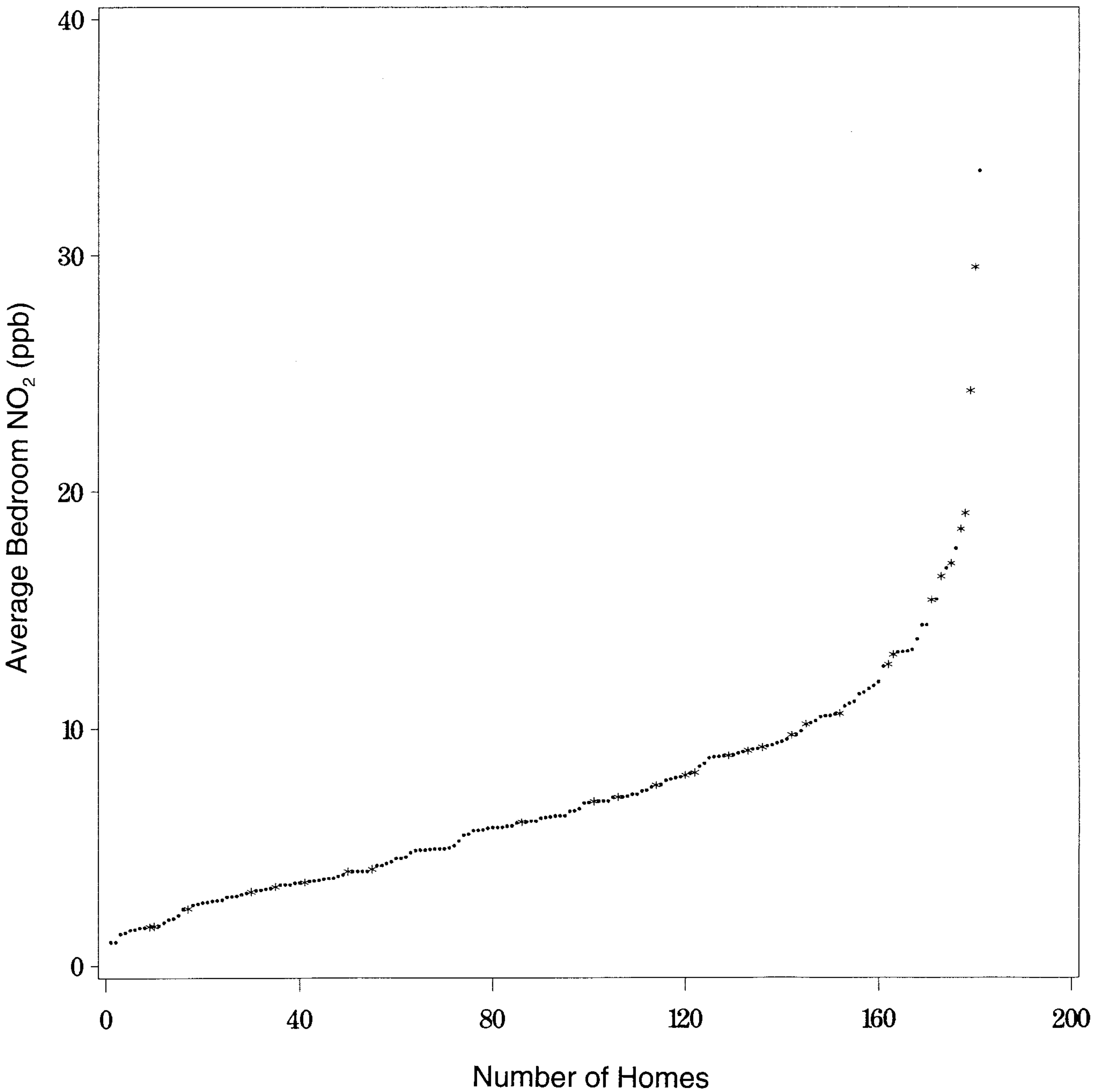

Figure 1C. Cumulative distribution of average winter bedroom NO_2 concentrations by type of cooking range: Electric range. * = homes with a floor or wall furnace, or a gas or kerosene space heater, or in which the cooking range was used for space heating; ● = all other homes.

to have floor or wall furnaces, and their occupants tended to use the range for space heating, or to use kerosene or gas space heaters.

During the winter, bedroom NO_2 concentrations varied inversely with the house size, represented by the living area in square feet (Figure 2). This finding follows theoretical expectations (Drye et al. 1989) of lower indoor NO_2 levels due to greater dilution and increased indoor surface area available for reaction of NO_2 (Pitts et al. 1989; Brauer et al. 1993). The multiple correlation coefficient (R^2) between the inverse of house size (1/area [sq ft]) and bedroom NO_2 was 0.22 ($p = 0.0001$) for homes with gas cooking ranges with pilot lights, 0.06 ($p = 0.0001$) for homes with gas ranges without pilot lights, and 0.07 ($p = 0.004$) for homes with electric ranges. This pattern of R^2 values may reflect the relative strengths of NO_2 sources and also the house size and age. Homes with gas cooking ranges with continuously burning pilot lights tended to be smaller and older than those with electric ranges or gas ranges with electronic ignition.

The distance of the infant's bedroom from the kitchen indicates the potential for dilution and chemisorption of NO_2 emitted by the cooking range before it reaches the sampler tube in the bedroom. The average distance between the kitchen and the bedroom was 28 ft for homes with continuously burning pilot lights, and 32 ft for homes with electric ranges or gas ranges without pilot lights. In regression models, the distance to the bedroom and the inverse square-footage of the home together explained 24% of the variability in average bedroom NO_2 levels for homes with gas ranges with continuously burning pilot lights, 11% for homes with gas ranges without pilot lights, and 6% for homes with electric ranges.

Multivariate Models

To estimate the effects of the household characteristics discussed above on bedroom NO_2 concentrations, we modeled the data from the winter of 1989/90. The sample of homes used in these analyses was restricted; homes with characteristics that were not representative of the sample at large were excluded. The characteristics of the censored homes included occupants who used the gas range for heat ($n = 52$ homes), average NO_2 concentrations greater than 100 ppb ($n = 9$ homes), and inverse square footage greater than 0.0017 (equivalent to 1/600 sq ft) ($n = 20$ homes), representing homes less than 40% of the average size.

Least squares regression models (which we called base models) were developed for two classes of homes, those with gas ranges and those with electric ranges. For homes with gas ranges, the included terms were type of pilot light (without pilot light versus continuously burning pilot light), inverse size of the home, type of furnace (central forced-air versus floor or wall), and distance from infant's bedroom to the kitchen. Together these factors explained 32% of the variability in winter mean bedroom NO_2 levels (all coefficients were statistically significant at $p < 0.001$). When the dependent variable, the mean winter NO_2 level, was logarithmically transformed, 30% of the variance was explained. A second model for homes with electric ranges included a term for type of furnace only. This base model explained 12% of the variability (7% when the winter mean NO_2 level was log-transformed).

Terms for the remaining household characteristics were added to these base regression models. For both categories of homes, coefficients for the age of the home and the presence of a fireplace were significant ($p < 0.05$). In homes with gas ranges, the coefficient for the presence of an electric oven was also significant ($p < 0.05$). Terms for the presence of an attached garage, gas or kerosene space heater, microwave oven, refrigerated air conditioning unit, or evaporative cooling unit were not significant when added to either of the base models.

In terms of explained variation, the best-fitting regression models were for the base model plus a term for the age of the home (which we called the base-plus model). The age of the home can be viewed as a surrogate measure correlated with other factors influencing bedroom NO_2 levels (e.g., the extent of weatherization and "tightness," and condition of cooking and heating appliances). For homes with gas ranges, the R^2 was 0.39 (0.41 for the log-transformed NO_2 concentration). For homes with electric ranges, the R^2 was 0.17 (0.15 for the log-transformed NO_2 concentration). After the age of the home was added to the models, no other characteristic explained a significant proportion of the variability.

The model for untransformed mean winter bedroom NO_2 levels in homes with gas ranges was

NO_2 = 14.6 + 6.5 × Range pilot (1 if yes, 0 if no) + 8.5 ×
Inverse volume (cu ft^{-1}) + 5.6 ×
Floor or wall furnace (1,0) − 0.07 ×
Distance to infant's bedroom (ft) − 7.9 ×
Built after 1970 (1,0).

For homes with electric ranges, the model was

NO_2 = 9.0 + 4.1 × Floor or wall furnace (1,0) − 3.0 ×
Built after 1970 (1,0).

Temperature and Precipitation

Meteorologic conditions, particularly temperature, are likely to influence the intensity and frequency of heating and cooking appliance use, as well as the exchange of indoor air with outdoor air. Using the winter data, we tested

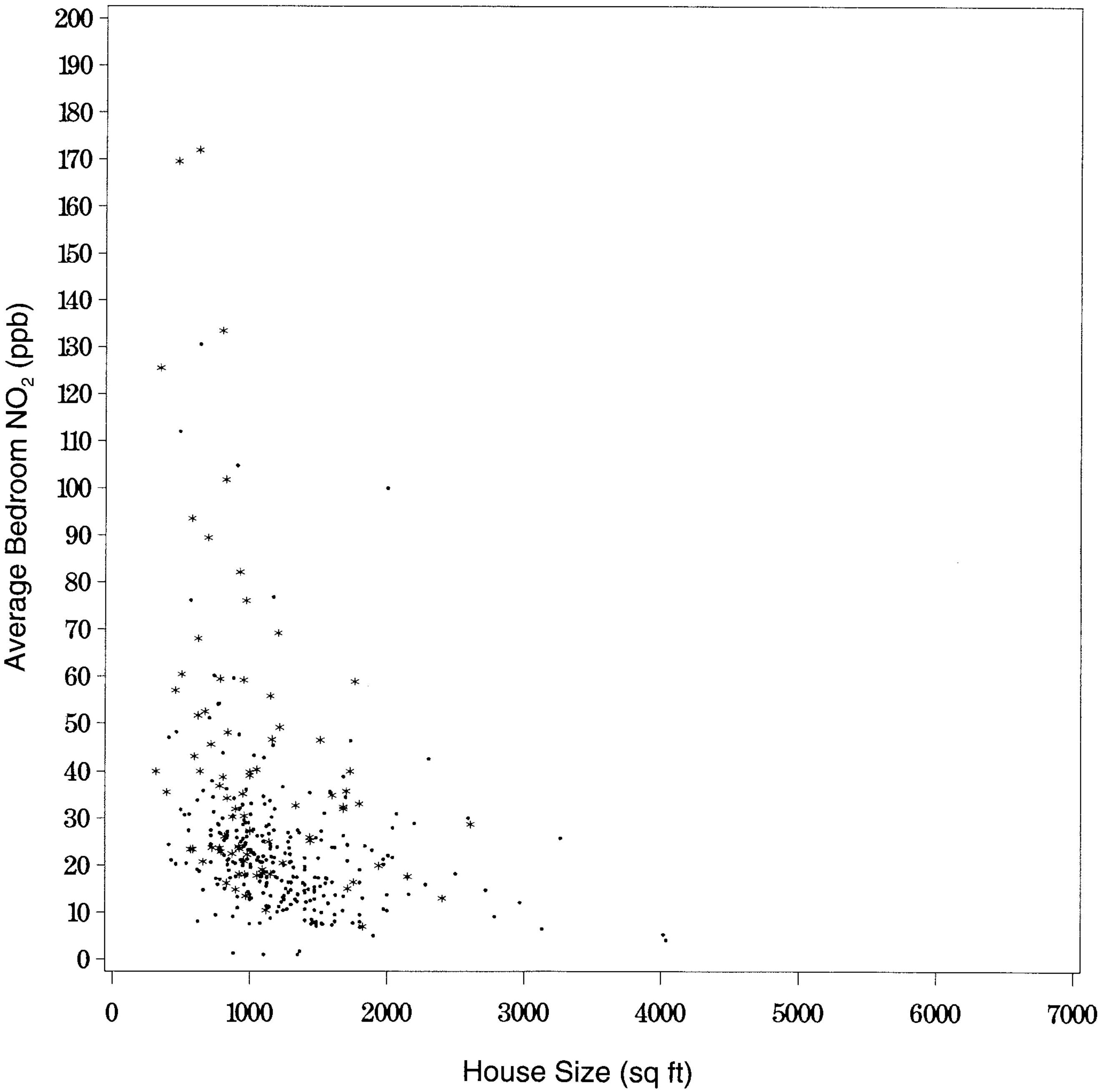

Figure 2A. Winter average bedroom NO_2 concentrations by house size and type of cooking range: Gas range with continuously lit pilot light.
* = homes with a floor or wall furnace, or a gas or kerosene space heater, or in which the cooking range was used for space heating; ● = all other homes.

