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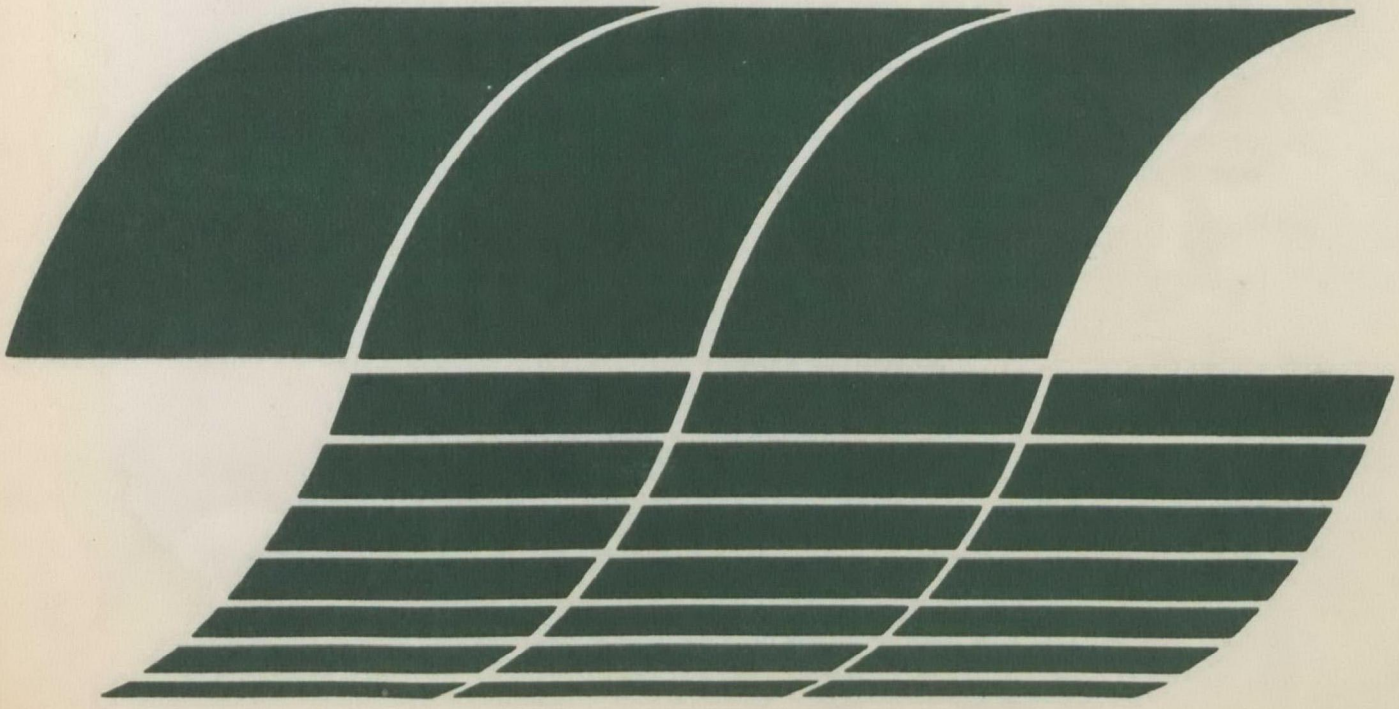
Indoor Air Pollution in the Residential Environment

Volume I
Data Collection, Analysis and Interpretation

Interagency Energy/Environment R&D Program Report



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Indoor Air Pollution In the Residential Environment
Volume I. Data Collection, Analysis, and Interpretation

by

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EXECUTIVE SUMMARY

INTRODUCTION

Between March 1976 and March 1978 GEOMET, Incorporated conducted a study of residential indoor air pollution for EPA and HUD. The work has been described in a series of GEOMET reports, the principal ones being:

The Status of Indoor Air Pollution Research--1976
EPA Report Number 600/4-77-029, May 1977

Survey of Indoor Air Quality Health Criteria and Standards
EPA Report Number 600/7-78-027, March 1978

Proceedings of the GEOMET Program Review Workshop--Air Pollution, Energy Conservation and Health Effects in the Indoor Residential Environment
GEOMET Report Number EF-646, September 1977

The GEOMET Indoor-Outdoor Air Pollution Model
GEOMET Report Number EF-628, February 1978

Indoor Air Pollution in the Residential Environment
Volume I - Data Collection, Analysis and Interpretation
Volume II - Field Monitoring Protocol, Indoor Episodic Pollutant Release Experiments and Numerical Analyses
GEOMET Report Number EF-688, August 1978.

This Executive Summary outlines the highlights of these reports.

OBJECTIVES OF THE STUDY

The indoor residential environment constitutes a major component of an individual's total exposure to air pollution. Residential air pollution has not been studied to a great extent in the past and has not been considered in the setting of regulatory standards for air pollution.

The recent national effort to conserve energy has led to a justifiable concern about the possible impact that energy conservation measures may have on indoor residential air quality. The following questions arise concerning the public health and welfare:

- What are the air pollution characteristics within residences?
- How do they relate to indoor-outdoor air exchange rates?
- How are they affected by energy conservation measures?
- What are the potential health effects of residential air pollution?

Questions of this kind prompted the decision by EPA and HUD to sponsor a comprehensive study of the air quality in residences. The experimental design for monitoring in residences, the mathematical and statistical techniques used to analyze the data, the significance of the findings, and the areas that warrant future research are briefly discussed in the following pages.

TECHNICAL APPROACH

Phase I of the project was a literature search of the indoor air pollution studies as described in published literature and unpublished ongoing research. Studies on indoor pollutant sources, pollutant distribution and behavior in the residential environment, monitoring technology for sampling in residences, indoor human activity and occupancy profiles, energy conservation measures in residential dwellings, health effects due to elevated indoor pollutant concentrations, and numerical models for predicting indoor air pollutant concentrations were examined. The comprehensive survey and assessment of the state-of-the-art determined monitoring techniques that required improvement, questions that warrant further research, and areas that had not been emphasized by previous work.

Phase II, an 18-month program of monitoring, analysis, and modeling, utilized sampling techniques that allow air quality monitoring in residences under real-life conditions. Analyses were performed to determine the indoor-outdoor air pollutant relationships for a large number of contaminants. Finally, two numerical models were formulated to realistically simulate the complex conditions involved in predicting pollutant concentrations.

Indoor air quality was monitored for continuous periods of approximately 14 days in each of five detached dwellings, two semidetached dwellings (townhouses), six apartment units, two mobile homes and one school. In addition, a 5-day period of monitoring was performed in one hospital. These structures were located in five metropolitan areas: Baltimore, Maryland; Washington, D.C.; Chicago, Illinois; Denver, Colorado; and Pittsburgh, Pennsylvania. A mobile laboratory fully equipped with the necessary monitoring equipment was placed in close proximity to the structure being monitored. Pollutant concentrations were measured at one location outdoors (adjacent to the building) and at three locations indoors (typically the kitchen, a bedroom and the living room). Four-minute samples of gaseous pollutants were obtained three times each hour from a continuous monitoring system which was used in conjunction with a programmable solenoid switching mechanism at each of the four locations. Twenty-four hour averages of particulate pollutants were measured in the same four locations. In addition to air pollution data, the experimental design called for monitoring of meteorological parameters, energy consumption, and daily family activity. Finally, experiments with an inert tracer (SF_6) were performed to determine the air exchange rate of each residence.

Analysis of the large data base generated by the field program was a multiphased procedure which ranged from interpreting isolated short-term behavior of indoor pollutant concentrations to establishing trends of the fluctuations of air pollutant concentrations in the residential environment. A data set from a 14-day monitoring period was treated as an independent entity; each pollutant was investigated separately. However, interelement comparisons were carried out, seasonal variations were examined, and a classification of residences from the perspective of air quality was undertaken. Analytical techniques used for data interpretation included simple observations, descriptive statistics and complex analytical expressions denoting the dynamic relationships involved in the explanation of the observed behavior of indoor pollutant concentrations.

In addition to data collection and analysis, two numerical models were formulated to predict the indoor pollutant concentrations. The GEOMET Indoor-Outdoor Air Pollution (GIOAP) model predicts indoor concentrations of gaseous pollutants. The fundamental principle involved in the formulation of the GIOAP model is the principle of mass balance. This model is a first order differential equation which dynamically relates the rate of change of an indoor pollutant concentration to the rate of introducing a pollutant indoors through ventilation, infiltration, recirculation, and indoor sources, and to the rate of removing the pollutant concentration from the indoor environment through the mechanisms of exfiltration, exhaust, indoor chemical sinks, and air cleaning devices. Validation studies performed with the GIOAP model indicate that it satisfactorily predicts corresponding observed values.

The TSP (total suspended particulate) empirical model was the second model formulated for this study. It is a steady-state model which was based on the available data. A portion of the TSP matter found indoors is of outdoor origin, while the remaining portion is attributed to indoor activities. Studies on particulate matter have concentrated on quantifying source strengths of individual indoor TSP generating mechanisms, such as vacuum cleaning, operating a fan, smoking, frying, house cleaning, using sprays, moving in and out of the house, ventilating devices, and others. This study did not attempt to measure the strength of individual TSP sources; rather, it provided a scale of the activity of each residence and quantified indoor TSP levels as a function of the family activity index. This approach took advantage of the data available to the project and utilized the questionnaire which was answered on a daily basis. The procedure used for the model formulation utilized a portion of the available data to define the indoor TSP source strength as a function of the activity scale, and the remaining data to verify the numerical predictions. The TSP model realistically predicts the observed indoor TSP concentrations.

Analysis of energy data collected in monitored residences demonstrated that the energy consumed is a function, among other factors, of the air exchange rate. It has also been demonstrated that changes in the air

exchange rate affect the residential air quality. The relationship between energy conservation measures and air quality in residences was studied by two methods: 1) analysis of the observed energy and air quality data; and 2) numerical simulations using the state-of-the-art models for estimating residential energy consumed and the GIOAP model for calculating the indoor pollutant concentrations.

RESULTS

The air quality in the indoor residential environment has been found to be markedly different from the ambient outdoor air quality. Three classes of air pollutants have been identified with respect to indoor-outdoor pollutant relationships:

1. Concentrations of carbon monoxide (CO), nitric oxide (NO), carbon dioxide (CO_2), hydrocarbons, and aldehydes in the residential environment were often higher than outdoors.

2. Indoor concentrations of nitrogen dioxide (NO_2), TSP, and respirable suspended particulate matter (RSP) are sometimes higher and sometimes lower than outdoors.