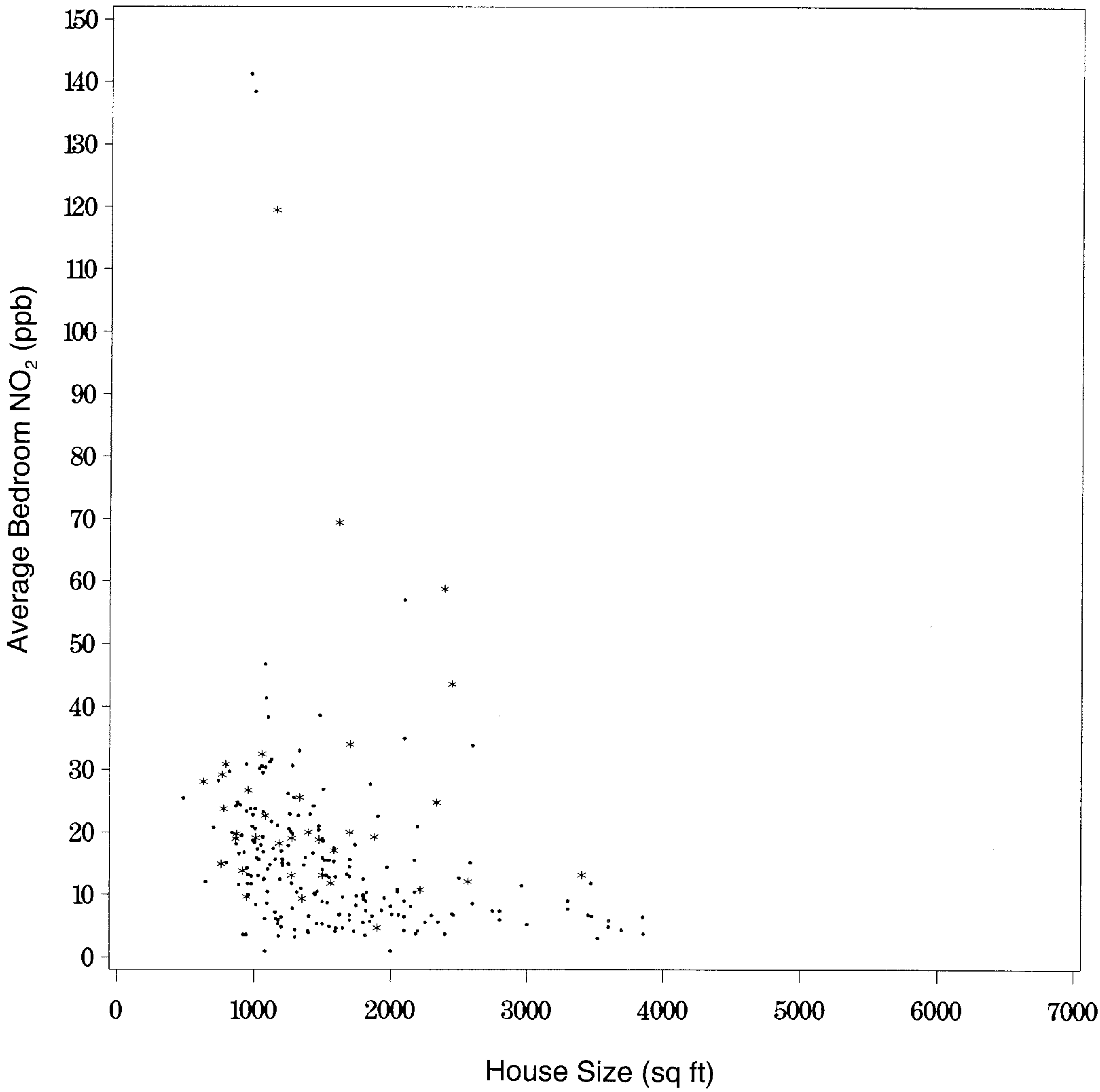

Figure 2B. Winter average bedroom NO_2 concentrations by house size and type of cooking range: Gas range without continuously lit pilot light.
* = homes with a floor or wall furnace, or a gas or kerosene space heater, or in which the cooking range was used for space heating; ● = all other homes.

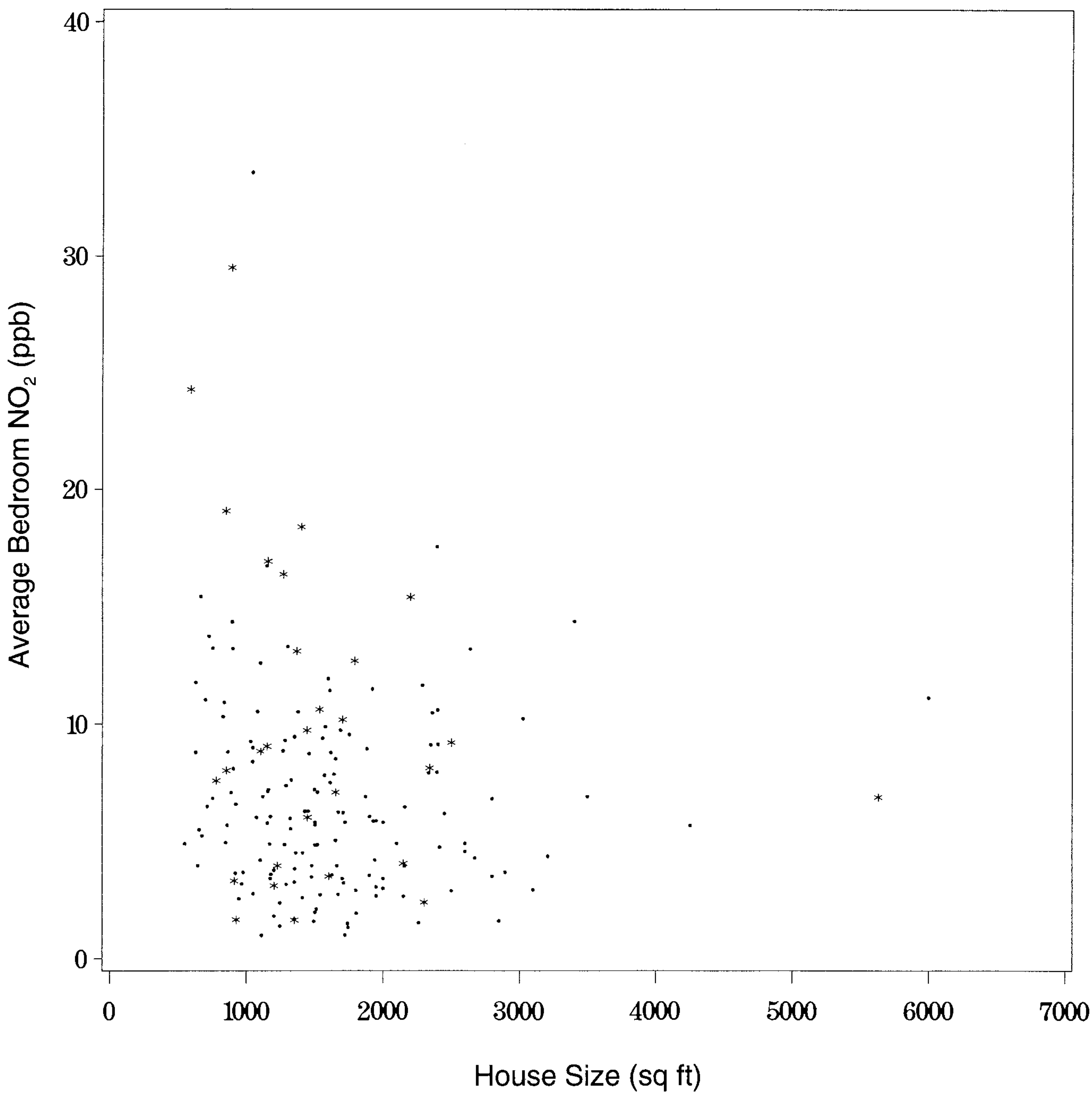

Figure 2C. Winter average bedroom NO_2 concentrations by house size and type of cooking range: Electric range. * = homes with a floor or wall furnace, or a gas or kerosene space heater, or in which the cooking range was used for space heating; ● = all other homes.

the hypothesis that higher average NO_2 levels would be associated with more heating-degree days. The total number of heating-degree days within the period during which each NO_2 sampler tube was exposed was calculated.

Homes with fewer heating-degree days provided fewer measurements. Accordingly, we also calculated the average heating-degree days per home by dividing each home's total by the number of sampler tubes obtained. Other analysis variables included the total and mean precipitation during the measurement periods.

We then generated multivariate linear regression models of the average bedroom NO_2 concentration as a function of each of the meteorologic analysis variables, after controlling for housing unit characteristics (i.e., range type, presence of continuously burning pilot lights, furnace type, inverse house volume, distance from the infant's bedroom to the kitchen, and house age). The coefficients were not statistically significant for any of the variables for homes with electric ranges. For homes with gas ranges the coefficients for total heating-degree days, total precipitation, and mean precipitation were significant ($p = 0.022$, 0.004, and 0.046, respectively) for models of the log-transformed mean winter NO_2 concentrations, although the contributions of these variables to the total explanatory power of the model were slight. The coefficient for the mean heating-degree days was also significant ($p < 0.05$) in the model of the log-transformed mean winter NO_2 concentration.

We hypothesized that increases in bedroom NO_2 levels associated with lower ambient temperature would be greatest in homes with floor and wall furnaces. When the regression analyses were repeated on the subset of homes that had gas ranges and floor or wall furnaces, 20% of the variability in average winter NO_2 concentrations (34% for the log-transformed NO_2 model) was explained by the base model. The coefficients for total temperature and total precipitation were statistically significant ($p < 0.05$), raising the R^2 to 0.27 when temperature was added and to 0.28 for both variables in the untransformed model, and to 0.43 for temperature and 0.46 for both variables in the log-transformed model. Bedroom NO_2 levels increased with decreasing temperature and increasing precipitation. However, the total number of heating-degree days was not significant in the untransformed model but was significant ($p = 0.01$) in the log-transformed NO_2 model.

Because averaging the data over all the 15-day sampling durations for the winter season may have masked a relation between NO_2 level and temperature, an alternative analysis was performed. Two sampler tubes exposed during the winter of 1989/90 were randomly selected from each home: one during a period associated with higher heating-degree days (mean total degrees per sample = 505) and one during a period associated with lower heating-degree days (mean total degrees per sample = 347). The mean bedroom NO_2 concentrations (and standard deviations) were similar during the two periods. The difference in concentrations between a pair of sampler tubes from a given household was not explained by the difference in heating-degree-day units associated with the pair of tubes ($R^2 = 0.004$, $p = 0.590$).

Model Verification

Models generated for the 1989/90 winter period were applied to data collected from households in the previous winter (1988/89). A total of 308 homes with gas ranges and 104 with electric ranges provided data during the winter of 1988/89, but were not enrolled in the study during 1989/90. For homes with gas ranges, the correlation between the observed bedroom NO_2 values in 1988/89 and the values predicted by the 1989/90 model was 0.46 ($p < 0.001$). This model included terms for the presence of a pilot light, floor or wall furnace, the home's square footage and the distance from the infant's bedroom to the kitchen (base model). Adding a term for the age of the home increased the correlation to 0.57 ($p < 0.001$) (base-plus model). The mean of both the observed and predicted values was 20 ppb, although the standard deviation was 12 ppb for the observed values but only 6 ppb for the predicted distribution. Adding terms for other household characteristics to the model did not improve the correlation between observed and predicted values.

For homes with electric ranges, the model that included a term for the presence of floor and wall furnaces yielded a correlation between observed and predicted bedroom NO_2 levels of 0.27 ($p = 0.006$). The multiple correlation coefficient R^2 increased to 0.43 with the addition of a term for age of the home ($p < 0.001$). The distribution of predicted bedroom NO_2 concentrations was tighter than the observed distribution (observed SD = 5 ppb; predicted SD = 2 ppb).

SECTION 2: SEASONAL AND YEAR-TO-YEAR PATTERNS

Overview

The primary goal of these analyses was to describe the extent of year-to-year variability in indoor NO_2 concentrations across the three-year study period and to identify factors contributing to the variation.

Description of the Data Set

The data set used in this analysis included 1,269 homes, 45% of which had gas ranges with continuously burning pilot lights, 30% had gas ranges without pilot lights, and the remainder had electric ranges. Homes with gas ranges with pilot lights had an average of 23 two-week measurement periods throughout the 18-month observation period. The distribution of coverage was similar for homes with gas ranges without pilot lights. In homes with electric ranges, there was an average of 12 two-week measurement periods per home. Individual households were enrolled in the study for a maximum of only 18 of the 36 months covered by this data set. Thus, for any given season of a given year, the homes under observation differed from those contributing data for other seasons.

The composition of the sample changed over time owing to enrollment of new households, release of households completing the protocol, and missing data. However, parameters for housing unit characteristics were fairly stable over the three years of data collection. As reported by Lambert and coworkers (1993), most of the participants lived in single-family detached units (73%) having one floor (79%) and constructed of stucco on a wood frame (77%). In 88% of the units, the water heaters were fueled by gas. The primary heating system was natural gas in 93% of the units. Central forced-air furnaces were used in 78% of the units, and floor or wall furnaces in 11%. Most of the homes were equipped with evaporative coolers (90%) rather than refrigerating air conditioners. Homes with gas ranges with continuously burning pilot lights were more than twice as likely as those with other range types to be heated by floor or wall furnaces. Floor or wall furnaces were more often present in older homes. Kerosene space heaters were used by only 1% of the households, most of which had electric ranges. Mobile home units and multifamily units were frequently equipped with ranges with continuously burning pilot lights (88% and 60%, respectively). Approximately one-third of homes had less than 1,000 sq ft of living space, one-third had between 1,000 and 1,500 sq ft, and the remaining third had more than 1,500 sq ft.

Temporal Patterns

Temporal patterns of bedroom NO_2 levels for homes with different types of cooking ranges are presented in Figure 3. Each point on the plot represents the daily average based on all households that provided data on that day. Several trends are evident. First, the duration of the period of elevated NO_2 levels varied from year to year. Second, the extent to which the bedroom NO_2 level was elevated during the winter varied from year to year. Third, there was year-to-year variation in the magnitude of differences in NO_2 concentrations among range-type groups.

Table 5 shows that bedroom NO_2 levels for homes with electric ranges averaged 7 ppb during all seasons and years (SD ranged from 4 to 12 ppb). During the summers of 1989 and 1990, homes with continuously burning pilot lights averaged 15 ppb NO_2 (SD = 9 ppb); homes with gas ranges without continuously burning pilot lights averaged 9 ppb NO_2 (SD = 5 ppb). During the winters of 1988/89 and 1989/90, average NO_2 levels in homes with gas ranges were approximately twice as high as during the subsequent summer months. But the distributions of NO_2 levels were surprisingly similar during the summer of 1988 and the winter of 1990/91 for homes with gas ranges.

This comparison does not, however, reflect the changing composition of the sample across the three-year period. Therefore, further analyses were performed, restricting the data set to homes providing measurements in a consecutive pair of winters or summers. For each pair of seasons, and range type, we calculated the distribution of bedroom NO_2 concentrations for homes providing at least three sampler tube measurements and the same number of measurements in each season of each year. Table 6 shows between-season differences of the same magnitudes observed in Figure 3 and Table 5. These data indicate that average bedroom NO_2 concentrations can vary significantly from year to year.