3. Indoor concentrations of sulfur dioxide (SO_2), ozone (O_3), sulfates (SO_4), nitrates (NO_3), and lead (Pb) are often lower than corresponding outdoor pollutant concentrations.

The observed indoor air pollutant concentrations were, on the average, not very high, but persistent moderate concentrations and at times elevated pollutart levels were observed in the monitored residences. Air pollution standards for the residential indoor environment have not been promulgated. However, field measurements from this program have established that concentrations of O_3, nonmethane hydrocarbons, and TSP matter exceed the National Ambient Air Quality Standards (NAAQS) in the indoor environment. The 8-hour NAAQS for CO was not exceeded by the registered indoor concentrations, but it was equaled several times. The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) has recommended standards for, among others, CO_2 and aldehydes. These standards have been exceeded by the observed concentrations of these contaminants and, on certain occasions, by a factor of two or three. The observed high levels of CO_2, nonmethane hydrocarbons, aldehydes and TSP matter may be attributed to indoor sources, while the elevated levels for the other pollutants may be caused by high ambient concentrations.

Two major classes of indoor residential environments have been identified by this study: 1) residences with indoor pollutant sources; and 2) residences without indoor pollutant sources. This classification is pollutant specific; it is quite possible that the same residence may belong in

one class for one pollutant and in another class for another. A few of the many possible indoor pollutant sources are gas appliances, smoking, cleaning and cooking activities, aerosol sprays, wall paint, and chipboard. Pollutants emitted by these sources include CO, NO, NO_2, organics, TSP and RSP matter, aldehydes, ammonia, and other contaminants. An attempt to put indoor sources in order of importance is not appropriate because their impact on the indoor environment depends on their frequency of use and mode of operation. However, for three pollutants (CO, NO, and NO_2), residences with gas appliances have stronger indoor sources than residences with electric appliances. The field program of this study has shown that the indoor air quality deteriorates when an indoor pollutant source is operating. It has also been observed that the adverse impact of an indoor air pollution source is accentuated in residences with low air exchange rates because the contaminated air cannot exfiltrate.

The air exchange rate is the parameter that associates energy conservation measures with air quality in residences. The data base collected for this project, combined with the results of numerical simulations carried out with the GIOAP model, demonstrates that from the perspective of air quality, reduction of the air exchange rate, an energy conserving measure, may lead to deterioration of the residential air quality. It has been determined that retrofitting existing residences down to an air exchange rate between 0.4 to 0.6 air changes per hour conserves energy without inducing drastic deterioration of the indoor air quality.

This study has clarified several important aspects of exposure to air pollutants in residential spaces. These results have shown that indoor air quality, as a composite, may present quite different exposure conditions than the surrounding ambient air quality. The study has confirmed three particular characteristics of indoor air quality that could have significant implications for the health and comfort of building occupants:

1. Emissions from gas-fueled appliances and a variety of other household sources can add considerably to indoor pollutant levels.

2. Buildings often protect individuals from high outdoor concentrations of the more reactive ambient gaseous pollutants, e.g., O_3, and probably from particulate matter with large mean mass diameter.

3. Measures taken to reduce the building air exchange rate also tend to increase the persistence over time of indoor pollutant levels.

These factors work in combination to govern indoor pollutant concentrations and should be viewed from both a short- and long-term perspective.

Investigation of the air quality control measures in the residential environment has shown that the few commercially available control devices are either inefficient, noisy, energy consuming, or expensive. Among the most frequently used air quality control instruments in the residential environment are the fan in the range hood and the panel filter in the HVAC system. The efficiency of these instruments needs to be studied and improved.

SIGNIFICANCE

This study has established that the character of the residential environment is unique and that conclusions reached by examination of the ambient environment do not necessarily apply to the indoor environment.

The present study on the residential air quality has significantly enhanced the scientific knowledge of the subject. The state-of-the-art, which was reviewed by a literature search in Phase I of this study, has been advanced by the enlargement of the available data base, the formulation and application of numerical models, the examination of the feasibility of an epidemiological program relating indoor air quality and health effects, and the investigation of the relationship between residential energy conservation measures and air quality.

The data base collected by the field program has greatly increased the available information, especially if the real-life aspects of the monitoring design are taken into consideration. The emphasis placed on the validation and application of numerical procedures for predicting residential pollutant concentrations is unique with this study and it points toward new avenues of relevant research. Technical questions resolved and assumptions verified appear throughout the text of the final report. However, one widespread assumption must be mentioned: it is incorrect to assume that the indoor environment shelters its inhabitants from all high ambient pollutant concentrations. This assumption is true only for certain pollutants. It is not always true for CO. Sheltering factors are currently under consideration but it would be misleading to establish a sheltering factor for CO concentrations, because this pollutant may be generated indoors.

The recent emphasis in energy conservation has increased the public awareness of the dynamics involved in the energy-environment complex. However, this awareness has been confined to the ambient outdoor environment. The present work has indicated that the indoor environment may be another area where the two apparently conflicting national goals manifest themselves. Both objectives can be realized if appropriate steps are taken. This study suggests a number of specific scenarios towards this goal. A most important step is that research on conservation of energy consumption in residences and on indoor air quality should be an integrated process. Protecting the welfare of individuals should not be examined in isolation either from the

energy or the air quality perspectives, rather the issue should be dealt with comprehensively. Coordinated effort will avoid unnecessary duplication and will speed up the resolution of several existing problems.

FUTURE NEEDS

In addition to problems resolved and questions answered, the indoor air quality assessment study has uncovered a series of new research requirements. Further research is needed on the indoor source emission rates, the chemical nature of certain air contaminants, such as aldehydes, RSP, organics, and others. New information on infrequently studied pollutants such as benzo-a-pyrene, asbestos, nitrosamines and others will provide additional insights on the health effects of the indoor air quality. Further research is warranted on residential air pollution control techniques and energy management procedures which conserve energy and do not affect the indoor air quality.

Possible emissions of oxides of nitrogen from residential gas furnaces have been the subject of recent controversy. Results of past studies have been inconclusive. The data obtained in the course of this study do not resolve this controversy since the experimental design did not call for monitoring in the furnace areas. Additional studies must be undertaken to examine this potentially serious source of indoor NO generation.

The next step in evaluating the importance of residential air quality is the assessment of health effects of indoor air pollution with an epidemiological study of community populations in a variety of indoor air environments. The research tools are available and the need for a comprehensive study is apparent. The eventual outcome of such an undertaking will lead to improved protection of the public health and may help conserve additional energy in residences.

"Retrofitting" is a term used by specialists to denote efforts toward reducing energy consumption in existing residences. Reduction of the residential air exchange rate is one form of retrofitting that affects the indoor air quality. Research must focus on forms of retrofitting that do not impact on the indoor air quality. Building codes for new residential structures are under consideration. The driving concern is energy conservation; however, protection of the occupants' health in the new residences should be an additional input. Thus, while air quality specifications are not integral parts of the proposed building codes, they must be considered in the determination of the code itself.

CONTENTS

FIGURES

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Many GEOMET scientists have contributed significantly to this project and two must be mentioned by name: Mr. John L. Swift, Project Manager of Phase I of this program, has contributed throughout the project by providing scientific and managerial assistance; Mr. John R. Ward has served as staff consulting advisor concerning statistical techniques and applications required by this project. In addition, we express our appreciation to Ms. Leonora L. Riley, Manager of Technical Support, and her staff, especially Mrs. Efegenia G. Maxwell, for the excellent effort involved in preparing and typing the final report.

Finally, the authors would like to acknowledge the occupants of the residences who participated in this program for their help and indulgence while their homes were being monitored.

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Gaithersburg, Maryland
August 31, 1978

SECTION 1

INTRODUCTION

The recent emphasis on reducing energy consumption for heating and cooling residences has precipitated scientific interest in residential air quality and its relationship to energy conservation measures. It has been recently recognized that indoor air quality may be as important as ambient air quality as a health factor; that substantial amounts of energy may be conserved in the residential environment by processes that may lead to deterioration of the indoor air quality; and that the relationships between outdoor pollution levels and indoor pollutant concentrations are not well established and warrant further research.

In response to those broad requirements, the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Housing and Urban Development (HUD) have jointly sponsored a study of the residential air environment. The project entitled "Indoor Air Pollution Assessment, Control and Health Effects" was undertaken by a multidisciplinary team directed by GEOMET, Incorporated. GEOMET was responsible for management as well as the health effects, air quality analysis, and modeling aspects of the technical program. GEOMET was assisted by the efforts of three subcontractors: Hittman Associates, Inc. for energy considerations; PEDCo Environmental Specialists, Inc. for field monitoring; and IIT Research Institute (IITRI) for analysis of organic contaminants released episodically in the indoor environment. Consultants from several major universities, in the fields of epidemiology, monitoring, and modeling of indoor air pollution, provided advice to the project through GEOMET.

The 24-mo study involved a literature search to define the state-of-the-art prior to this undertaking, and an 18-mo period of monitoring, analysis, and interpretation. The results of the literature search have been described by GEOMET and its subcontractors in an EPA publication entitled "The Status of Indoor Air Pollution Research, 1976." The final report of the project consists of two volumes and an executive summary. The executive summary presents an overview of the project. Volume I of the final report, the present document, is entitled "Indoor Air Pollution in the Residential Environment: Data Collection, Analysis and Interpretation." Volume II entitled "Field Monitoring Protocol, Indoor Episodic Pollutant Release Experiment and Numerical Analyses," presents all of the supportive documents including further information on the experimental design and the monitoring instruments housed in the mobile laboratory, the numerical methods for the GEOMET Indoor-Outdoor Air Pollution (GIOAP) model, and the IITRI reports on the episodic release of pollutants.

The indoor environment was studied comprehensively; information on the air quality, meteorology, energy, air exchange rates, and family activities was collected. Over 250 pages of computer output and data sheets were required to list the raw data obtained from each of the

22 monitoring periods. While analysis, numerical models, and data interpretation are the subject of this final report, it is apparent that the wealth of the data collected can be the subject of additional research by the authors of this document and by others who wish to study this large data base.

Section 1 of this volume is a brief outline of the final report; Section 2 discusses the experimental design, the analysis procedures, and the data interpretation. The GIOAP model and the steady-state TSP model are two numerical models formulated during the course of this study in order to predict indoor pollutant concentrations; the models are discussed in Section 3 of this volume. Energy considerations are the subject of Section 4. Section 5 discusses the relationships between energy conservation measures and indoor air quality in residences. Section 6 lists the references cited in this report.