Temperature

Observed year-to-year differences in bedroom NO_2 concentrations may have been the result of fluctuations in temperature. For instance, it is likely that unusually cool weather would be associated with increased use of supplemental heating sources such as unvented space heaters and gas ranges. On the other hand, unusually cool summers would tend to reduce the frequency with which windows were opened and decrease use of evaporative coolers, thereby reducing air exchange rates. Yet Figure 4, which

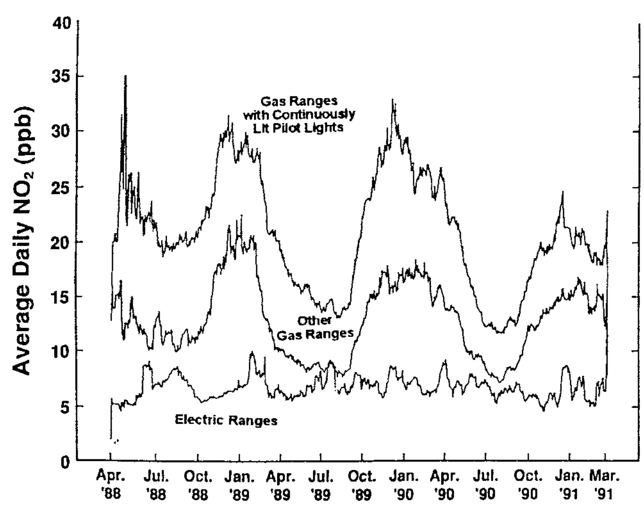

Figure 3. Temporal profiles of daily bedroom NO_2 concentrations averaged across all homes by type of cooking range.

shows the distribution of average daily temperatures across each season, does not suggest strong differences in temperature among the three winters or summers.

Table 5. Number of Samples and Distributions of Bedroom Nitrogen Dioxide Concentrations (ppb) by Season, Year, and Type of Cooking Range

Season and Year	Gas Range With Pilot Light	Gas Range Without PilotLight	Electric Range
Summer 1988			
Tubes[a]	704	474	217
n[b]	149	93	67
Mean	20.32	11.70	7.97
SD	11.60	6.16	5.11
Median	18.10	10.84	6.39
Winter 1988/89			
Tubes	1,453	851	415
n	254	144	127
Mean	28.58	19.76	7.85
SD	26.33	23.30	11.77
Median	22.89	15.33	5.75
Summer 1989			
Tubes	2,341	1,468	662
n	341	209	183
Mean	15.25	9.03	7.35
SD	8.31	4.92	5.69
Median	13.66	8.07	6.15
Winter 1989/90			
Tubes	2,247	1,416	578
n	358	240	183
Mean	27.72	16.92	7.30
SD	24.81	16.61	5.01
Median	22.01	13.88	6.27
Summer 1990			
Tubes	1,926	1,645	591
n	284	222	163
Mean	14.80	9.24	6.95
SD	9.57	4.54	3.87
Median	13.29	8.44	5.97
Winter 1990/91			
Tubes	1,001	994	321
n	157	155	92
Mean	20.87	15.01	6.29
SD	13.02	12.84	4.32
Median	17.33	12.42	5.59

[a] Number of sampler tubes used in all homes in that season and year.

[b] Number of homes for the season and year; basis of statistics.

To further investigate the relation between seasonal temperatures and bedroom NO_2 levels, weighted daily temperature data were used to calculate the average temperature during the time period for which sampler tubes in a given household were exposed. In regression models, the mean temperature during the period when the tubes were exposed explained less than 5% of the variability in the average bedroom NO_2 ($p > 0.05$). That the distributions of NO_2 were not significantly different during the summer of 1988 and the winter of 1990/91 when median temperatures during these periods were 79°F and 41°F, respectively, further supports the conclusion that seasonal temperature estimates were not a strong predictor of the seasonal average indoor NO_2 concentration.

Ambient Nitrogen Dioxide Concentrations

We then explored the hypothesis that the observed pattern of yearly differences in bedroom NO_2 concentrations reflected variability in ambient (outdoor) NO_2 levels. As documented by Lambert and coworkers (1993), the NO_2

Table 6. Comparison of Mean Bedroom Nitrogen Dioxide Concentrations (ppb) Within the Same Homes Across Pairs of Seasons[a]

Pair of Seasons	Gas Range With Pilot Light	Gas Range Without Pilot Light	Electric Range
Summer 1988	*n* = 301	*n* = 214	*n* = 47
Mean (SD)	21.5 (19.0)[b]	10.4 (6.6)[b]	8.3 (12.4)
Summer 1989			
Mean (SD)	16.0 (11.7)	8.4 (5.1)	6.6 (4.2)
Winter 1988/89	*n* = 541	n = 214	*n* = 52
Mean (SD)	28.7 (33.5)	14.1 (8.8)	6.7 (4.5)
Winter 1989/90			
Mean (SD)	27.6 (32.2)	14.9 (9.8)	6.3 (4.6)
Summer 1989	*n* = 495	*n* = 357	*n* = 42
Mean (SD)	14.9 (9.0)	9.1 (6.5)	6.4 (3.0)
Summer 1990			
Mean (SD)	15.2 (9.9)	9.7 (6.5)	5.8 (3.1)
Winter 1989/90	*n* = 354	*n* = 336	*n* = 37
Mean (SD)	26.7 (22.7)[c]	17.1 (18.4)	7.5 (8.2)
Winter 1990/91			
Mean (SD)	21.2 (13.3)	15.2 (13.9)	6.3 (4.6)

[a] Homes providing at least three measurements and the same number of measurements in the pair of consecutive seasons.

[b] Difference in means based on Student's paired *t* test is statistically significant with a value of $p < 0.001$.

[c] Difference in means based on Student's paired *t* test is statistically significant with a value of $p < 0.05$.

levels in samples collected at 11 outdoor sites averaged 15 ppb during the winter months and 10 ppb during the summer months. Figure 5 shows that, within a given season, there were only slight differences in ambient concentrations across the three years. Median levels were 2 ppb higher during the summer of 1988 than the other summers, but the number of sampler tubes was small and the difference was not statistically significant.

Household Characteristics

The next step was to explore the effects of key household variables on the seasonal and year-to-year variability in bedroom NO_2 levels. In addition to the presence of continuously burning pilot lights, past studies have shown that use of the cooking range for heat, unvented gas or kerosene space heaters, and vented heaters with faulty flues, back drafting, or leaky combustion chambers are likely to be the other principal indoor sources of bedroom NO_2 (Wilson et al. 1986; Ryan et al. 1988b). These problems are more frequently associated with floor and wall furnaces, which are more prevalent in older houses.

In most years of the study, between 10% and 12% of the parents in homes with gas ranges and continuously burning pilot lights reported that they used the cooking range for space heating. Among homes with gas ranges without pilot lights, 4% to 6% of the households reported using the range

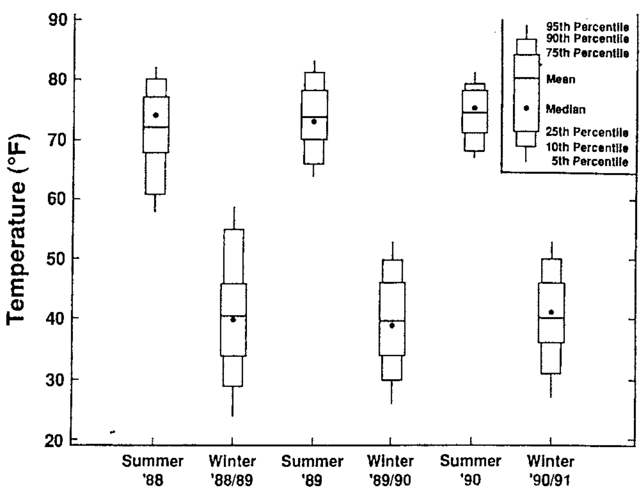

Figure 4. Distributions of daily average temperature (°F) by season and year.

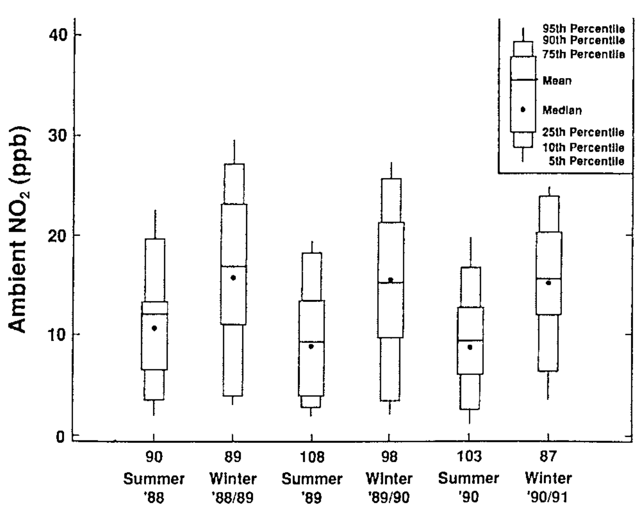

Figure 5. Distributions of average ambient NO_2 concentrations in samples collected at 11 outdoor sites, by season and year. The numbers below the bars indicate the number of sampler tubes obtained for that season and year.

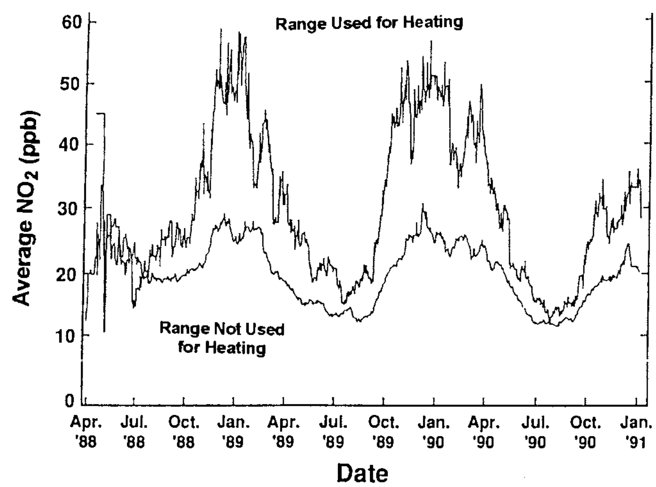

Figure 6A. Temporal profile of daily bedroom NO_2 concentrations averaged across all homes where occupants reported ever using the gas cooking range for space heating and homes with gas ranges with continuously burning pilot lights: Gas range without pilot lights;

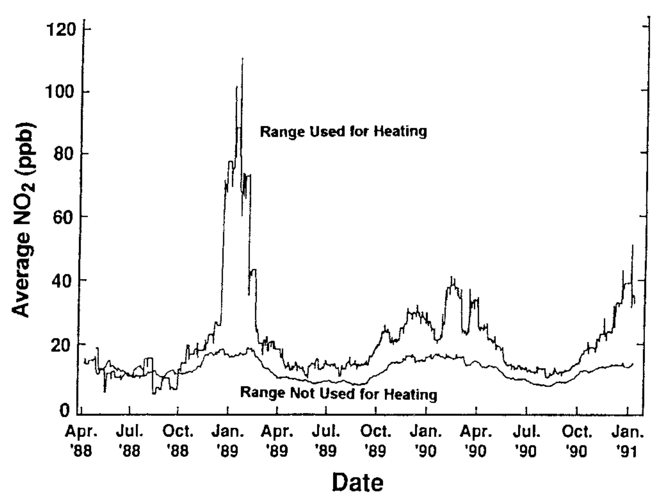

Figure 6B. Temporal profile of daily bedroom NO_2 concentrations averaged across all homes where occupants reported ever using the gas cooking range for space heating and homes with gas ranges with continuously burning pilot lights: Gas range with pilot lights.

for space heating. Figure 6 compares the temporal variability in bedroom NO_2 concentrations in homes, with stratification by whether or not the range was reported to be used for space heating. Reported use of the cooking range for space heating was associated with higher levels of NO_2 throughout the year. Among households with gas ranges with continuously burning pilot lights who reported using the range for space heating, NO_2 levels averaged approximately 22 ppb higher during the winters of 1988/89 and 1989/90, but only approximately 8 ppb higher during the winter of 1990/91. Among households with gas ranges without pilot lights who reported using the range for space heating, NO_2 averages were 38 ppb higher during the winter of 1988/89, but only 15 ppb higher during the subsequent two winters. During the summers, households that reported using the range for heat had average NO_2 levels that were 3 to 6 ppb higher than the rest of the households.

After excluding households in which the cooking range was used for space heating, we divided the sample into mutually exclusive categories to describe the increase in seasonal variability associated with other sources of NO_2. Figures 7, 8, and 9 show the median monthly bedroom NO_2 concentrations for homes providing measurements in each NO_2 source category during 1989. Figure 8 shows the contributions of other sources to the NO_2 levels in homes with gas ranges without pilot lights. In Figure 9, the baseline is homes with gas ranges that have continuously burning pilot lights, illustrating the effect on bedroom NO_2 levels of having an unvented kerosene or gas space heater and the effect of having a floor or wall furnace.

Figures 7, 8, and 9 demonstrate that other indoor sources increased the average bedroom NO_2 levels and their seasonal variability. The presence of a floor or wall furnace increased both the overall concentration and the seasonal variability in bedroom NO_2 to the levels observed in homes with stronger cooking range sources. Homes with unvented gas or kerosene space heaters showed steep month-to-month fluctuations in NO_2 concentrations that may reflect intermittent use.

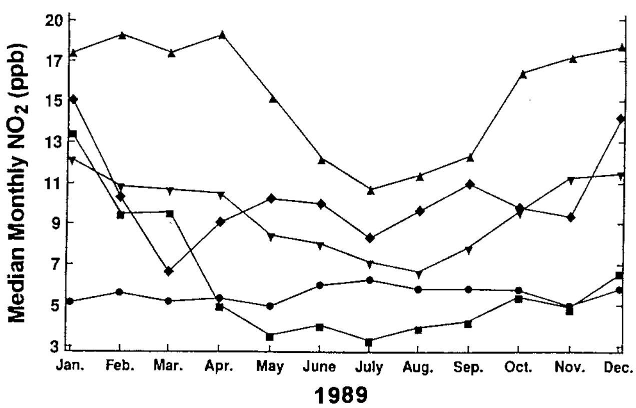

Figure 7. Temporal profile of median monthly bedroom NO_2 concentrations for 1989 by sources present in homes when the baseline is homes with electric ranges and no other NO_2 sources: (●) electric range without other sources (n = 119); (■) electric range with gas or kerosene space heaters (n = 6); (◆) electric range with floor or wall furnace (n = 11); (▼) gas range (no pilot light) but without other sources (n = 248); (▲) gas range with pilot lights but without other sources (n = 377).