SECTION 2

THE AIR QUALITY OF THE INDOOR RESIDENTIAL ENVIRONMENT: EXPERIMENTAL DESIGN, ANALYSIS PROCEDURES, AND DATA INTERPRETATION

The air quality of the indoor residential environment will be characterized by the information collected from the 18-mo monitoring program of the indoor air quality assessment project. The monitoring design and the initial format of the processed data are outlined in the opening section. The question of air quality zones within a residence is addressed next, followed by a discussion of the analytical procedure for investigation, which leads subsequently to consideration of each pollutant separately. The data base is interpreted from the perspective of individual pollutant behavior.

FIELD PROGRAM DESIGN: DATA COLLECTION

The objectives of this research program include the determination of indoor pollutant concentrations, the identification of indoor pollutant sources, and the estimation of indor pollutant concentrations. In order to realize these objectives, an 18-mo field monitoring program was undertaken. Indoor air quality was monitored for continuous periods of approximately 14 d in each of the five detached dwellings, two semidetached dwellings (townhouses), six apartment units, two mobile homes, and one school; in addition, a 5-d period of monitoring was performed in one hospital. Three of the dwellings were referred to as experimental in the sense that they were designed to conserve energy. The remaining dwellings are referred to as conventional or by their structural type. These structures are located in five metropolitan areas: Baltimore, Washington, D.C. , Chicago, Denver, and Pittsburgh. The dwellings in Baltimore, Washington, D.C., and Chicago were monitored twice to obtain seasonal variations.

Details of the monitoring design, the instrumentation, and the mobile laboratory (van) used in the field study appear in Volume II. However, brief descriptions of the above items are provided in this section. The mobile laboratory, fully equipped with the necessary monitoring equipment, is placed in close proximity to the structure being monitored. Gas concentrations are measured at one location outdoors (adjacent to the building) and at three locations indoors (typically, the kitchen, a bedroom, and the living room). Twenty-four-hour averages of particulate pollutants are measured in the same four locations. These field observations have been classified in seven generic categories; see Table 1. The energy data will be discussed separately in Section 4 of this document.

Four-minute samples of gaseous pollutants are obtained three times each hour from a continuous monitoring system which is used in conjunction with a programmable solenoid switching mechanism at each of the four locations. Figure 1 presents a diagram of the sampling system for continuous monitoring. Air samples from each location are carried in through Teflon

tubing at a rate of 10 l/min. At the sampling trailer each sample line is connected to a pump and a three-way solenoid valve. When the Teflon solenoid valve is activated, the sample is introduced into a 91.4 cm (3 ft) glass manifold. A pump purges a sampling line when the line is not activated. Each line is activated by a programmable timer system in a predetermined sequence. The monitoring sequence is as follows: outdoor, kitchen, master bedroom, and activity room (often the living room).

TABLE 1. DATA CLASSIFICATION

1. Continuous monitoring:	CO, NO, NO_2, SO_2, O_3, CH_4, THC, CO_2
2. Intermittent monitoring:	TSP, RSP, $SO_4^{=}$, NO_3^{-}, ALD, Pb, and organic compounds
3. Physical data:	Outdoor: wind speed and direction Indoor and outdoor: temperature and relative humidity
4. Energy data:	kWh for heating, air conditioning, and total house consumption Furnace efficiency Number of door openings and closings Structural specifications House blueprints Crack length investigation
5. Tracer data:	Air exchange rate; indoor zone identification
6. Family daily logs:	Daily occupant activity record
7. Elemental analysis:	Proton-induced X-ray emission analysis (PIXE)

Eight pollutants are monitored continuously by the above system: CO, NO, NO_2, SO_2, O_3, CH_4, THC, and CO_2. Specifications of the instruments used in the project are provided in Table 2. Since meteorological conditions affect the outdoor pollution levels, pollutant reaction rates, and air exchange rates, and are therefore of importance in this study, they are monitored continuously by instruments listed in Table 2.

Twenty-four-hour averages are obtained for Total Suspended Particulate (TSP) matter and for Respirable Suspended Particulate (RSP) matter. Indoor and outdoor levels for nitrates, sulfates, and lead are obtained by chemical analysis of the TSP samples. Four-hour sampling periods are required for determining indoor aldehyde levels (ambient aldehyde levels are obtained from 24-h samples). Ammonia concentrations are obtained

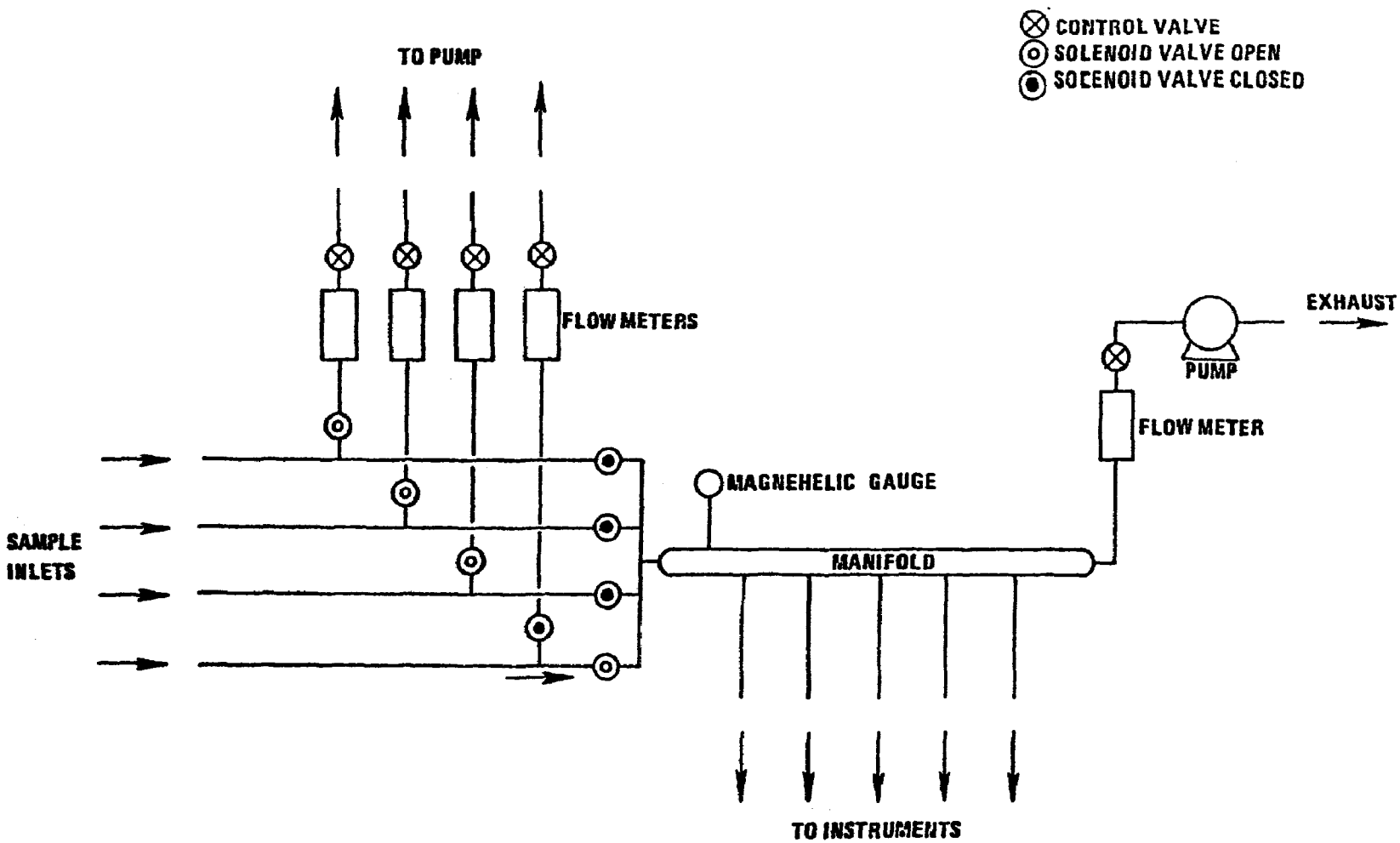


Figure 1. Sampling system for continuous monitors.

TABLE 2. CONTINUOUS MONITORING EQUIPMENT SPECIFICATIONS EMPLOYED FOR MONITORING INDOOR-OUTDOOR POLLUTANTS

Pollutant	Principle of Detection	Manufacturer, Model	Concentration (ppm) Range(s)	Limit of Detection	Response Time to 90% or Greater	Precision
NO	Chemiluminescent	Meloy NA-520-2	0-0.5 0-1.0 0-2.0 0-5.0	0.005	100 s	± 1% Full Scale
NO_x ($NO + NO_2$)	Chemiluminescent	Meloy-NA-520-2	0-0.5 0-1.0 0-2.0 0-5.0	0.005	100 s	± 1% Full Scale
CO_2	Nondispersive Infrared	Beckman-865	0-2,500 0-50,000	25 500	2.5 s	± 1% Full Scale
CO	Nondispersive Infrared with flowing Ref. Cell	Beckman-865	0-50	0.50	2.5 s	± 1% Full Scale
O_3	Chemiluminescent	Meloy-OA-350-2	0-0.5	0.005	15 s	± 2% Full Scale
SO_2	Flame Photometric	Meloy-SA-185-2A	0-0.5	0.005	60 s	± 1% Full Scale
CH_4	Flame Ionization with Selective THC Oxidizer	MSA-11-2	0-5 0-20	0.05 0.20	15 s	± 1% Full Scale
THC	Flame Ionization with Selective THC Oxidizer	MSA-11-2	0-5 0-20	0.05 0.20	15 s	± 1% Full Scale
Wind/Speed Direction	Direction-Synchro Speed-d. c. Magneto	Bendix Arovane 141/120	0-100 mph 0-540°	0.5 mph 5°	--	± 1% Full Scale
Temperature, Relative Humidity	Bimetallic Strip, Human Hair	Weather Measure H-311	Adjustable 0-100%	1°F 1% RH	--	± 1% Full Scale

from hourly samples. Ammonia is introduced into the environment by cleaning the kitchen floor with ammonia cleansers. The instrument specifications for intermittently monitored pollutants are given in Table 3.