Cooking Range Use

We speculated that patterns of cooking range use would vary with family size, season, and the use of other cooking appliances such as microwave ovens. Range use may have contributed to the seasonal and year-to-year fluctuations in

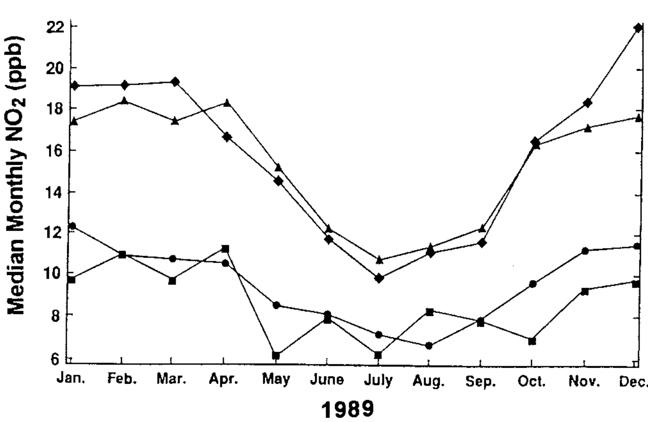

Figure 8. Temporal profile of median monthly bedroom NO_2 concentrations for 1989 by sources present in homes when the baseline is homes with gas ranges without continuously burning pilot lights and no other NO_2 sources: (●) gas (no pilot light) range but without other sources (n = 248); (■) gas (no pilot light) range with gas or kerosene space heaters (n = 6); (◆) gas (no pilot light) range with floor or wall furnace (n = 16); (▲) gas range with pilot lights but without other sources (n = 377).

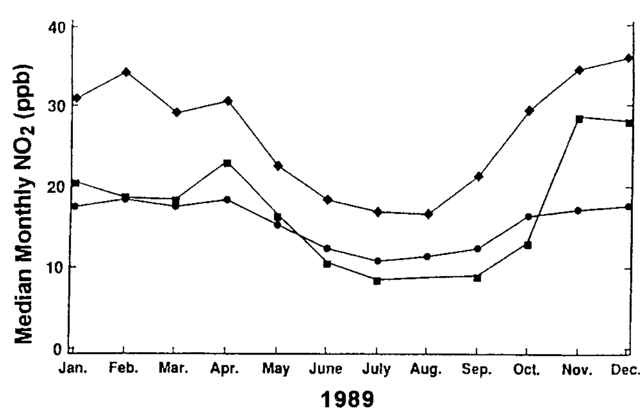

Figure 9. Temporal profile of median monthly bedroom NO_2 concentrations for 1989 by sources present in homes when the baseline is homes with gas ranges with continuously burning pilot lights and no other NO_2 sources: (●) gas range with pilot lights but without other sources (n = 377); (■) gas range with pilot light and gas or kerosene space heaters (n = 6); (◆) gas range with pilot light and floor or wall furnace (n = 44).

bedroom NO_2 concentrations described above. Using the data collected on household range use on one day during each two-week period, we calculated an index of seasonal average range use in each year for each home. These data provide an indication of typical patterns rather than a documentation of the actual patterns during particular two-week intervals. Table 7 shows the average minutes per day of range use reported during each season of each year. The median use of the range was about 10 to 15 minutes per day longer during the winter than during the summer for all range types. There does not appear to be a difference in range use across the three winters studied. For all range types, average range use during the summer of 1988 was longer than during the other summers. This pattern of range use was evaluated as an explanation for the elevated indoor NO_2 concentrations observed during the summer of 1988.

Table 7. Average Use of Cooking Range by Season, Year, and Type of Cooking Range

Season and Year	Gas Range With Pilot Light	Gas Range Without Pilot Light	Electric Range
Summer 1988			
n[a]	142	85	70
Mean (minutes/day)	51.1	46.6	51.2
SD	43.9	35.1	39.1
Median	43.2	42.5	41.7
Winter 1988/89			
n	238	147	118
Mean (minutes/day)	58.8	51.1	47.3
SD	57.7	37.2	32.6
Median	56.8	41.9	42.2
Summer 1989			
n	316	207	164
Mean (minutes/day)	38.9	40.0	40.0
SD	28.9	25.8	25.8
Median	32.8	33.2	37.5
Winter 1989/90			
n	345	240	165
Mean (minutes/day)	55.4	52.8	53.3
SD	52.1	37.7	37.9
Median	45.0	45.0	45.8
Summer 1990			
n	284	222	147
Mean (minutes/day)	36.1	40.6	39.4
SD	28.9	29.4	26.1
Median	30.09	33.3	35.0
Winter 1990/91			
n	157	155	86
Mean (minutes/day)	54.0	51.5	55.6
SD	42.2	35.9	40.6
Median	41.2	44.7	41.4

[a] Number of homes with data for the season.

Regression models for homes providing data in pairs of seasons were constructed in which the dependent variable was the difference in average bedroom NO_2 concentrations between a pair of seasons, and the independent variable was the difference in average cooking range use between the seasons. Similar models were generated using the relative differences in NO_2 concentrations and range use (i.e.,

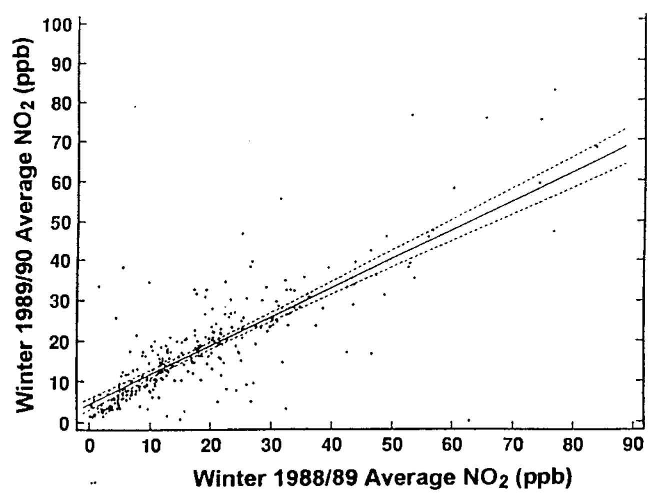

Figure 10. Regression of winter 1989/90 average bedroom NO_2 concentrations on winter 1988/89 average bedroom NO_2 concentrations for 294 homes. Dashed line represents 95% confidence interval.

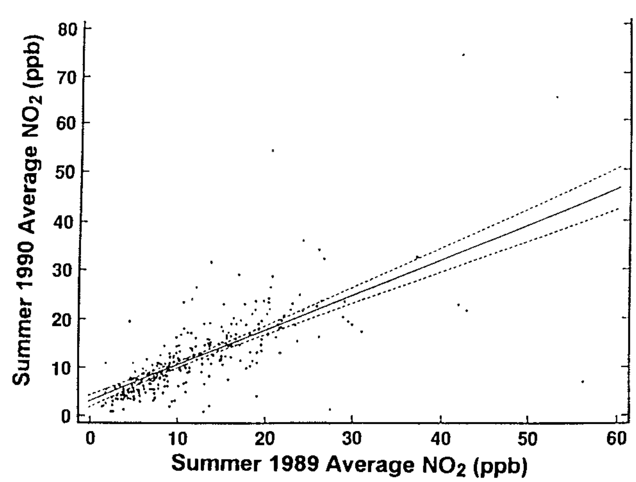

Figure 11. Regression of summer 1990 average bedroom NO_2 concentrations on summer 1989 average bedroom NO_2 concentrations for 306 homes. Dashed line represents 95% confidence interval.

the difference as a proportion of the average). The multiple correlation coefficients, R^2, associated with the models were small and never above 0.06, and differences in range use were not strong predictors of the variation in seasonal average bedroom NO_2 level either between consecutive winters or between summer and winter seasons.

Seasonal Variations in Nitrogen Dioxide Concentrations

We examined the extent to which NO_2 values recorded in one season or year predicted exposures during subsequent periods. Figures 10, 11, and 12 illustrate the relation between average bedroom NO_2 levels recorded in a pair of similar winters, a pair of similar summers, and a pair of consecutive winter and summer seasons (see Table 8 for model parameters). The plots are for the full sample (i.e., households with all cooking range and heating system types). All three plots show substantial scatter; average concentrations in some homes differed by a factor of 2 between consecutive summers or consecutive winters. Homes with values near the limit of detection during one season but with elevated concentrations (e.g., greater than 20 ppb) the following season may be homes in which the protocol was not followed (i.e., sampler tubes were never uncapped) during the first season. Table 9 shows the Pearson correlation coefficients between all pairs of winter and summer seasons, stratified by range type and heating system (e.g., floor or wall furnace versus central forced-air heating system). The seasonal correlations tend to be higher for categories of homes with stronger sources of NO_2 emissions (i.e., higher correlations for homes with gas ranges with continuously burning pilot lights versus homes with gas ranges without pilot lights versus homes with electric ranges).

The results of linear regression analysis show that 66% of the variation in the average bedroom NO_2 levels recorded during the winter of 1989/90 is explained by concentrations recorded in the winter of 1988/89 (Figure 10); the intercept is 3.8 ppb. Homes with average concentrations greater than 100 ppb were excluded from this analysis because of their undue influence; inclusion of these points brings the R^2 to 0.81. Only 48% of the variability in concentrations recorded in the summer of 1990 is explained by concentrations recorded in the summer of 1989 (intercept = 3.0 ppb) (Figure 11). Finally, 38% of the variability in concentrations during the winter of 1989/90 is explained by the variability in concentrations recorded during the previous summer (intercept = –0.3) (Figure 12).

DISCUSSION

Previous studies have shown gas cooking ranges with continuously burning pilot lights to be strong predictors of residential indoor NO_2 levels (Quackenboss et al. 1986; Wilson et al. 1986; Ryan et al. 1988b; Spengler et al. 1990). Although the type of range and its ignition system most strongly influence indoor NO_2 levels, the presence of other indoor NO_2 sources and the condition of gas-fueled appliances have also been demonstrated to influence indoor NO_2 levels. The use of the range burners or oven for space heating, the use of unvented gas or kerosene space heaters in the home, and the presence of vented furnaces with faulty flues, back drafting, or leaky combustion chambers strongly affect indoor levels of NO_2 (Wilson et al. 1986; Ryan et al. 1988b). Other home characteristics also have been associated with NO_2 levels. Households with microwave ovens may have lower NO_2 levels because the gas

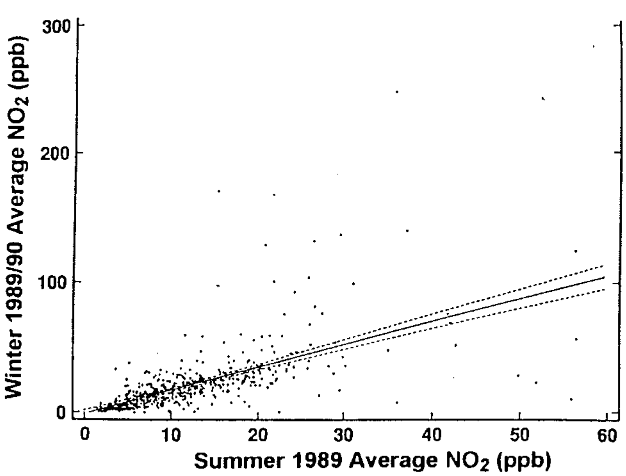

Figure 12. Regression of winter 1989/90 average bedroom NO_2 concentrations on summer 1989 average indoor NO_2 concentrations for 548 homes. Dashed line represents 95% confidence interval.

Table 8. Model Parameters for Linear Regressions of Mean Bedroom Nitrogen Dioxide Concentrations Between Seasons and Years

	Regression Parameters			
Model	Constant	β	R^2	SEE
Winter 1989/90 on winter 1988/89[a]	3.6006	0.7368	0.66	0.0309
Summer 1990 on summer 1989[b]	2.9764	0.7321	0.48	0.0435
Winter 1989/90 on summer 1989[c]	−0.2679	1.7781	0.38	0.0979

[a] Corresponds to linear regression fit depicted in Figure 10.
[b] Corresponds to linear regression fit depicted in Figure 11.
[c] Corresponds to linear regression fit depicted in Figure 12.

range is used less frequently (Marbury et al. 1988). A larger house size provides a greater opportunity for dilution of indoor NO_2 resulting in generally lower NO_2 concentrations (Colome et al. 1994; Wallace 1994). Older houses, typically associated with smaller size and the presence of older appliances, tend to have higher NO_2 levels. Attached garages, when used for automobiles, may lead to increased in-home NO_2 concentrations from automobile exhaust, as indicated by carbon monoxide measurements in southern California homes (Colome et al. 1994). Evaporative air conditioners tend to increase air exchange rates, whereas refrigeration units tend to decrease ventilation. Finally, fireplaces can increase air exchange rates by drawing air up the chimney.

In this study of Albuquerque homes, there was a distinct seasonal pattern to the indoor NO_2 concentrations in homes with gas cooking stoves: the winter concentrations were twice the summer concentrations. The bedroom NO_2 concentrations in homes with gas ranges with continuously burning pilot lights averaged 10 ppb higher than those in homes with gas ranges with electronic ignition or manually lit burners. Bedroom concentrations in homes with electric ranges showed little evidence of seasonal variation and averaged approximately 10 ppb. Homes in which occupants used the gas cooking range for supplemental space heating had substantially higher bedroom NO_2 concentrations in the winter. Homes that had wall or floor furnaces and homes built before 1970 consistently had higher NO_2 concentrations. Homes built before 1970 were on average smaller than those built later (1,157 sq ft versus 1,567 sq ft). In smaller homes, the infant's bedroom was closer to the kitchen, and smaller homes also provided less surface area for NO_2 reactions and smaller volume for dilution.