TABLE 3. INTERMITTENT SAMPLING AND ANALYTICAL METHODS FOR INDOOR-OUTDOOR POLLUTANT MONITORING

Pollutant	Sampling Rate (1 min)	Sampling Period (hours)	Analytical Method	Limit of Detection (Working)
Total Suspended Particulates	100	24	Filtration/gravimetric	0.1 $\mu g/m^3$
Respirable Suspended Particulates (3.5 μg)	50	24	Dichotomous/gravimetric	0.1 $\mu g/m^3$
Organic Vapors	0.2	24	Charcoal absorption/ gas chromotography	ppb as CH_4
Aliphatic Aldehydes	0.5	4	Bubbler/MBTH	1.5 $\mu g/m^3$
Ammonia	0.5	1	Bubbler/phenate	5 $\mu g/m^3$
Sulfates from TSP Samples	100	24	Filtration/methyl-thymol blue	0.5 $\mu g/m^3$
Nitrates from TSP Samples	100	24	Filtration/brucine	0.1 $\mu g/m^3$
Lead from TSP Samples	100	24	Filtration/atomic absorption	0.005 $\mu g/m^3$
Elemental Analysis Atomic No. 16 through 35 Plus No. 82	1	Continuous	Streaker sampler/ PIXE	ppb to ppt

Time sequence total filter samplers, designed at Florida State University (FSU), are used to obtain a continuous time record for elemental analysis. A Nuclepore filter strip is placed over the intake to produce an 85-mm long strip sample of one-week duration and 2-h time resolution. Proton-induced X-ray emission (PIXE) analysis is performed on these aerosol samples by sequentially bombarding 2-mm wide segments of the strip. Spectral analysis, formulated by Dr. J.W. Nelson of FSU and his team, is utilized in this project for the determination of elemental content of aerosols.

The various types of data (continuous pollutant data, physical data, etc.) are collected via strip chart recorders; the data are then taken from the strip charts and entered onto coding forms (each type of data has its own specific coding form). Next, decks of punched cards are prepared for each type of data from the coding forms. Then each card deck (and in certain cases additional inputs) is used as an input to a program that creates a disk file. The result is a set of three disk files: continuous pollutant data, physical data, and 24-h sampling data. These files are used as inputs to a collection of programs that produce data tables and reports. Finally, the three disk files are input to a program that creates the data tape used by GEOMET and also produces a listing of the entire tape. For more detailed information concerning the data processing procedure described in this paragraph, refer to Volume II.

CHARACTERIZATION OF THE OBSERVED INDOOR AIR QUALITY

The large data base generated by the 18-mo monitoring program provides a unique opportunity for detailed analyses of isolated pollutant events and statistical interpretation of identified patterns. The outdoor pollutant concentrations, the indoor pollutant sources, the air exchange rates, the chemical nature of each pollutant, and the behavioral patterns of the inhabitants are among the parameters that determine indoor residential air quality. The observed variation of indoor pollutant concentrations is caused by a complex dynamic system which involves these and other parameters. The dynamics of this system are examined in subsequent discussions on the formulation and validation of the GEOMET Indoor-Outdoor Air Pollution (GIOAP) model. The short-term history, time periods of 24 h or less, of residential pollutant concentrations can be numerically simulated by the GIOAP model. However, the establishment of identifiable pollutant variation patterns and the characterization of the indoor air quality require extensive interpretation of the observed data.

Four-minute average pollutant concentrations are obtained sequentially from the four sampling sites. While the 4-min averages can be used for a detailed examination of the observations, the fundamental concentration for data interpretation is the hourly average concentration. The initial step in the analysis of the data relates to the uniformity of pollutant levels indoors. Corresponding hourly average pollutant concentrations in the three indoor sampling sites are not always equal. The problem is best seen in terms of the following questions. Do indoor zones (independent areas) with distinct pollutant patterns exist? Does the hourly average of the three corresponding indoor concentrations adequately characterize the residential air quality? Statistical tests easily answer the questions; however, the problem is not simply a statistical one but a many faceted one. Air pollution measurements are made in order to determine

the potential impact of high pollutant concentrations on human health. Therefore, conclusions on the existence of independent indoor zones must consider the health significance of the existing indoor concentration gradients in addition to the statistical results. Thus, it is the magnitude of the differences that is of importance and not the existence of the differences.

The null hypothesis, tested by a two-tailed, paired t-test, is that the mean of the differences of the concentrations of corresponding hourly pollutant averages from two indoor sites is equal to zero. For each residence investigated, a table is generated which summarizes this statistical test for all pollutants. Table 4 illustrates the results for the Chicago experimental residence. As the table indicates, the null hypothesis is rejected in more cases than it is accepted. Comparison of the observed range and the calculated mean of the differences for the illustrated residence, and for all residences sampled in this project, leads to the following resolution of the question posed earlier: corresponding hourly indoor pollutant concentrations are not uniform throughout a residence, but the existing differences between sampled indoor sites are small and probably of minimal health significance. The data interpretation will therefore proceed by assuming that one indoor hourly average concentration per pollutant characterizes the residential air quality for that hour.

The one-zone representation of observed data critically reflects on the data analysis. The following remarks will help to clarify this interpretation of the data:

1. In this extensive analytical study of indoor air quality, Shair and Heitner (1974) assumed that no pollutant gradients exist in the indoor environment. The data base of this study verifies that the pollutant gradient in the residential environment is negligible. A study of the air quality in a scientific laboratory by West (1977) shows an almost uniform distribution of an inert tracer continuously released in the laboratory. Similar experiments in residential environments show that an equilibrium situation is reached throughout the house within an hour (see Figure 2).

2. The majority of the dwellings sampled in this project had an air exchange rate (ν) of 0.4 air changes per hour or more. Distinct zones may exist in houses with very low air exchange rates ($\nu \leq 0.2$ air changes per hour) because dispersion of the indoor pollutants in these dwellings is expected to be very slow.

3. The one-zone concept does not require instantaneous mixing because it is based on the behavior of hourly average pollutant concentrations.

TABLE 4. STATISTICAL SUMMARY OF THE ZONE CONCEPT
Level of Significance 0.01
Building: Chicago Experimental Residence, Visit #1

Pollutant Observed	Zones											
	Kitchen-Bedroom				Kitchen-Livingroom				Bedroom-Livingroom			
	df	μ_D	σ_D	t	df	μ_D	σ_D	t	df	μ_D	σ_D	t
CO	311	- 0.09	0.37	-4.35	310	0.02	0.37	0.74*	311	0.11	0.45	4.19
SO_2	344	- 1.40	3.42	-7.58	345	-0.61	3.15	-3.62	344	0.80	1.72	8.61
NO	348	- 0.88	4.42	-3.70	347	-0.68	4.31	-2.96	347	0.18	4.99	0.67*
NO_2	345	0.67	4.35	2.86	344	0.20	4.44	0.82*	345	-0.43	4.49	-1.79*
O_3	349	0.00	0.03	0.28*	349	0.00	0.03	-1.00*	349	0.00	0.06	-0.63*
CH_4	329	0.02	0.18	1.56*	329	0.01	0.13	1.87*	329	0.00	0.15	-0.24*
CO_2	347	-27.62	105.14	-4.90	348	-0.01	67.37	0.00*	346	27.79	127.84	4.05
THC-CH_4	316	- 0.11	0.56	-3.35	316	-0.37	0.90	-7.34	318	-0.26	0.90	-5.19
TSP	13	12.95	13.95	3.47	12	2.78	14.89	0.67	12	-9.24	5.05	-6.60
$SO_4^{=}$	13	- 0.04	1.45	- 0.09*	11	-0.07	1.07	-0.22*	11	-0.20	1.33	-0.52*
NO_3^-	11	- 0.02	0.15	-0.38*	10	-0.05	0.07	-2.65*	10	-0.07	0.13	-1.90*

df - degrees of freedom
μ_D - mean of the differences
σ_D - standard deviation of the differences
t - paired t-statistic
* - accept the null hypothesis; i.e., H_o: $\mu_D = 0$

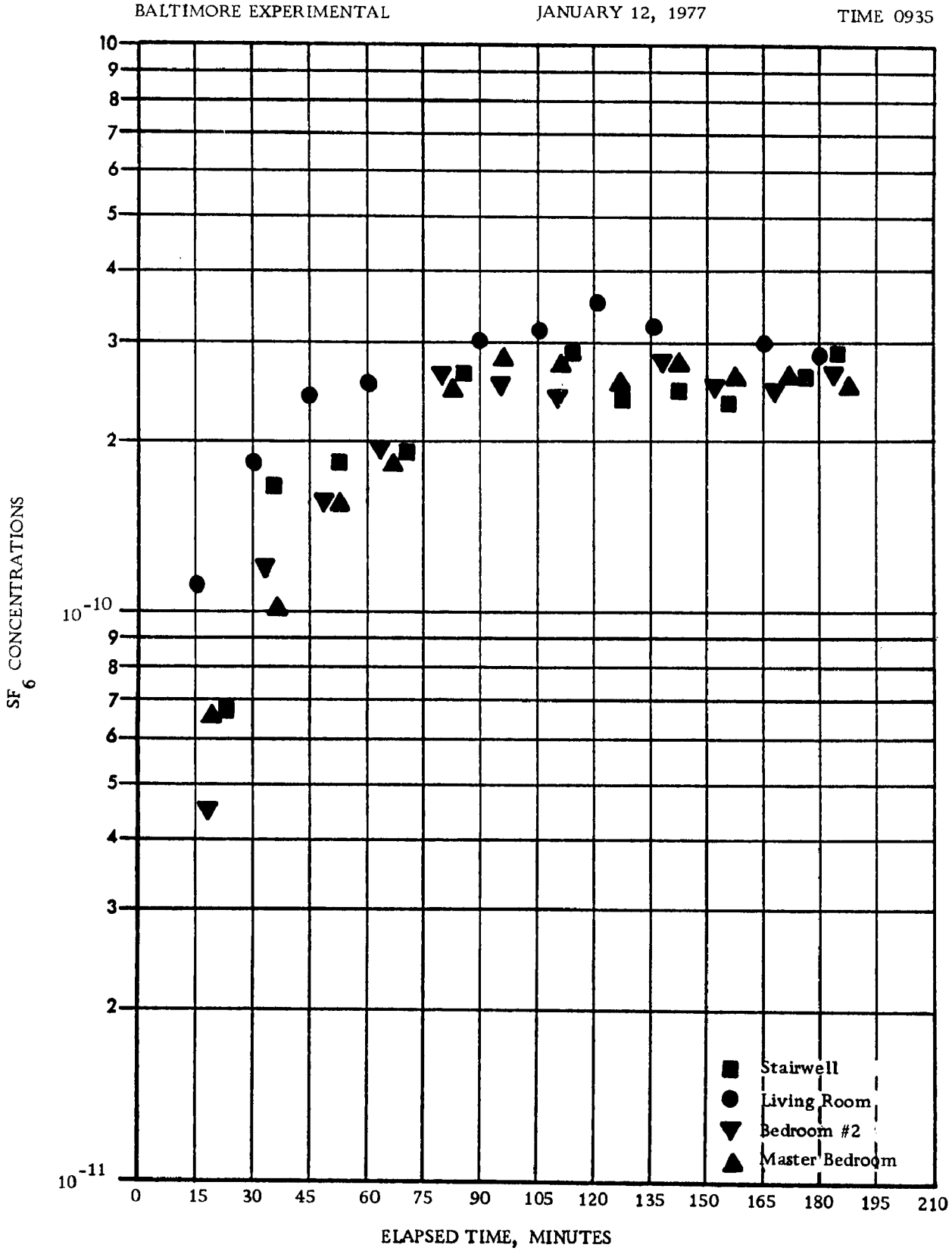


Figure 2. Equilibrium situation.