Table 9. Pearson Correlation Coefficients of Bedroom Nitrogen Dioxide Concentrations Over Pairs of Seasons by Type of Cooking Range and Heating System

	Gas Range With Pilot Light		Gas Range Without Pilot Light		Electric Range	
Pair of Seasons	Central	Floor or Wall	Central	Floor or Wall	Central	Floor or Wall
Summer 1988 Summer 1989	0.82[a] $n = 95$	0.46 $n = 14$	0.70[a] $n = 62$	0.33 $n = 5$	0.59[a] $n = 51$	0.91[b] $n = 6$
Summer 1989 Summer 1990	0.56[a] $n = 115$	0.60[a] $n = 28$	0.86[a] $n = 87$	0.55 $n = 4$	0.28c $n = 60$	−0.32 $n = 5$
Winter 1988/89 Winter 1989/90	0.88[a] $n = 125$	0.98[a] $n = 22$	0.63[a] $n = 72$	0.96[b] $n = 5$	0.38[b] $n = 66$	0.96[b] $n = 7$
Winter 1989/90 Winter 1990/91	0.53[a] $n = 89$	0.61[b] $n = 16$	0.92[a] $n = 96$	0.74[b] $n = 11$	0.81a $n = 43$	0.80 $n = 4$
Summer 1988 Winter 1988/89	0.60[a] $n = 111$	0.37 $n = 18$	0.53[a] $n = 73$	0.12 $n = 7$	0.44[a] $n = 54$	0.36 $n = 6$
Summer 1989 Winter 1989/90	0.50[a] $n = 211$	0.47[b] $n = 45$	0.75[a] $n = 152$	0.84[b] $n = 8$	0.36[a] $n = 114$	−0.91 $n = 9$
Summer 1990 Winter 1990/91	0.53[a] $n = 123$	0.61[b] $n = 24$	0.76[a] $n = 142$	0.79[b] $n = 13$	0.45[a] $n = 78$	0.78 $n = 4$
Summer 1988 Winter 1989/90	0.49[a] $n = 54$	0.57 $n = 10$	0.35[b] $n = 32$	0.33 $n = 4$	−0.00 $n = 21$	1.0 $n = 2$
Summer 1989 Winter 1990/91	0.45[a] $n = 36$	0.61[c] $n = 13$	0.82[a] $n = 36$	0.97 $n = 3$	0.28 $n = 15$	– $n = 1$

[a] For this correlation coefficient, r, comparing mean bedroom NO_2 concentrations across a pair of seasons, $p < 0.005$.

[b] For this correlation coefficient, r, comparing mean bedroom NO_2 concentrations across a pair of seasons, $p < 0.01$.

[c] For this correlation coefficient, r, comparing mean bedroom NO_2 concentrations across a pair of seasons, $p < 0.05$.

Regression analysis confirmed that pilot lights and wall or floor furnaces were also important predictors of NO_2 concentration, as were the inverse square footage and age of the home. Other factors that were also statistically significant but explained little of the overall variance included the distance from the kitchen to the infant's bedroom and the number of heating-degree days associated with the sample. Bedroom NO_2 concentrations were lower in homes with fireplaces. Fireplaces were more prevalent in larger homes, and their presence may increase the air exchange rate (Modera and Sonderegger 1980). Table 10 presents the multivariate regression parameters for the base and base-plus models.

The finding that the distance from the kitchen to the bedroom explained 6% of the variability in bedroom NO_2 levels in the bedrooms of homes with electric cooking ranges was unexpected. However, other findings from the regression analyses of determinants of indoor NO_2 concentration followed expectations. More of the variance was explained in models for homes with gas ranges, and the coefficients for a number of household characteristics were statistically significant. In homes with electric ranges, the coefficient for the home's inverse square footage was not statistically significant. We speculate that in homes with electric stoves, just as in those with gas stoves, the bedroom-to-kitchen distance serves as a surrogate measure of house size and of the indoor surface areas available for reaction with NO_2 that enters the house with outdoor air. It is also plausible that the larger homes were located in more peripheral areas of the city where traffic density and ambient NO_2 levels are lower.

The bedroom NO_2 concentrations measured in one winter season were modestly correlated ($r = 0.66$) with those in the succeeding winter; a lower correlation was observed between consecutive summers ($r = 0.48$). Correlations tended to be higher for homes with gas ranges with pilot lights than for homes with other range types. For homes with gas ranges with continuously burning pilot lights, the bedroom NO_2 values differed by an average of 5.5 ppb between one pair of winters but only by 1 ppb between a different pair of consecutive winters. These differences were not solely a reflection of uniformly higher NO_2 levels. The between-year correlations also differed; not only were concentrations higher during 1989/90 than 1990/91, but the ranking of the homes differed from winter to winter. For homes with gas ranges with pilot lights, winter-to-winter correlations (r) across the three winters ranged from a low of 0.53 to a high of 0.88. These findings differ somewhat from those of Houthuijs and coworkers (1990), who reported high year-to-year reliability in one-week average NO_2 measurements collected during two consecutive winters in 56 homes in the Netherlands; the distribution of average personal NO_2 exposures in this study differed by only 2 ppb, and the test-retest correlation was 0.89 for bedroom measurements. The contrast between the findings may reflect housing characteristics and source strength.

We explored several possible explanations for the year-to-year differences. The differences were not related to temperature patterns, nor was there a change in the protocols for monitor placement or sample analysis between the sampling periods. Examination of the yearly patterns of outdoor concentrations did not reveal a trend. The lack of temporal variation across homes without indoor NO_2 sources (i.e., electric range homes without gas appliances) supports the conclusion that the year-to-year trends were not a consequence of fluctuation in ambient NO_2 levels. The observed patterns, therefore, are hypothesized to reflect occupant behaviors that influenced the air exchange rate or NO_2 source use or both. The difference in the extent of temporal variability between groups of homes with different source factors supports this hypothesis. But our analysis did not show a strong relation between range use and bedroom NO_2 levels. The variable used (24-hour recall once every two weeks) may not have been sufficiently sensitive to detect the range-use activities that were driving the NO_2 patterns.

The base and base-plus models developed from the 1989/90 winter data set were used to predict winter bedroom NO_2 concentrations in an independent set of homes monitored in the winter of 1988/89. Values predicted by the base model and observed values were significantly correlated ($r = 0.46$). The base-plus model improved the correlation to 0.57. Although the means of the predicted and observed values were the same, the standard deviation of the predicted values was half that of the observed values. Model performance should be evaluated against the criterion of predicting concentrations in a set of homes without accounting for year-to-year differences in source use, temperature, subject compliance with the monitoring protocol, and other factors. The model explains less than half of the variance within the test set of homes. For these homes one winter season can predict only 44% of the variation in the bedroom NO_2 concentrations measured in the next winter season. A model that predicts 32% of the variation in an independent sample of homes measured in a different winter season might reflect the best that can be done with a limited set of descriptors to characterize a home. We acknowledge that we did not have ambient NO_2 measurements specific to each home, which may have explained further variation in the models and increased predictive power.

Table 10. Summary of Models Predicting Mean Winter Bedroom Nitrogen Dioxide Levels

	Base Model								Base-Plus Model							
	Gas Range				Electric Range				Gas Range				Electric Range			
	Arithmetic		Logarithmic		Arithmetic		Logarithmic		Arithmetic		Logarithmic		Arithmetic		Logarithmic	
	β	R^2	β	R^2	β	R^2	β	R^2	β	R^2	β	R^2	β	R^2	β	R^2
Intercept	9.59[a]		2.27[a]		5.44[a]		1.64[a]		17.88[a]		2.70[a]		9.15[a]		2.41[a]	
Range type and pilot lights	4.55[a]	0.09	0.32[a]	0.12					6.45[a]	0.1	0.48[a]	0.14				
Inverse size of home	11.12[a]	0.11	0.64[a]	0.11	3.15[b]	0.08	0.32	0.07	6.16[a]	0.08	0.39[a]	0.09	1.87	0.09	0.09	0.05
Kitchen-to-bed roomdistance	−0.12[a]	0.03	−0.01[a]	0.04	−0.03	0.01	−0.004	0.02	−0.06	0.03	−0.01[b]	0.03	0.04	0.02	−0.01	0.02
Heating system	11.55[a]	0.09	0.46[a]	0.04	4.50[a]	0.07	0.45[a]	0.05	6.13[a]	0.08	0.21[b]	0.05	3.35[b]	0.07	0.20	0.04
Age of home									−7.56[a]	0.1	−0.48[a]	0.1	−2.09[b]	0.03	−0.39[a]	0.05
Fireplace									−2.28[b]	0.01	0.12[b]	0.01	−1.57	0.01	−0.14	0.01
Electric oven									−2.84	0	−0.23[b]	0.01	0	0	0	0
Attached garage									0.49	0	0.04	0	0.8	0	−0.05	0
Microwave oven									1.23	0	−0.09	0	−0.41	0	−0.13	0.02
Total R^2		0.32		0.30		0.17		0.12		0.40		0.43		0.23		0.19

[a] For this coefficient in the multivariate linear regression model, $p < 0.01$.

[b] For this coefficient in the multivariate linear regression model, $p < 0.05$.

Comparison data are available from a number of other U.S. cities. In the Harvard Six-Cities Study (Ferris et al. 1979), indoor and outdoor NO_2 was monitored over two winter and two summer months using Palmes tubes. We considered data from that study as providing comparisons to a community with low ambient NO_2 concentrations (Topeka, KS) and to a more developed urban area with higher ambient NO_2 levels (St. Louis, MO). Indoor NO_2 data from several seasons are also available from other studies for approximately 500 homes in the greater Boston area (Ryan et al. 1988b) and 600 homes in southern California (Colome et al. 1994).

The cumulative frequency distributions of summer and winter bedroom NO_2 values are plotted in Figures 13, 14, and 15 for Topeka, St. Louis, southern California, Boston, and Albuquerque. The data are plotted separately for homes with electric ranges, and for homes with gas ranges with and without continuously burning pilot lights. Irrespective

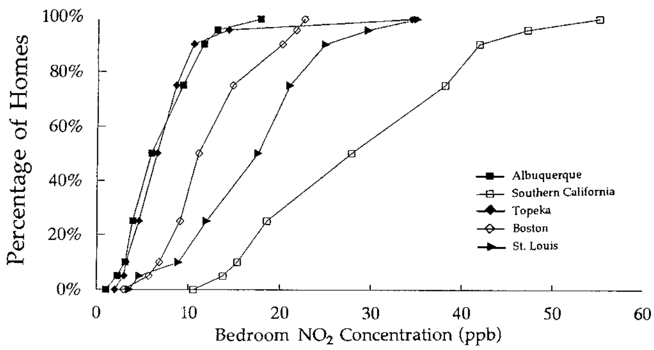

Figure 13A. Cumulative distributions of bedroom NO_2 levels for homes with electric ranges in Albuquerque and several other areas in the United States for summer season.

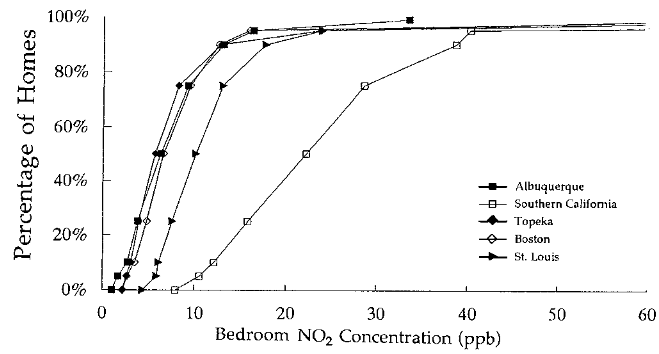

Figure 13B. Cumulative distributions of bedroom NO_2 levels for homes with electric ranges in Albuquerque and several other areas in the United States for winter season.

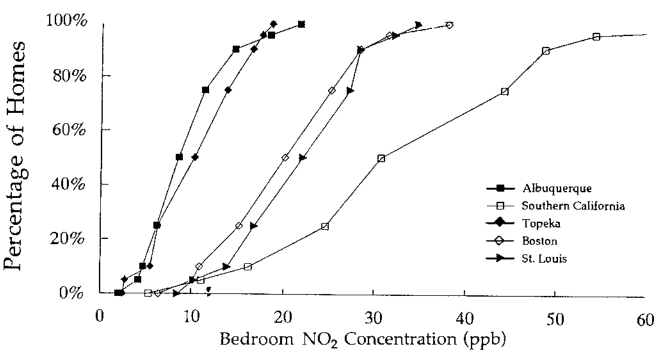

Figure 14A. Cumulative distributions of bedroom NO_2 levels for homes with gas ranges without pilot lights in Albuquerque and several other areas in the United States for summer season.

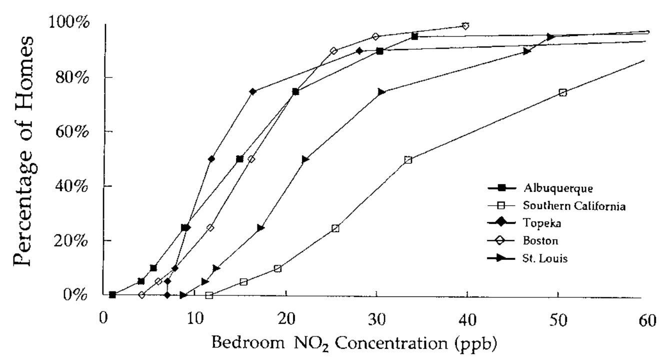

Figure 14B. Cumulative distributions of bedroom NO_2 levels for homes with gas ranges without pilot lights in Albuquerque and several other areas in the United States for winter season.

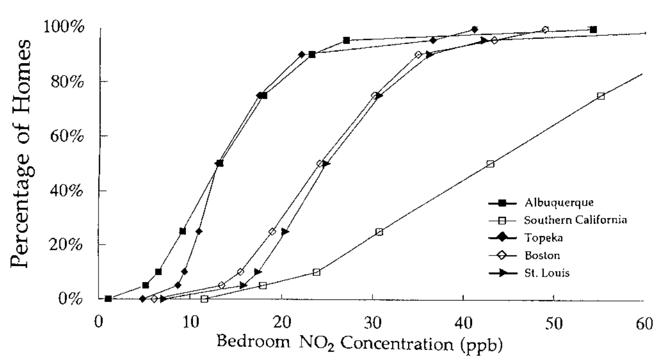

Figure 15A. Cumulative distributions of bedroom NO_2 levels for homes with gas ranges with continuously burning pilot lights in Albuquerque and several other areas in the United States for summer season.

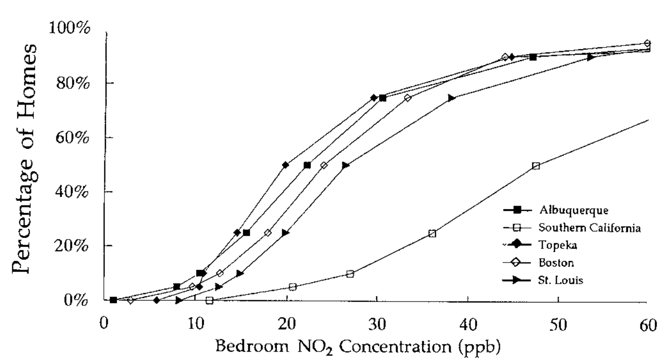

Figure 15B. Cumulative distributions of bedroom NO_2 levels for homes with gas ranges with continuously burning pilot lights in Albuquerque and several other areas in the United States for winter season.

of range type, the bedroom concentrations in St. Louis and southern California are consistently higher than those in the other communities. Nitrogen dioxide levels in Albuquerque homes with electric ranges are similar to those observed in Topeka during both winter and summer and in Boston during winter. Similar trends are apparent for homes with gas stoves. In the summer, homes in Albuquerque are well ventilated, and in homes with gas ranges, bedroom NO_2 levels approach the values observed in homes with electric ranges. During the winter, the median concentration in Albuquerque homes with gas ranges with pilot lights is only 2 ppb less than the median value in Boston homes and 5 ppb less than that in St. Louis homes. However, at the upper percentiles (> 80%) the concentrations in Albuquerque are higher than those in Boston for homes with gas ranges without pilot lights and, to a lesser extent, for homes with electric ranges. Wall and floor furnaces have been associated with higher indoor NO_2 concentrations in Albuquerque and southern California during winter, and these types of heaters are not typically present in Boston homes.

The collection of several measurements from each household during a given season, and over several seasons and years, has provided an opportunity to study the potential exposure misclassification associated with more limited monitoring efforts. These same design features, however, raise difficult statistical issues, including repeated measures and unequal coverage across the study period and between homes within a given season. We attempted to address these problems by using the within-home average concentration for a given season and including only homes represented in a pair of seasons for cross-seasonal comparisons. The use of within-household averages based on three to six measurements per home also increased the stability of the seasonal estimates (Lambert et al. 1992). Finally, we tested the sensitivity of our results by applying several analytic approaches; the consistency of findings gives credence to the temporal trends documented above.

During the past 15 years, Palmes tubes have been used in many epidemiologic studies of indoor air quality and respiratory health, and have come to be regarded as a standard method of measurement. Although there is a potential for errors due to interference by other nitrogen compounds, particularly nitrous acid (HONO) (Spicer et al. 1993), we do not see any error that would lead to bias in the comparisons made in this report. Further, we documented indoor HONO levels in a sample of 10 households participating in this study (Spengler et al. 1993) and found the indoor concentrations to be low (1.8 to 8.1 ppb, mean = 4.7 ppb), suggesting that only a small upward error in apparent NO_2 concentration is present.

Exposure assessment and epidemiologic investigations typically use either source description or limited exposure measurements to characterize exposure to NO_2. In the absence of information on the year-to-year stability of indoor NO_2 levels, it has been assumed that measurements collected in one year offer a sufficiently accurate index of concentrations in other years. Our finding that the distribution of bedroom NO_2 concentrations can differ significantly from year to year suggests that measurements taken in different years should not be interpreted as replications of one another. Rather, because source-use patterns and ambient conditions are likely to vary, data collected during different years should be interpreted as representing different situations.

These results underscore the potential for exposure misclassification if exposure is classified by single measurements. Previous analyses have demonstrated the implications of the choice of exposure indicators on the outcome of epidemiologic studies (Shy et al. 1978; Gladen and Rogan 1979; Ozkaynak et al. 1986). Brunekreef and coworkers (1986, 1987) showed that variability in exposure measurements can lead to bias in the regression coefficients, reducing the power of a study to detect a significant association. On the other hand, Lebret (1990) has shown that random error in exposure indicators can also lead to an overestimate of effects. As discussed by Lambert and coworkers (1992), misclassification can be reduced through repeated measures and consideration of the sample timing. Our analysis provides further support for the idea that prospective designs in which exposure measurements are closely matched in time with the health measurement of interest are needed for studying health and exposure relationships.

Finally, these results have important implications for exposure assessment in a policy context. If the distribution of indoor NO_2 concentrations in communities is strongly influenced by the time at which the measurements are collected, the exposure models used for determining whether air quality standards have been met must allow for year-to-year variability in indoor NO_2 levels.

ACKNOWLEDGMENTS

We are grateful for the conscientious efforts of the Albuquerque families that participated in this research. We thank the members of the field study team at the University of New Mexico (Kay Browning, Diane Corry, Genevieve Degani, Pamela England, Dawn Hamilton, Louise Kahn, Veronica Ketchbaw, Val King, Anna Kratochvil, Teri Law, Dona Lewis, Beth Meysenberg, Bella Montgomery, Emilie O'Mara, Delinda Scenters, and Anna Reade) for their energy and enthusiasm, diligence, and attention to detail. We also thank the members of the Air Quality Laboratory at the Harvard School of Public Health (Robert DeVivo, David Harlos, Beth Owens, Jenny Su, and Laurie Wast) for their careful analyses of the many thousands of NO_2 sampler tubes used in this study.

REFERENCES

Atkinson R. 1988. Atmospheric transformations of automotive emissions. In: Air Pollution, The Automobile, and Public Health (Watson AY, Bates RR, Kennedy D, eds.) pp. 99–132. National Academy Press, Washington, DC.

Boleij JSM, Lebret E, Hoek F, Noy D, Brunekreef D. 1986. The use of Palmes diffusion tubes for measuring NO_2 in homes. Atmos Environ 20:597–600.

Brauer M, Rasmussen TB, Kjaergaard SK. 1993. Indoor nitrous acid: Formation and human exposure effects. In: Indoor Air '93: Proceedings of the 6th International Conference on Indoor Air Quality and Climate, Vol. 3, Combustion Products, Risk Assessment, Policies (Jantunen M, Kalliokoski P, Kukkonen E, Saarela K, Seppanen O, Vuorelma H, eds.) pp. 141–146. Laboratory of Heating, Ventilating, and Air Conditioning, Indoor Air '93, Helsinki, Finland.

Brunekreef B, Boleij JSM, Hoek F, Lebret E, Noy D. 1986. Variation of indoor nitrogen dioxide concentrations over a one-year period. Environ Int 12:279–282.

Brunekreef B, Noy D, Clausing P. 1987. Variability of exposure measurements in environmental epidemiology. Am J Epidemiol 125:892–898.

Clausing P, Mak JK, Spengler JD, Letz R. 1986. Personal NO_2 exposures of high school students. Environ Int 12:413–417.

Colome SD, Wilson AL, Tian Y. 1994. California Residential Indoor Air Quality Study, Vol. 2, Report to Gas Research Institute, Pacific Gas & Electric Company, Southern California Gas Company, San Diego Gas & Electric Company. Integrated Environmental Services, Irvine, CA.

Dockery DW, Spengler JD, Reed MP, Ware J. 1981. Relationships among personal, indoor and outdoor NO_2 measurements. Environ Int 5:101–107.

Drye EE, Ozkaynak H, Burbank B, Billick IH, Baker PE, Spengler JD, Ryan PB, Colome SD. 1989. Development of models for predicting the distribution of indoor nitrogen dioxide concentrations. J Air Waste Manage Assoc 39:1169–1177.

Ferris BG Jr, Speizer FE, Spengler JD, Dockery DW, Bishop YMM, Wolfson M, Humble C. 1979. Effects of sulfur oxides and respirable particles on human health: Methodology and demography of populations in study. Am Rev Respir Dis 120:767–779.

Gladen B, Rogan WJ. 1979. Misclassification and the design of environmental studies. Am J Epidemiol 109:607–616.

Goldstein BD, Melia RJW, Chinn S, Florey C du V, Clark D, John HH. 1979 The relationship between respiratory illness in primary school children and the use of gas for cooking: II. Factors affecting nitrogen dioxide levels in the home. Int J Epidemiol 8:339–345.

Goldstein IF, Andrews LR, Harel D. 1988. Assessment of human exposure to nitrogen dioxide, carbon monoxide, and respirable particulates in New York inner-city residences. Atmos Environ 22:2127–2139.

Harlos D, Marbury M, Samet J, Spengler J. 1987. Relating indoor NO_2 levels to infants' personal exposures. Atmos Environ 21:369–376.

Houthuijs D, Dijkstra L, Brunekreef B, Boliej JSM. 1990. Reproducibility of personal exposure estimates for nitrogen dioxide over a two year period. Atmos Environ 24A:435–437.

Jenkins PL, Phillips TJ, Mulberg EJ, Hui SP. 1992. Activity patterns of Californians: Use of and proximity to indoor pollutant sources. Atmos Environ 1992:2141–2148.

Lambert WE, Samet JM, Hunt WC, Skipper BJ, Schwab M, Spengler JD. 1993. Nitrogen Dioxide and Respiratory Infection in Infants. Part II, Assessment of Exposure to Nitrogen Dioxide. Research Report Number 58. Health Effects Institute, Cambridge, MA.

Lambert WE, Samet JM, Skipper BJ, Cushing AH, Hunt WC, Young SA, McLaren LC, Schwab M, Spengler JD. 1994. Nitrogen Dioxide and Respiratory Infection in Infants. Part III, Quality Assurance in an Epidemiological Study. Research Report Number 58. Health Effects Institute, Cambridge, MA.

Lambert WE, Samet JM, Stidley CA, Spengler JD. 1992. Classification of residential exposure to nitrogen dioxide. Atmos Environ 26A:2185–2192.

Leaderer BP, Zagraniski RT, Berwick M, Stolwijk JAJ. 1986. Assessment of exposure to indoor air contaminants from combustion sources: Methodology and application. Am J Epidemiol 124:275–289.

Lebowitz MD, Holberg C, Boer B, Hayes C. 1985. Respiratory symptoms and peak flow associated with indoor and outdoor air pollutants in the southwest. J Air Pollut Control Assoc 35:1154–1158.

Lebret E. 1990. Error in exposure measures. Toxicol Indust Health 6:147–156.

Marbury MC, Harlos DP, Samet JM, Spengler JD. 1988. Indoor residential NO_2 concentrations in Albuquerque, New Mexico. J Air Pollut Control Assoc 38:392–398.

Modera MP, Sonderegger RC. 1980. Determination of In-Situ Performance of Fireplaces. Report prepared by the U.S. Department of Energy. Energy Performance of Buildings Group, Energy & Environmental Division, Lawrence Berkeley Laboratory, Berkeley, CA.

National Oceanic and Atmospheric Administration. 1988–1992 (Annually). Local Climatological Data. National Climate Data Center, Asheville, NC.

Noy D, Willers H, Winkes A. 1986. Estimating human exposure to nitrogen dioxide: Results from a personal monitoring study among housewives. Environ Int 12:407–411.

Ozkaynak H, Ryan PB, Spengler JD, Laird NM. 1986. Bias due to misclassification of personal exposures in epidemiological studies of indoor and outdoor air pollution. Environ Int 12:389–393.

Palmes ED, Gunnison AF, DiMattio J, Tomcyzk C. 1976. Personal sampler for nitrogen dioxide. Am Ind Hyg Assoc J 37:570–577.

Pitts JN Jr, Biermann HW, Tuazon EC, Green M, Long WD, Winer AM. 1989. Time-resolved identification and measurement of indoor air pollutants by spectroscopic techniques: Gaseous nitrous acid, methanol, formaldehyde and formic acid. J Air Pollut Control Assoc 39:1344–1347.

Quackenboss J, Spengler JD, Kanaek MS, Letz R, Duffy CP. 1986. Personal exposure to NO_2: Relationship to indoor/outdoor air quality and activity patterns. Environ Sci Technol 20:775–783.

Ryan PB, Soczek ML, Spengler JD, Billick IH. 1988a. The Boston residential NO_2 characterization study: I. Preliminary evaluation of survey methodology. J Air Polllut Control Assoc 38:22–27.

Ryan PB, Soczek ML, Treitman RD, Spengler JD, Billick IH. 1988b. The Boston residential NO_2 characterization study: II. Survey methodology and population concentration estimates. Atmos Environ 22:2115–2125.

Ryan PB, Spengler JD, Schwab M, Soczek ML. 1990. Personal monitoring for nitrogen dioxide: Boston personal monitoring study. In: Proceedings of the First International Symposium on Total Exposure Assessment Methodology: A New Horizon, Las Vegas, Nevada, November 1989, pp. 38–65. Air and Waste Management Association, Pittsburgh, PA.

Samet JM, Lambert WE, Skipper BJ, Cushing AH, Hunt WC, Young SA, McLaren LC, Schwab M, Spengler JD. 1993. Nitrogen Dioxide and Respiratory Illness in Children. Part I, Health Outcomes. Research Report Number 58. Health Effects Institute, Cambridge, MA.

Samet JM, Lambert WE, Skipper BJ, Cushing AH, McLaren LC, Schwab M, Spengler JD. 1992. A study of respiratory illnesses in infants and NO_2 exposure. Arch Environ Health 47:57–63.

Samet JM, Spengler JD. 1989. Nitrogen Dioxide and Respiratory Infections: Pilot Studies. Research Report Number 28. Health Effects Institute, Cambridge, MA.

Schwab M, Spengler JD, Ryan PB, Billick IH, Colome SD. 1994. Personal exposure to nitrogen dioxide in the Los Angeles basin. J Air Waste Manage Assoc 44:39–47.

Shy CM, Kleinbaum DG, Morgenstern H. 1978. The effect of misclassification of exposure status in epidemiological studies of air pollution and health effects. Bull NY Acad Med 54:1155–1165.

Spengler JD, Brauer M, Samet JM, Lambert WE. 1993. Nitrous acid in Albuquerque, New Mexico, homes. Environ Sci Technol 27:841–845.

Spengler JD, Duffy CP, Letz RP, Tibbitts TW, Ferris BG Jr. 1983. Nitrogen dioxide inside and outside 137 homes and implications for ambient air quality standards and health effects research. Environ Sci Technol 17:164–168.