4. In certain cases the observed differences are statistically significant, but the one-zone concept does not require uniform residential concentration, rather it states that the existing differences between the average house concentration and the concentration of each separate site are very small and of minor significance to the well-being of the inhabitants.

The interpretation of the large data base generated by the monitoring of the residential environment endeavors to identify significant relations between pollution levels indoors and ambient pollution concentrations and the occurrence of augmenting or sheltering effects caused by residential structures. The air quality information sampled from each of the monitored dwellings is routinely summarized in a series of descriptive tables, statistical illustrations, diagrams, and histograms. In agreement with the one-zone concept, the average hourly indoor and outdoor concentrations of each of the pollutants monitored are listed in Table 5. Long-term averages are more suitable for identifying daily patterns than are the hourly averages, because the latter are influenced by transient variations. Three-hour, 8-h activity-period averages and 24-h averages are routinely generated for every gaseous pollutant. Table 6 is an example of these averages for both the indoor and outdoor pollutant (in this case CO) concentration. Previous studies have calculated night and day averages for corresponding outdoor and indoor pollutant concentrations; Table 6 shows that in this project "activity" averages have been estimated. The first period (hours 0-6) represents the nighttime period with minimal indoor inhabitant activity; the second period (hours 7-19) is the daytime average which summarizes the typically active hours of each 24-h period; and the third period (hours 20-23) shows pollutant concentrations averaged over the transient period between (the active daytime hours) and the inactive nighttime hours.

The data base generated for each dwelling is considered a separate entity or unit of data in the analysis of observations. For each such unit the observed concentration range for a pollutant is of interest. Table 7 illustrates a summary of the concentration ranges for each day of the monitoring period and for the entire monitoring period for all sites. While these bounds show the extreme concentrations, they provide no information on the concentration distribution of the sampled pollutants. The percent distribution (for an example, see Table 8) depicts how the observed values are distributed. The concentration range for a given pollutant is divided into 10 intervals, and the frequency concentrations occurrring within each interval is calculated. Information presented in the percent frequency distribution table may be graphically illustrated as in Figure 3. The range of the observed pollutant concentrations is divided into 10 intervals denoted by index numbers from 1 to 10 for each

TABLE 5. DAILY INDOOR-OUTDOOR CONCENTRATION SUMMARIES

SITE#: 9
VISIT#: 1
POLLUTANT: CO
POLLUTANT UNITS: PPM

		HOURS																						
DATE	LOC	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
77/ 5/ 9	OUT	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.3	1.0	2.0	-1.0	0.0	0.0	0.3
77/ 5/ 9	IN	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	2.4	3.1	2.9	3.0	3.0	3.1	3.2	3.0	2.8	2.8	-1.0	1.3	1.0	1.9
77/ 5/10	OUT	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	1.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.3
77/ 5/10	IN	1.0	1.7	1.1	1.0	1.4	1.2	1.4	1.7	2.2	2.1	1.8	1.2	1.1	1.1	1.1	1.1	2.0	2.2	1.1	1.4	1.7	2.2	2.1	1.7	1.9
77/ 5/11	OUT	0.7	1.3	0.7	0.0	0.0	0.3	1.7	3.0	1.7	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.0	0.3	0.7	1.0	0.5	2.7	2.7
77/ 5/11	IN	2.1	2.6	1.8	1.2	1.3	1.3	2.2	3.6	4.3	4.1	3.0	1.8	2.1	2.1	2.3	3.0	3.0	2.9	2.1	2.0	1.8	1.1	2.2	3.2	
77/ 5/12	OUT	1.3	1.0	1.0	0.7	0.0	0.3	1.3	3.3	3.0	3.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
77/ 5/12	IN	3.1	2.4	2.0	1.8	1.2	1.2	1.9	3.3	4.4	4.6	3.7	2.1	1.3	1.3	1.3	0.9	0.8	0.9	0.9	0.3	0.1	0.0	1.2	0.0	
77/ 5/13	OUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.3	1.0	1.0	0.3	0.0	0.0	0.7	0.3	0.3	2.0	1.3	0.0	0.0	0.0
77/ 5/13	IN	1.0	0.9	1.1	1.3	1.6	1.9	1.9	1.2	1.9	2.1	3.4	2.8	2.8	2.4	1.9	1.6	2.0	2.2	1.9	2.0	2.0	2.0	1.6	1.1	
77/ 5/14	OUT	0.7	0.3	0.3	1.0	1.0	1.0	1.0	1.3	0.7	0.0	1.0	-1.0	-1.0	-1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	1.3	
77/ 5/14	IN	1.6	1.9	1.7	2.1	2.0	2.0	1.7	1.2	1.8	1.4	1.5	-1.0	-1.0	-1.0	1.5	2.3	2.3	2.0	2.0	1.0	1.0	1.4	1.8	2.0	
77/ 5/15	OUT	2.3	1.7	0.3	0.0	0.0	0.0	0.0	0.0	1.7	0.0	3.0	2.0	2.3	1.7	1.0	1.0	0.3	1.0	2.0	2.3	2.3	1.7	0.3	0.3	
77/ 5/15	IN	2.2	2.3	1.9	1.3	1.3	1.1	0.8	0.4	0.9	2.6	2.7	2.6	3.2	3.2	2.3	2.1	1.0	1.7	2.7	3.0	2.9	2.8	1.9	1.1	
77/ 5/16	OUT	0.0	0.0	0.0	0.0	0.0	0.0	1.3	1.3	2.3	3.0	3.3	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	2.3	2.0	1.7	
77/ 5/16	IN	1.7	2.0	1.6	1.1	0.7	0.7	1.3	2.2	2.7	3.9	5.4	4.3	2.2	1.6	2.1	2.0	2.0	2.8	2.6	2.3	1.6	2.3	2.9	3.0	
77/ 5/17	OUT	1.0	1.0	1.0	0.3	0.0	0.0	0.7	1.7	2.0	2.7	1.0	0.0	0.7	1.0	0.0	0.0	0.0	0.0	0.0	0.3	2.0	4.0	5.0	5.0	
77/ 5/17	IN	2.3	2.4	2.1	1.4	1.1	0.9	1.1	1.9	2.9	5.0	5.2	4.8	3.2	3.0	2.8	2.0	1.8	1.5	1.0	0.8	1.3	3.0	4.0	4.7	
77/ 5/18	OUT	3.0	3.0	2.7	2.0	2.0	2.7	3.0	4.0	3.7	2.3	1.5	0.7	0.0	0.3	0.3	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	
77/ 5/18	IN	4.8	4.3	3.4	3.3	3.0	3.2	3.3	3.4	4.1	4.1	3.3	1.8	1.6	1.6	1.2	1.4	1.7	2.6	1.8	1.3	1.7	1.8	2.6	2.2	
77/ 5/19	OUT	0.3	0.3	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	1.0	0.7	1.3	1.0	1.0	0.3	0.3	0.0	0.7	1.0	2.0	1.0	0.7	
77/ 5/19	IN	2.3	2.1	1.3	1.3	1.3	1.2	1.2	1.6	2.3	1.4	1.0	2.4	2.6	3.0	2.1	1.0	0.9	0.4	1.1	1.2	1.7	1.6	1.6	1.2	
77/ 5/20	OUT	0.3	0.7	1.0	0.0	0.0	0.0	0.0	1.0	1.3	1.0	1.5	1.7	1.3	1.3	1.0	0.3	0.5	2.0	0.7	1.3	3.7	6.3	6.0	5.0	
77/ 5/20	IN	1.1	2.3	2.0	1.4	1.2	1.0	1.0	1.3	2.0	2.2	3.2	3.1	3.7	4.0	3.3	2.8	1.9	4.0	2.7	2.9	3.7	6.1	7.4	7.0	
77/ 5/21	OUT	2.7	3.0	2.3	2.0	1.0	1.0	1.3	1.0	1.3	1.0	1.3	3.0	4.0	4.0	3.7	2.3	0.5	1.0	1.0	1.0	1.7	2.3	3.0	0.7	
77/ 5/21	IN	5.4	4.5	3.9	3.6	3.2	2.3	2.3	2.3	2.6	2.2	2.9	4.9	5.3	5.8	4.3	2.7	1.5	1.1	1.0	1.0	2.1	3.1	3.3	2.6	
77/ 5/22	OUT	0.7	0.3	0.7	1.3	1.0	0.0	0.3	0.0	0.7	0.3	1.0	0.3	0.7	0.3	1.0	0.7	0.0	0.0	0.0	0.0	1.3	3.5	4.3	3.3	
77/ 5/22	IN	1.6	1.2	1.9	1.7	1.4	1.1	0.4	1.3	1.6	2.6	2.5	1.3	1.0	1.1	1.0	1.0	1.7	1.6	1.8	1.4	2.2	3.8	4.9	4.8	
77/ 5/23	OUT	3.0	2.7	2.3	2.0	2.0	2.0	3.3	3.3	3.7	1.3	1.7	1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	
77/ 5/23	IN	4.3	3.7	3.4	2.7	2.2	2.3	2.6	3.0	4.0	3.9	3.1	2.9	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	

* The designation (-1.0) indicates missing data.