Spengler JD, Ryan PB, Schwab M, Billick IH, Colome SD, Becker E. 1990. An overview of the Los Angeles personal monitoring study. In: Proceedings of the First International Symposium on Total Exposure Assessment Methodology: A New Horizon, Las Vegas, Nevada, November 1989, pp. 66–85. Air and Waste Management Association, Pittsburgh, PA.

Spicer CW, Yanagisawa Y, Mulik JD, Billick IH. 1993. The prevalence of nitrous acid in indoor air and its impact on NO_2 measurements made by passive samplers. In: Indoor Air '93: Proceedings of the 6th International Conference on Indoor Air Quality and Climate. Vol. 3, Combustion Products, Risk Assessment, Policies (Jantunen M, Kalliokoski P, Kukkonen E, Saarela K, Seppanen O, Vuorelma H, eds.). pp. 277–282. Laboratory of Heating, Ventilating, and Air Conditioning, Helsinki University of Technology, Espoo, Finland.

Szalai A. 1972. The Use of Time: Daily Activities of Urban and Suburban Populations in Twelve Countries. Mouton, The Hague.

Wallace L. 1994. Frequency distributions of residential air exchange rates (abstract). In: Program/Abstracts, Joint 1994 Conference of the International Society for Environmental Epidemiology and International Society for Exposure Analysis, September 18–21, 1994, Research Triangle Park, NC.

Wilson AL, Colome SD, Baker ED, Becker EW. 1986. Residential Indoor Air Quality Characterization Study of Nitrogen Dioxide, Phase I. Volume 2: Final Report. Southern California Gas Company, Los Angeles, CA.

ABOUT THE AUTHORS

John D. Spengler, Ph.D., directed the exposure assessement component of the research program. He is Professor of Environmental Health Sciences at the Harvard School of Public Health. He received his Ph.D. in atmospheric sciences from the State University of New York at Albany and an M.S. in environmental health sciences from the Harvard School of Public Health. His research has focused on measuring air pollutants inside homes and on assessing personal exposures.

Margo Schwab, Ph.D., coordinated the handling and statistical analysis of the NO_2 exposure data set at the Harvard School of Public Health. She received her Ph.D. in geography from Clark University and her research has focused on assessment of population exposure to chemical contaminants.

Aidan McDermott, M.A., performed the statistical programming to support the analyses presented in this report. He received his M.A. in mathematics and statistics from the University of Edinburgh, Scotland.

William E. Lambert, Ph.D., coordinated data collection. He is a Research Associate Professor in the Department of Internal Medicine, and the Epidemiology and Cancer Control Program at the University of New Mexico Health Sciences Center. He received his Ph.D. in social ecology from the University of California, Irvine. His research interests include the assessment of exposure to air pollutants and the measurement of health effects in the community setting.

Jonathan M. Samet, M.D., M.S., is the Principal Investigator of the research project. Currently, he is Professor and Chair of the Department of Epidemiology at The Johns Hopkins University School of Hygiene and Public Health. He received his M.D. degree from the University of Rochester School of Medicine and Dentistry, and received clinical training in internal medicine and the subspecialty of pulmonary diseases. He completed a three-year fellowship in clinical epidemiology at the Channing Laboratory, Harvard Medical School, and received an M.S. in epidemiology from the Harvard School of Public Health. His research interests focus on environmental and occupational epidemiology and the effects of chemical and radioactive agents on the lung.

PUBLICATIONS RESULTING FROM THIS RESEARCH

Samet JM, Utell MJ. 1990. The risk of nitrogen dioxide: What have we learned from epidemiological and clinical studies? Toxicol Ind Health 6:247–262.

Samet JM, Lambert WE. 1991. Epidemiologic approaches for assessing the risks from complex mixtures in indoor air. Environ Health Perspect 95:71–74.

Lambert WE, Samet JM, Stidley CA, Spengler JD. 1992. Classification of exposure to residential nitrogen dioxide. Atmos Environ 26A:2185–2192.

Samet JM, Lambert WE, Skipper BJ, Cushing AH, McLaren LC, Schwab M, Spengler JD. 1992. A study of respiratory illnesses in infants and nitrogen dioxide exposure. Arch Environ Health 47:57–63.

Lambert WE, Samet JM, Skipper BJ, Cushing AH, Hunt WC, Young SA, Schwab M, Spengler JD. 1993. Residential exposures to nitrogen dioxide and respiratory illnesses in infants. In: Indoor Air '93: Proceedings of the 6th International Conference on Indoor Air Quality and Climate. Vol. 1, Health Effects (Jaakola JJK, Ilmarinen R, Seppanen O, eds.). pp. 435–440. Laboratory of Heating, Ventilating, and Air Conditioning, Helsinki University of Technology, Espoo, Finland.

Samet JM, Cushing AH, Lambert WE, Hunt WC, McLaren LC, Young SA, Skipper BJ. 1993. Comparability of parent reports of respiratory illnesses with clinical diagnoses in infants. Am Rev Respir Dis 148:441–446.

Samet JM, Lambert WE, Skipper BJ, Cushing AH, Hunt WC, Young SA, McLaren LC, Schwab M, Spengler JD. 1993. Nitrogen dioxide and respiratory illness in infants. Am Rev Respir Dis 148:1258–1265.

Schwab M, Spengler JD, McDermott A, Samet JM, Lambert WE. 1993. Seasonal and yearly patterns of indoor nitrogen dioxide levels: Data from Albuquerque, New Mexico. In: Indoor Air '93: Proceedings of the 6th International Conference on Indoor Air Quality and Climate. Vol. 3, Combustion Products, Risk Assessment, Policies (Jantunen M, Kalliokoski P, Kukkonen E, Saarela K, Seppanen O, Vuorelma H, eds.). pp 205–210. Laboratory of Heating, Ventilating, and Air Conditioning, Helsinki University of Technology, Espoo, Finland.

Spengler JD, Brauer M, Samet JM, Lambert WE. 1993. Nitrous acid in Albuquerque, New Mexico, homes. Environ Sci Technol 27:841–845.

Schwab M, Spengler JD, McDermott A, Samet JM, Lambert WE. 1994. Seasonal and yearly patterns of nitrogen dioxide levels: Data from Albuquerque, New Mexico. Indoor Air 4:8–22.

ABBREVIATIONS

β	linear regression model coefficient
HONO	nitrous acid
NO_2	nitrogen dioxide
ppb	parts per billion
r	sample correlation coefficient
R^2	multiple correlation coefficient
SD	standard deviation
SEE	standard error of the estimate

HEI

INTRODUCTION

As Part IV of HEI Research Report Number 58, *Nitrogen Dioxide and Respiratory Illness in Children*, this report by Dr. Spengler and colleagues continues the presentation of data obtained during a prospective study of the effect of exposure to nitrogen dioxide (NO_2)* on respiratory illness in infants. Parts I, II, and III were Health Outcomes (Samet et al. 1993), Assessment of Exposure to Nitrogen Dioxide (Lambert et al. 1993), and Quality Assurance in an Epidemiologic Study (Lambert et al. 1994). Part IV describes the results of analyses aimed at characterizing the influence of housing characteristics, occupant behavior, and meteorologic factors on NO_2 levels in a sample of more than 1,400 bedrooms of infants in Albuquerque, NM. Part V, which addresses the frequency of infants' exposure to peak concentrations of NO_2 in homes with gas stoves, is forthcoming.

A draft final report was submitted to HEI in December 1994, and a revised report, submitted in June 1996, was accepted for publication by the HEI Health Review Committee in July 1996. During the review of the Investigators' Report, the Health Review Committee and the investigators had the opportunity to exchange comments and to clarify issues in the Investigators' Report and the Health Review Committee's Commentary. The following Commentary is intended to serve as an aid to the sponsors of HEI and the public by highlighting both the strengths and the limitations of the study.

SCIENTIFIC BACKGROUND

Oxides of nitrogen are common air pollutants both indoors and outdoors. The most abundant are NO_2 and nitric oxide (NO). Nitrogen dioxide is derived primarily from NO, a product of the combustion of fossil fuel by industrial operations, electric power generation, and motor vehicles (Morrow 1984; Finlayson-Pitts and Pitts 1986). In the atmosphere, NO is oxidized rapidly by ozone and organic gases, and more slowly by oxygen, to form NO_2 (Urone 1976; National Research Council 1991b).

During the 1970s, laboratory and field studies showed that unvented kerosene and gas space heaters and gas appliances such as cooking ranges are potential sources of indoor oxides of nitrogen. Indoor concentrations of these pollutants often exceed outdoor concentrations (National Research Council 1991a; Samet 1991; U.S. Environmental Protection Agency 1993). Exhaust from automobiles in attached garages can add to indoor NO_2 levels (Samet 1991). Cigarette smoke is another source of indoor NO_2, but families with cigarette smokers were not included in this study.

For a detailed discussion of the context of this study and the rationale for studying the association between exposure to indoor NO_2 and respiratory illness in infants, the reader is encouraged to consult Part I of this Research Report. Briefly, by the mid 1980s, a large body of toxicologic data indicated that exposing laboratory animals to moderately high concentrations of NO_2 adversely affected several lung components that are important in resisting and controlling infectious microorganisms. In addition, epidemiologic investigations raised the suspicion that children exposed to elevated levels of NO_2, in either outdoor or indoor air, may be more prone to develop respiratory illnesses than children living in areas with lower levels of ambient NO_2 (reviewed by the U.S. Environmental Protection Agency [1993] and in the HEI Health Review Committee's Commentary on Parts I and II of this Research Report.

For these reasons, HEI funded a prospective study to evaluate whether exposure to NO_2 affects the incidence or duration of respiratory illnesses in infants during their first 18 months of life. Dr. Jonathan Samet, the Principal Investigator, and his colleagues at the University of New Mexico and the Harvard School of Public Health designed the study to minimize misclassifications of exposure levels and health outcomes, which were limitations of some earlier investigations. The main findings on health effects and exposure assessment were reported in Parts I and II of this Research Report (Samet et al. 1993a; Lambert et al. 1994) and in the peer-reviewed literature (Samet et al. 1993b). In this report, Dr. Spengler and colleagues evaluate factors associated with variations in indoor NO_2 concentrations and examine seasonal and year-to-year variability.

OBJECTIVES AND STUDY DESIGN

The objective of the overall study was to determine whether respiratory infections in infants increase in frequency or duration, or both, after exposure to elevated levels of NO_2. A secondary goal, which was necessary for achieving the main objective, was to provide accurate assessments of NO_2 exposure in the study population. Outdoor levels of NO_2 in Albuquerque are usually low, and do

* A list of abbreviations appears at the end of the Investigators' Report for your reference.

not significantly affect indoor levels. Therefore, gas ranges and unvented gas appliances represent the principal indoor sources of human exposures to NO_2 in the Albuquerque area (Harlos et al. 1987; Marbury et al. 1988; Samet and Spengler 1989).

The main objective of Part IV was to characterize the temporal variation in NO_2 in the infants' bedrooms and develop empirical models that would predict those concentrations. The specific aims of the analyses reported here were:

1. To determine whether the variation in NO_2 concentrations in the infants' bedrooms was associated with housing characteristics (including age, size, and type of construction of the house, type of furnace, and presence of a gas or kerosene space heater, fireplace, evaporative cooler, or attached garage), and type and use of cooking range (gas range with continuously burning pilot light, gas range with electronic ignition or manually lit pilot light, or electric range, use of the cooking range for space heating, and minutes of cooking range use per season or year); and
2. To determine seasonal and year-to-year variations in bedroom NO_2 concentrations.

The investigators collected their data during the winters (November 1 through March 15) of 1988/89, 1989/90, and 1990/91, and the summers (May 1 through September 30) of 1988, 1989, and 1990. They placed passive diffusion samplers for NO_2 (Palmes tubes) at various locations in the homes (in the infant's bedroom, kitchen, and family room for homes with gas ranges; only in the infant's bedroom for homes with electric ranges) and at 11 outdoor locations in Albuquerque. In this study, measurements of NO_2 in the infants' bedrooms provided the most complete coverage for longitudinal analyses, and the investigators focused their analyses on these data. The other measurements were used in the analyses in Parts I and II of this Research Report.

Dr. Spengler and colleagues oversaw the production of the Palmes tubes at the Air Quality Laboratory of the Harvard School of Public Health and shipped them to the University of New Mexico, where project staff labeled them with bar codes before placing them in subjects' homes or outdoors. After a two-week exposure period, the tubes were returned to the University of New Mexico, the barcode labels were optically scanned, and the dates and times of tube opening and closing were keyed into a computer. The tubes were then shipped to the Harvard School of Public Health for NO_2 analysis. At Harvard, the staff optically scanned the tube labels and compared the inventory with the shipping list produced by the University of New Mexico. A detailed discussion of the quality control and quality assurance procedures for NO_2 measurements can be found in Parts II and III of this Research Report.

Because the investigators were interested in the effect of housing characteristics on NO_2 levels, when a participant changed residence during the study period (5% of all participants), they treated the data obtained in each new house separately from the data obtained in the previous residence. No house was studied for longer than the 18-month observation period for each infant; therefore, the investigators did not collect data for each house over the full length of the study. However, infants were enrolled over a 30-month period; thus, the analyses are based on data collected over a three-year period from April 1988 through March 1991.

TECHNICAL EVALUATION

ATTAINMENT OF STUDY OBJECTIVES

The investigators successfully attained the major objectives for this part of the study. They evaluated factors thought to be associated with variations in bedroom NO_2 concentrations and characterized the variability of bedroom NO_2 concentrations across seasons and years. They developed multivariate models based on data collected in one season and used them to determine how closely the data produced from the model matched bedroom NO_2 levels measured in a previous year.

ASSESSMENT OF METHODS AND STUDY DESIGN

The study design and methods that the investigators used to assess levels of exposure were generally sound and, as discussed in the HEI Health Review Committee's Commentary on Parts I and II, represent a significant improvement over many earlier efforts in this field. In addition to obtaining repeated measurements of NO_2 concentrations in multiple locations in the subjects' homes throughout the entire observation period, the investigators designed and followed well-defined quality control and quality assurance procedures, paying careful attention to a variety of factors that could affect the collection of data on NO_2 concentrations. Rigorous procedures to track sample collections were implemented. Because of these procedures, the overall study provides one of the largest and most reliable data bases on indoor NO_2 concentrations.

ANALYTICAL AND STATISTICAL METHODS

Dr. Spengler and colleagues adopted a three-step modeling approach to predict bedroom NO_2 levels. First, they used linear regression techniques to relate housing characteristics to average bedroom NO_2 concentrations measured in the winter of 1989/90. Linear regressions were developed for both untransformed and log-transformed averages. The investigators analyzed housing characteristics individually in the regressions and then jointly in multiple regressions. They next developed separate multivariate models (called "base models") for homes with gas ranges and homes with electric ranges. From these, they developed other models by adding the age of the home (called "base-plus models"). The rationale for including the age of the home is that it can act as a surrogate measure for other factors influencing bedroom NO_2 levels, such as "tightness" of the home and the condition of cooking and heating appliances. The investigators also explored the effects of ambient temperature and precipitation on bedroom NO_2 levels. Finally, they tested the multivariate models developed from data collected during the winter of 1989/90 for their ability to reconstruct indoor NO_2 levels in a separate set of households monitored during the winter of 1988/89. Although outdoor NO_2 concentrations were measured over the course of the study, they were not used in these analyses, and their absence may have affected the accuracy of the models (see the section on Results and Interpretation).

The validation analysis using the model of 1989/90 to reconstruct 1988/89 data is a strong feature of this study. Two items, however, distract and can cause confusion. First, the authors report that the mean of the predicted and observed average NO_2 levels are equal. However, if the average concentrations for 1988/89 and 1989/90 were approximately the same, then the observed and predicted averages would be expected to be equal, because the average of the model predictions equals the mean value of the observed data.

Second, the authors note that the standard deviation of the observed average NO_2 levels is 12 ppm and the standard deviation of the predicted average NO_2 levels is 6 ppm. This may be a feature of the regression analysis used to derive the model. Regression models produce a "regression to the mean" effect, so the prediction levels will have a smaller standard deviation than the observed levels.

The model validation would have been enhanced if the investigators had contrasted the correlations of the predicted average NO_2 concentrations and the observed average NO_2 concentrations with the multiple correlation coefficients of the models. The square of the correlation between the observed and predicted average NO_2 levels measures a model's validity. The difference between the square of a model's multiple correlation and the square of the correlation of the observed and predicted average NO_2 levels is a direct measure of overfitting in a model.

RESULTS AND INTERPRETATION

Variations in Bedroom Nitrogen Dioxide Concentrations Among Homes in a Single Winter

The investigators focused most of their measurements on the winter season, when the use of appliances that produce NO_2 is generally highest. As expected, they found that bedroom NO_2 concentrations were consistently higher in homes with gas cooking stoves than in homes with electric ranges. Gas ranges with continuously burning pilot lights produced higher bedroom levels of NO_2 than did gas ranges with electronic or manual ignition. Homes with any type of gas cooking range had higher bedroom NO_2 levels during the winter than during the summer; these levels increased if the gas range was used for supplemental space heating.

This part of the overall study provided data that confirmed previous investigations: homes with wall or floor furnaces had higher bedroom levels of NO_2 than did homes with central, forced-air furnaces (Wilson et al. 1986); bedroom NO_2 levels were lower in homes with a fireplace than in homes without a fireplace, presumably because indoor air was lost up the chimney; and bedroom NO_2 levels were higher in homes built before 1970, which tended to be smaller than homes built after that year (NO_2 in indoor air is diluted as the house volume increases, and large homes also provide more surfaces to react with NO_2 and remove it from indoor air [Spicer et al. 1986]). New information contributed by this study indicated that bedroom NO_2 levels were inversely related to the distance from the kitchen to the bedroom. The authors proposed that the distance from the kitchen to the bedroom can serve as a surrogate measure of house size. Another new finding was that decreasing temperature and increasing precipitation caused bedroom NO_2 levels to rise. These meteorologic factors could increase the use of cooking and heating appliances and decrease the exchange of indoor air with outdoor air.

It is important to note that the mean bedroom NO_2 levels reported in this study fall in the middle to lower range of levels reported in other studies. The NO_2 levels reported by Dr. Spengler and colleagues are lower than those found in bedrooms in heavily polluted areas of the country and in poorly ventilated inner-city apartments (Table 1 in this

Commentary). Thus, the study results may not be generalizable to areas of the country with different climates, types of architecture, or ambient levels of NO_2.

Year-to-Year and Seasonal Variations in Bedroom Nitrogen Dioxide Concentrations

The repeated measurements over the three-year study showed no temporal variability in bedroom NO_2 levels in homes with electric cooking ranges. However, in homes with gas appliances, several trends were evident. The duration of the period during which NO_2 levels in infants' bedrooms were elevated and the extent to which they were elevated during the winter months varied from year to year. The magnitude of the differences in NO_2 levels between homes having gas ranges with pilot lights and homes having gas ranges without pilot lights also varied from year to year. Because these comparisons did not reflect the changing composition of the study population (and thus the changing housing characteristics), the investigators next restricted their data set to homes providing measurements in a consecutive pair of winters or summers. An important new finding emerged: namely, in seasonal comparisons between years (winter to winter or summer to summer), differences in average bedroom NO_2 concentrations were statistically significant. The investigators were unable to explain these year-to-year variations by changes in temperature, ambient outdoor NO_2 levels, or the household characteristics described above. They proposed that the differences in bedroom NO_2 levels across years resulted from variations in the behavior of the occupants, which could have affected the rate of air exchange between outdoors and indoors, or the use of appliances that produce NO_2, or both.

The predictive models that were generated from data collected over one winter did not have strong capabilities to reconstruct the indoor NO_2 levels in Albuquerque bedrooms measured over a preceding winter. This lack of power might be due to the generally low levels of indoor NO_2 or to the study design. The investigators did not match outdoor NO_2 measurements with indoor measurements. Including outdoor NO_2 levels in the models would have allowed them to address indoor-outdoor issues in homes with and without indoor NO_2 sources and allow for more detailed modeling.

IMPLICATIONS FOR FUTURE RESEARCH

The finding that bedroom levels of NO_2 can differ significantly from season to season, from year to year, and with housing characteristics, has important implications for exposure classification in future epidemiologic studies. It

Table 1. Winter Bedroom Nitrogen Dioxide Concentrations in Dwellings with Gas Cooking Ranges

Study Location	Housing Type	Average NO_2 (ppb)
Albuquerque, NM*	Majority single family, unattached	21–29 (with pilot light) 15–20 (without pilot light)
Southern, CA	Mixed single family attached, unattached, condominium	28–40
New Haven, CT	Single family, unattached	14.6
Albuquerque, NM	Mixed	20–36
California	Mobile homes	19.9
Portage, WI	Mixed	11–17
Tucson, AZ	Mixed	23
Boston, MA	Mixed	25.8 (winter/spring)
New York, NY	Apartments	33.4–40.3
Watertown, MA	Not given	23.4–24.4 (Nov, Dec)
Middlesbrough, U.K.	Not given	30.7
Middlesbrough, U.K.	Not given	31.8

* These data are from Table 5 of the Investigators' Report; the data for all the other studies are taken from Table 7-16 of U.S. Environmental Protection Agency (1993).

suggests that concentrations measured in one year cannot be considered as an accurate index of concentrations in other years. The spatial, temporal, and seasonal variations in indoor NO_2 concentrations observed in this study emphasize the importance of prospective study designs that closely match exposure measurements and health outcomes.

CONCLUSIONS

Dr. Spengler and colleagues reported the effects of housing characteristics and meteorologic factors on repeated measurements of NO_2 levels in the bedrooms of infants in Albuquerque. The investigators obtained detailed information on the multiple factors that influence indoor NO_2 levels. As expected, these included the presence of gas cooking ranges, particularly those with continuously burning pilot lights, the use of the gas stove or burners for space heating, the presence of wall or floor furnaces, and the size of the house. They also found significant year-to-year variation in bedroom NO_2 levels that could not be substantially explained by changes in temperature, ambient levels of NO_2, or housing characteristics. The variation in NO_2 levels across years has important implications for designing and interpreting epidemiologic studies that use NO_2 measurements taken at one point in time to represent NO_2 levels at different time points. Thus, the results of this study emphasize the need to time closely repeated measurements of NO_2 levels with measurements of health outcomes in order to reduce the chances of exposure misclassification.

ACKNOWLEDGMENTS

The Health Review Committee wishes to thank Dr. Brian Leaderer and the ad hoc reviewers for their help in evaluating the scientific merit of the Investigators' Report, and Dr. Bernard Jacobson for his assistance in preparing this Commentary. The Committee also acknowledges Ms. Virgi Hepner, Ms. Genevieve MacLellan, Mr. Robert J. Jaret, Ms. Valerie Anne Kelleher, Ms. Malti Sharma, and Ms. Mary Stilwell for producing this report.

REFERENCES

Finlayson-Pitts BJ, Pitts JN. 1986. Atmospheric Chemistry: Fundamentals and Experimental Techniques, pp. 522–548. John Wiley & Sons, New York, NY.

Harlos DP, Marbury M, Samet J, Spengler JD. 1987. Relating indoor NO_2 levels to infant personal exposures. Atmos Environ 21:369–376.

Lambert WE, Samet JM, Hunt WC, Skipper BJ, Schwab M, Spengler JD. 1993. Nitrogen Dioxide and Respiratory Illness in Children: Part II, Assessment of Exposure to Nitrogen Dioxide. Research Report Number 58. Health Effects Institute, Cambridge, MA.

Lambert WE, Samet JM, Skipper BJ, Cushing AH, Hunt WC, Young SA, McLaren LC, Schwab M, Spengler JD. 1994. Nitrogen Dioxide and Respiratory Illness in Children: Part III. Quality Assurance in an Epidemiologic Study. Research Report Number 58. Health Effects Institute, Cambridge, MA.

Marbury MC, Harlos DP, Samet JM, Spengler JD. 1988. Indoor residential NO_2 concentrations in Albuquerque, NM. J Air Pollut Control Assoc 38:392–398.

Morrow PE. 1984. Toxicological data on NO_X: An overview. J Toxicol Environ Health 13:205–227.

National Research Council. 1991a. Human Exposure Assessment for Airborne Pollutants: Advances and Opportunities. National Academy of Sciences, Washington, DC.

National Research Council. 1991b. Rethinking the Ozone Problem in Urban and Regional Air Pollution. National Academy Press, Washington, DC.

Samet JM. 1991. Nitrogen dioxide. In: Indoor Air Pollution: A Health Perspective (Samet JL, Spengler JD, eds.) pp. 170–186. Johns Hopkins University Press, Baltimore, MD.

Samet JM, Lambert WE, Skipper BJ, Cushing AH, Hunt WC, Young SA, McLaren LC, Schwab M, Spengler JD. 1993a. Nitrogen Dioxide and Respiratory Illness in Children: Part I. Health Outcomes. Research Report Number 58. Health Effects Institute, Cambridge, MA.

Samet JM, Lambert WE, Skipper BJ, Cushing AH, Hunt WC, Young SA, McLaren LC, Schwab M, Spengler JD. 1993b. Nitrogen Dioxide and Respiratory Illness in Children. Am Rev Respir Dis 148:1258–1265.

Samet JM, Spengler JD. 1989. Nitrogen Dioxide and Respiratory Infection: Pilot Investigations. Research Report Number 28. Health Effects Institute, Cambridge, MA.

Spicer CW, Coutant RW, Ward GF. 1986. Investigation of nitrogen dioxide removal from indoor air. Report Number GRI-86/0303. Gas Research Institute, Chicago, IL.

Urone P. 1976. The primary air pollutants—gaseous: Their occurrence, sources and effects. In: Air Pollution, 3rd ed, Vol. I (Stern AC, ed.) pp. 24–75. Academic Press, New York, NY.

U.S. Environmental Protection Agency. 1993. Review Draft, Air Quality Criteria for Nitrogen Oxides. EPA/600/8–91/049aA. Office of Research and Development, Washington, DC.

Wilson AL, Colome SD, Baker PE, Becker EW. 1986. Residential characterization study of nitrogen dioxide: Phase I, Vol. 1, 2, and 3. Southern California Gas Co., Los Angeles, CA.

RELATED HEI PUBLICATIONS:
NITROGEN DIOXIDE

Research Reports

Report No.	Title	Principal Investigator	Publication Date
15	Susceptibility to Virus Infection with Exposure to Nitrogen Dioxide	T.J. Kulle	1988
18	Respiratory Infections in Coal Miners Exposed to Nitrogen Oxides	M. Jacobson	1988
20	Modulation of Pulmonary Defense Mechanisms Against Viral and Bacterial Infections by Acute Exposures to Nitrogen Dioxide	G.J. Jakab	1988
24	Altered Susceptibility to Viral Respiratory Infection During Short-Term Exposure to Nitrogen Dioxide	R.M. Rose	1989
28	Nitrogen Dioxide and Respiratory Infection: Pilot Investigations	J.M. Samet	1989
43	Mechanisms of Nitrogen Dioxide Toxicity in Humans	M.J. Utell	1991
47	Murine Respiratory Mycoplasmosis: A Model to Study Effects of Oxidants	J.K. Davis	1991
58	Nitrogen Dioxide and Respiratory Illness in Children	J.M. Samet	1993
	Part I: Health Outcomes		1993
	Part II: Assessment of Exposure to Nitrogen Dioxide		1993
	Part III: Quality Assurance in an Epidemiologic Study		1994
60	Failure of Ozone and Nitrogen Dioxide to Enhance Lung Tumor Development in Hamsters	H. Witschi	1993
70	Oxidant and Acid Aerosol Exposure in Healthy Subjects and Subjects with Asthma		
	Part I: Effects of Oxidants, Combined with Sulfuric or Nitric Acid, on the Pulmonary Function of Adolescents with Asthma	J.Q. Koenig	1994

Copies of these reports can be obtained by writing or calling the Health Effects Institute, 955 Massachusetts Avenue, Cambridge, MA 02139. Phone (617) 876-6700. FAX (617) 876-6709. E-mail pubs@healtheffects.org

HEI

HEI HEALTH EFFECTS INSTITUTE 955 Massachusetts Avenue, Cambridge, MA 02139 (617) 876-6700

Research Report Number 58 **December 1996**