TABLE 6. POLLUTANT CONCENTRATION SUMMARIES FOR 3-h, 8-h, ACTIVITY PERIOD, AND 24-h AVERAGES

SITE#: 9
VISIT#: 1
POLLUTANT: CO
POLLUTANT UNITS: PPM

		3-HOUR AVERAGES								8-HOUR AVERAGES			ACTIVITY AVERAGES			24-HOUR AVERAGE
DATE	LOC	0-2	3-5	6-8	9-11	12-14	15-17	18-20	21-23	0-7	8-15	16-23	0-6	7-19	20-23	
77/ 5/ 9	OUT	-1.0	-1.0	-1.0	0.5	1.0	1.1	1.4	0.1	-1.0	0.8	0.8	-1.0	1.0	0.1	0.8
77/ 5/ 9	IN	-1.0	-1.0	-1.0	2.8	3.0	3.1	2.8	1.4	-1.0	2.9	2.3	-1.0	2.9	1.4	2.6
77/ 5/10	OUT	0.0	0.1	0.3	0.1	0.0	0.4	0.0	0.1	0.0	0.2	0.1	0.0	0.2	0.1	0.1
77/ 5/10	IN	1.3	1.2	1.8	1.7	1.1	1.7	1.8	1.9	1.3	1.5	1.8	1.3	1.6	2.0	1.5
77/ 5/11	OUT	0.0	0.1	2.1	0.1	0.0	0.4	0.7	2.1	1.0	0.3	1.2	0.7	0.6	1.8	0.8
77/ 5/11	IN	2.2	1.3	3.4	3.0	2.2	3.0	2.0	2.3	2.0	2.8	2.3	1.8	2.8	2.1	2.4
77/ 5/12	OUT	1.1	0.3	2.6	1.1	0.0	0.0	0.0	0.0	1.1	0.8	0.0	0.8	0.7	0.0	0.6
77/ 5/12	IN	2.5	1.4	3.2	3.4	1.3	0.9	0.4	0.4	2.1	2.4	0.5	2.0	2.0	0.3	1.7
77/ 5/13	OUT	0.0	0.0	0.0	0.4	0.8	0.2	0.9	0.4	0.0	0.5	0.6	0.0	0.4	0.8	0.3
77/ 5/13	IN	1.0	1.6	1.7	2.7	2.4	2.0	2.0	1.6	1.3	2.3	1.8	1.4	2.2	1.7	1.8
77/ 5/14	OUT	0.4	1.0	1.0	0.8	0.0	0.0	0.0	0.9	0.8	0.3	0.3	0.8	0.3	0.7	0.5
77/ 5/14	IN	1.7	2.0	1.6	1.5	1.5	2.2	1.3	1.7	1.8	1.8	1.7	1.8	1.7	1.6	1.7
77/ 5/15	OUT	1.4	0.0	0.6	1.3	1.7	0.8	2.2	0.8	0.5	1.5	1.3	0.6	1.3	1.2	1.1
77/ 5/15	IN	2.1	1.3	0.7	2.6	2.9	1.5	2.9	1.9	1.4	2.4	2.1	1.6	2.2	2.2	2.0
77/ 5/16	OUT	0.0	0.0	1.7	2.6	0.0	0.0	0.3	2.0	0.3	1.2	0.8	0.2	0.9	1.7	0.8
77/ 5/16	IN	1.7	0.8	2.1	4.6	2.0	2.3	2.1	2.7	1.4	3.0	2.4	1.3	2.8	2.4	2.3
77/ 5/17	OUT	1.0	0.1	1.4	1.2	0.6	0.0	0.8	4.7	0.7	0.9	2.0	0.6	0.7	4.0	1.2
77/ 5/17	IN	2.2	1.1	1.9	5.0	3.0	1.8	1.0	3.9	1.6	3.6	2.3	1.6	2.8	3.3	2.5
77/ 5/18	OUT	3.2	2.2	3.6	1.5	0.2	0.7	0.0	0.0	2.9	1.1	0.3	2.8	1.1	0.0	1.4
77/ 5/18	IN	4.2	3.2	3.6	3.0	1.4	1.9	1.6	2.2	3.6	2.3	1.9	3.6	2.3	2.1	2.6
77/ 5/19	OUT	0.2	0.0	0.4	0.2	1.0	0.6	0.6	1.2	0.2	0.6	0.7	0.1	0.6	1.2	0.5
77/ 5/19	IN	1.9	1.3	1.7	1.6	2.6	0.8	1.3	1.4	1.5	2.0	1.2	1.5	1.6	1.5	1.6
77/ 5/20	OUT	0.7	0.0	0.8	1.4	1.2	0.7	1.9	5.8	0.4	1.2	3.4	0.3	1.1	5.3	1.6
77/ 5/20	IN	1.8	1.2	1.4	2.8	3.7	2.6	3.1	6.9	1.4	3.0	4.6	1.4	2.8	6.1	3.0
77/ 5/21	OUT	2.7	1.3	1.2	1.8	3.9	1.4	1.2	2.0	1.8	2.6	1.4	1.9	2.0	1.9	1.9
77/ 5/21	IN	4.6	3.0	2.4	3.3	5.1	1.8	1.4	3.0	3.5	3.8	2.0	3.6	2.9	2.8	3.1
77/ 5/22	OUT	0.6	0.8	0.3	0.6	0.7	0.2	0.4	3.7	0.5	0.6	1.5	0.6	0.4	3.1	0.9
77/ 5/22	IN	1.6	1.4	1.1	2.1	1.0	1.4	1.8	4.5	1.3	1.5	2.8	1.3	1.5	3.9	1.9
77/ 5/23	OUT	2.7	2.0	3.4	1.3	-1.0	-1.0	-1.0	-1.0	2.6	1.9	-1.0	2.5	2.2	-1.0	2.4
77/ 5/23	IN	3.8	2.4	3.2	3.3	-1.0	-1.0	-1.0	-1.0	3.0	3.5	-1.0	3.0	3.4	-1.0	3.2

* The designation (-1.0) indicates missing data.

TABLE 7. MAXIMA AND MINIMA FOR 1-h, 3-h, 8-h, AND DAILY AVERAGE POLLUTANT CONCENTRATIONS

SITE#: 1
VISIT#: 1
POLLUTANT: CO
POLLUTANT UNITS: PPM

DATE MM/DD/YY	ZONE	1-HOUR AVERAGES MIN	1-HOUR AVERAGES MAX	3-HOUR AVERAGES MIN	3-HOUR AVERAGES MAX	8-HOUR AVERAGES MIN	8-HOUR AVERAGES MAX	DAILY AVERAGES MIN	DAILY AVERAGES MAX
7/12/76	AMBIENT	0.00	2.33	0.11	1.89	0.75	1.21	1.00	1.00
7/12/76	KITCHEN	0.00	3.00	0.11	2.33	0.37	1.61	1.11	1.11
7/12/76	BEDROOM	0.00	2.33	0.11	2.11	0.46	1.48	1.10	1.10
7/12/76	LIVINGROOM	0.00	2.33	0.00	2.11	0.37	1.50	1.06	1.06
7/12/76	INDOOR AVERAGE	0.00	2.44	0.07	2.19	0.40	1.53	1.09	1.09
7/13/76	AMBIENT	0.00	4.67	0.00	4.44	0.00	3.75	1.85	1.85
7/13/76	KITCHEN	0.00	5.33	0.00	5.00	0.00	4.37	2.15	2.15
7/13/76	BEDROOM	0.00	5.00	0.00	4.67	0.00	4.04	2.06	2.06
7/13/76	LIVINGROOM	0.00	5.00	0.00	4.78	0.00	4.17	2.08	2.08
7/13/76	INDOOR AVERAGE	0.00	5.11	0.00	4.81	0.00	4.19	2.10	2.10
7/14/76	AMBIENT	0.00	4.33	0.33	3.89	0.83	3.42	2.03	2.03
7/14/76	KITCHEN	1.00	4.67	1.44	4.22	1.50	4.17	2.63	2.63
7/14/76	BEDROOM	0.33	5.33	1.22	4.44	1.54	4.21	2.61	2.61
7/14/76	LIVINGROOM	0.33	5.67	1.11	4.89	1.42	4.46	2.57	2.57
7/14/76	INDOOR AVERAGE	0.56	5.22	1.30	4.52	1.49	4.28	2.60	2.60
7/15/76	AMBIENT	0.00	7.33	0.44	5.89	1.00	5.08	2.66	2.66
7/15/76	KITCHEN	1.33	4.00	1.44	3.67	1.92	2.88	2.44	2.44
7/15/76	BEDROOM	1.00	4.33	1.22	3.89	1.91	2.79	2.46	2.46
7/15/76	LIVINGROOM	1.00	4.67	1.33	4.00	1.96	2.71	2.45	2.45
7/15/76	INDOOR AVERAGE	1.11	4.22	1.33	3.85	1.93	2.79	2.45	2.45
7/16/76	AMBIENT	0.00	3.00	0.44	2.56	1.09	1.38	1.21	1.21
7/16/76	KITCHEN	0.33	3.67	0.89	3.22	1.33	2.58	1.99	1.99
7/16/76	BEDROOM	0.33	3.67	0.78	3.44	1.25	2.54	1.99	1.99
7/16/76	LIVINGROOM	0.67	4.00	0.89	3.67	1.38	2.63	2.07	2.07
7/16/76	INDOOR AVERAGE	0.44	3.56	0.85	3.44	1.32	2.58	2.01	2.01
7/17/76	AMBIENT	0.00	5.00	0.00	3.67	0.17	2.79	1.46	1.46
7/17/76	KITCHEN	0.00	5.00	0.00	4.11	0.21	3.38	2.07	2.07
7/17/76	BEDROOM	0.00	5.33	0.00	4.44	0.46	3.42	2.15	2.15
7/17/76	LIVINGROOM	0.00	5.00	0.00	4.33	0.50	3.33	2.17	2.17
7/17/76	INDOOR AVERAGE	0.00	5.11	0.00	4.30	0.39	3.38	2.13	2.13
7/18/76	AMBIENT	1.00	4.00	1.11	3.56	1.22	2.67	2.05	2.05
7/18/76	KITCHEN	2.00	3.67	2.44	3.11	2.79	3.00	2.88	2.88
7/18/76	BEDROOM	1.67	3.67	2.44	3.00	2.75	2.94	2.83	2.83
7/18/76	LIVINGROOM	2.00	3.33	2.44	3.17	2.63	3.06	2.81	2.81
7/18/76	INDOOR AVERAGE	2.00	3.44	2.44	3.05	2.72	3.00	2.84	2.84
OVERALL	AMBIENT	0.00	7.33	0.00	5.89	0.00	5.08	0.44	3.84
OVERALL	KITCHEN	0.00	5.33	0.00	5.00	0.00	4.37	0.48	2.88
OVERALL	BEDROOM	0.00	5.67	0.00	4.67	0.00	4.21	0.48	3.97
OVERALL	LIVINGROOM	0.00	5.67	0.00	4.89	0.00	4.46	0.49	3.89
OVERALL	INDOOR AVERAGE	0.00	5.22	0.00	4.81	0.00	4.28	0.49	3.93

TABLE 8. PERCENTAGE FREQUENCY DISTRIBUTION

SITE NUMBER: 1
VISIT NUMBER: 1
POLLUTANT: CO
UNITS: PPM
ZONE: OUTDOOR
NUMBER OF HOURS: 385

INTERVAL			PERCENTAGE
	<	0.00	0.0
[	0.00,	0.73)	43.4
[	0.73,	1.47)	17.9
[	1.47,	2.20)	13.2
[	2.20,	2.93)	5.2
[	2.93,	3.66)	10.1
[	3.66,	4.40)	7.8
[	4.40,	5.13)	1.0
[	5.13,	5.86)	0.5
[	5.86,	6.60)	0.5
[	6.60,	7.33)	0.0
> OR =		7.33	0.3

NOTES:
1) [,) INDICATES THAT THE INTERVAL IS CLOSED ON THE LEFT AND OPEN ON THE RIGHT.
2) -1. INDICATES A MISSING VALUE.

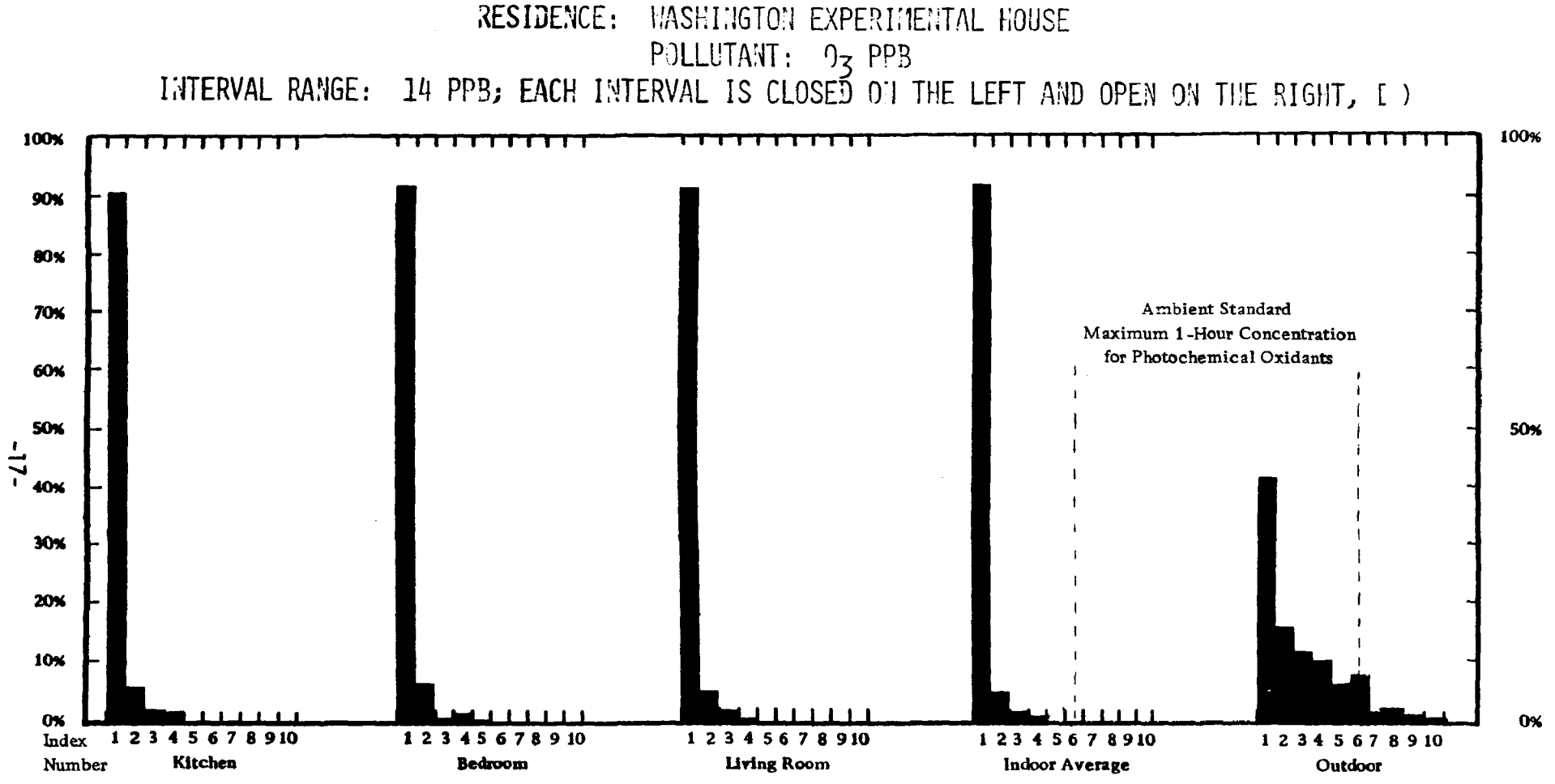


Figure 3. Percentage of hourly average O_3 concentrations.

sampled location. The vertical axis is the percentage of hourly averages that the pollutant concentrations are in the various intervals indicated by the index numbers on the horizontal axis. This particular example indicates that the observed ambient ozone concentrations in the Washington experimental house are above the 1-h NAAQS for 10% of the monitored hours (approximately 32 h). It also shows that the indoor ozone concentrations are extremely low, well within the NAAQS. Thus, this particular dwelling, with no apparent indoor ozone sources, provides a shelter from high ambient ozone concentrations.

A widespread assumption made by the public is that the indoor environment provides a shelter from high outdoor pollution levels. The ratio frequency distribution generated by calculating the ratio of hourly ambient pollutant concentrations over the corresponding indoor average concentration investigates the validity of this general assumption. Interval values from 0.0 to 5.0 in steps of 0.25 are considered for the ratio values; the percentage of the hours for which the ratio falls in any given interval is tabulated for each pollutant (see Table 9).

Detailed analysis of the data requires an examination of all observations; however, a summary of the sampled concentrations has been generated as an indication of the data collected by this project. Table 10 is an illustration of such a summary; it shows the observed total concentration range, and the observed ranges in 85% of the concentration values. It also shows whether or not there has been a violation of outdoor and indoor (if any) pollutant standards. In addition, it demonstrates the existing relationship between the outdoor and indoor values.

The tables described above are among the techniques used to interpret the data and identify typical patterns. In addition, occurrences of maximum concentrations are of interest. Table 11 identifies time periods with high pollutant levels.

Each of the techniques outlined above is applied to a given house-pollutant combination and has been utilized in the pollutant data interpretation. Additionally, factors such as interelement relationships, seasonal comparisons, family composition, and fuel used for cooking have been examined and will be discussed in the balance of this section.

Carbon Monoxide (CO)

Indoor CO concentrations are generally higher than corresponding outdoor levels in all residences monitored. High indoor concentrations may be attributed to two factors: 1) indoor CO emission sources, such as gas-fired cooking appliances, attached garages, faulty furnaces, and cigarette smoking; and 2) the residence time of CO levels is apparently longer in the indoor environment than the time required for ambient peaks to dissipate to lower levels.

TABLE 9. RATIO FREQUENCY DISTRIBUTION

SITE NUMBER: 17
VISIT NUMBER: 1
POLLUTANT: CO
UNITS: PPM
RATIO: AMBIENT /INDOOR AVERAGE
NUMBER OF HOURS: 370

INTERVAL		PERCENTAGE
<	0.00	0.0
[0.00,	0.25)	83.2
[0.25,	0.50)	8.4
[0.50,	0.75)	4.9
[0.75,	1.00)	1.6
[1.00,	1.25)	0.5
[1.25,	1.50)	0.8
[1.50,	1.75)	0.0
[1.75,	2.00)	0.0
[2.00,	2.25)	0.3
[2.25,	2.50)	0.0
[2.50,	2.75)	0.0
[2.75,	3.00)	0.0
[3.00,	3.25)	0.3
[3.25,	3.50)	0.0
[3.50,	3.75)	0.0
[3.75,	4.00)	0.0
[4.00,	4.25)	0.0
[4.25,	4.50)	0.0
[4.50,	4.75)	0.0
[4.75,	5.00)	0.0
> OR =	5.00	0.0

NOTES:
1) [,) INDICATES THAT THE INTERVAL IS CLOSED ON THE LEFT AND OPEN ON THE RIGHT.
2) -1. INDICATES A MISSING VALUE.

TABLE 10. POLLUTANT SUMMARY FOR CO_{ppm}

STANDARDS: NATIONAL AMBIENT 8h - 9 ppm
1h - 35ppm

ASHRAE: 8h - 26ppm

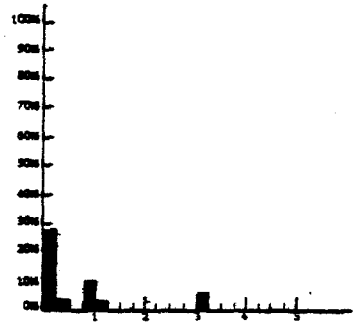
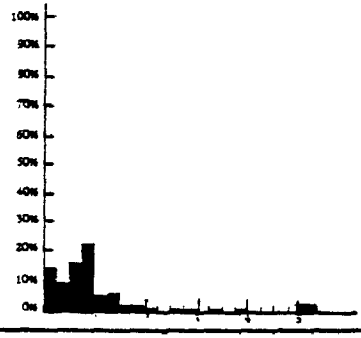
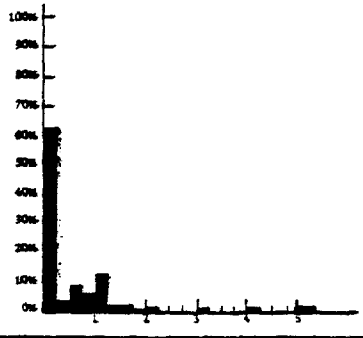
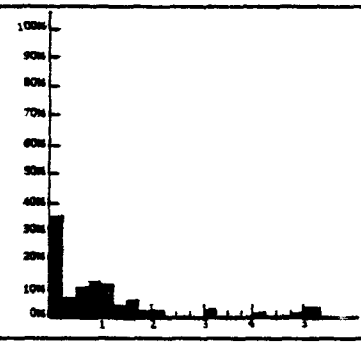
RESIDENCE	TIME PERIOD	RANGE OUTDOOR TOTAL	OUTDOOR 85%	INDOOR AVG TOTAL	INDOOR AVG 85%	KITCHEN TOTAL	KITCHEN 85%	BEDROOM TOTAL	BEDROOM 85%	LIVING ROOM TOTAL	LIVING ROOM 85%	FREQUENCY DISTRIBUTION OF AMBIENT/INDOOR VALUES
BALTIMORE EXPERIMENTAL I.	1 HOUR	0.-2.0	0.2	0.-2.0	0.2	0.-2.0	0.2	0.-2.0	0.2	0.-2.0	0.2	
	3 HOURS	0.-1.7		0.-1.8		0.-1.6		0.-1.9		0.-1.9		
	8 HOURS	0.-.71		0.-.75		0.-.71		0.-.83		0.-.75		
	24 HOURS	0.-.48		0.-.60		0.-.54		0.-.68		0.-.58		
WASHINGTON CONVENTIONAL I.	1 HOUR	0.-7.3	3.5	0.-5.2	3.5	0.-5.3	3.5	0.-5.7	3.5	0.-5.7	3.5	
	3 HOURS	0.-5.9		0.-4.8		0.-5.0		0.-4.7		0.-4.9		
	8 HOURS	0.-5.0		0.-4.3		0.-4.3		0.-4.2		0.-4.5		
	24 HOURS	.4-3.8		.5-3.9		.5-2.9		.5-4.0		.5-3.9		
BALTIMORE CONVENTIONAL I.	1 HOUR	0.-2.3	0.9	0.-4.6	1.4	0.-6.0	1.4	0.-4.0	1.4	0.-5.7	1.4	
	3 HOURS	0.-1.9		0.-3.5		0.-3.6		0.-2.8		0.-4.0		
	8 HOURS	0.-1.3		0.-3.0		0.-3.2		0.-2.5		0.-3.4		
	24 HOURS	.01-1.3		.16-2.3		.21-2.4		.11-2.0		.14-2.4		
WASHINGTON EXPERIMENTAL I.	1 HOUR	0.-4.0	1.6	0.-4.2	2.0	0.-4.3	2.0	0.-5.7	2.0	0.-4.0	2.0	
	3 HOURS	0.-3.6		0.-3.8		0.-3.7		0.-4.2		0.-3.6		
	8 HOURS	0.-2.7		0.-3.0		0.-2.8		0.-3.5		0.-2.8		
	24 HOURS	.07-1.6		.27-2.5		.27-2.5		.30-2.4		.24-2.6		

TABLE 11. IDENTIFICATION OF TIME INTERVALS WITH MAXIMUM POLLUTANT CONCENTRATIONS

POLLUTANT CO2 --PPM Baltimore-Conventional House

MONITORING PERIOD SUMMARY (*--FREQ)

Zone		MAX 1-HR AV.	TIME OF MAX 1-HR AV. DAY	TIME OF MAX 1-HR AV. HR	MAX 3-HR AV.	TIME OF MAX 3-HR AV. DAY	TIME OF MAX 3-HR AV. PERIOD	MAX 8-HR AV.	TIME OF MAX 8-HR AV. DAY	TIME OF MAX 8-HR AV. PERIOD	MAX 24-HR AV.	DAY OF MAX 24-HR AV.
Outdoor	1	751.3	82976	16	461.8	82976	6	395.5	82976	1	376.4	82976
Kitchen	2	1605.3	82976	16	1308.0	82976	5	1178.2	82976	2	882.1	82976
Living Room	3	1294.0	82976	16	1173.6	82976	6	963.8	82976	2	832.2	82976
Bedroom	4	1664.0	82976	15	1340.6	82976	5	1149.9	82976	2	862.6	82976
Indoor Average	5	1463.6	82976	15	1236.5	82976	5	1097.3	82976	2	859.0	82976

Indoor concentration peaks of CO tend to lag behind outdoor CO peaks. Due to the CO emissions, this behavior may be shortened in houses with indoor sources. The observed large fluctuations of the hourly CO concentrations display a local structure without a general pattern. However, examination of the CO data base from several weekdays leads to identification of a typical pattern with respect to 3-h averages. Typically, the time periods 0800-1000 and 1900-2100 exhibit the highest observed CO levels. These 3-h indoor peaks correspond to outdoor peaks caused by automobile traffic during the typical urban rush hours (0600-0800 and 1700-1900). The association of rush-hour traffic and typical indoor high level periods reflect the time lag monitored earlier. Figure 4 illustrates the indoor and outdoor variation of CO concentrations for a typical day, in a dwelling with indoor CO sources. The indoor peak at hours 1400 to 1600 is not a typically observed elevation of the indoor concentrations.

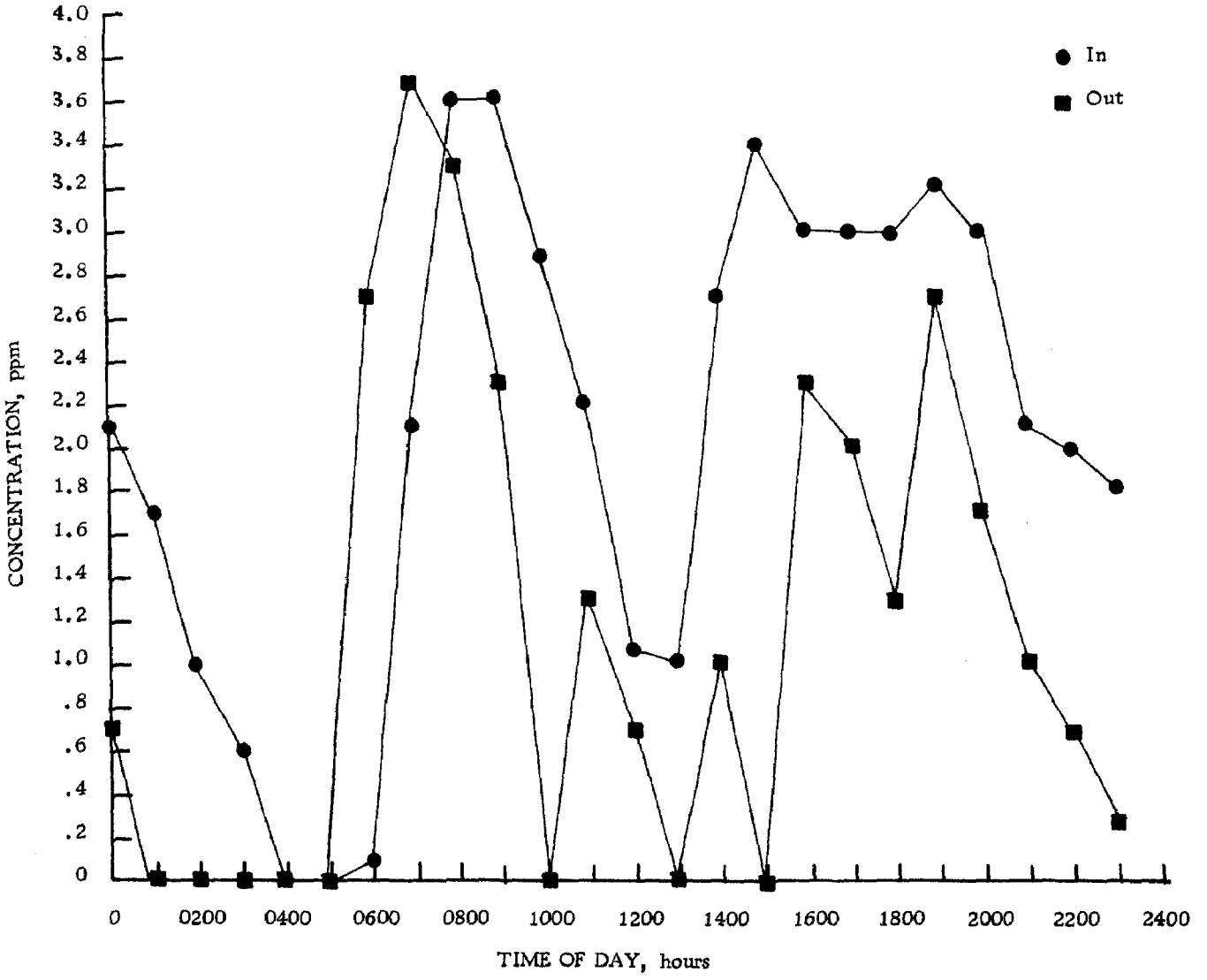


Figure 4. Indoor and outdoor carbon monoxide (CO) variation at the Baltimore conventional residence.

Seasonal variations in outdoor CO concentrations have not been identified. A seasonal effect, however, has emerged from the investigation of indoor CO levels. The data base obtained from six dwellings, monitored once during the summer and a second time during the winter, show that CO indoor concentrations are generally higher in the winter than in the summer. The observed higher winter CO levels may be attributed to many factors such as tighter houses, regularly operating gas furnaces, and increased indoor social activities.

Increases in outdoor CO concentrations do not lead to proportional increases in the indoor CO concentrations. However, long-term averages of CO in dwellings with no indoor CO sources are equivalent to the corresponding outdoor averages. This trend has been observed in the electric houses with nonsmoking occupants which were sampled during the course of this project. In houses of this type the indoor environment does not shelter its occupants from high CO levels since the exposure to CO concentrations is equivalent to the corresponding indoor and outdoor exposure. In houses with indoor CO sources, the observed indoor long-term averages are higher than the ambient CO concentrations, leading to higher indoor than outdoor exposures to CO levels and to increasing possibilities of adverse health effects.

Observed measurements of CO concentrations both indoors and outdoors are generally not considered high enough to cause a health hazard. The highest hourly outdoor level observed during this program was 15.7 ppm; whereas the maximum hourly indoor level observed was 22.0 ppm. The majority of the observed hourly indoor CO concentrations are between 2.3 and 6.0 ppm, while observed hourly ambient concentrations fall between 1.0 and 2.5 ppm. The hourly NAAQS of 35 ppm has not been violated by either indoor or outdoor observed levels. The 8-h NAAQS is 9 ppm. This standard has not been exceeded by the observed indoor or outdoor data; however, 8-h average CO concentrations of 9.0 ppm have been sampled in a few cases in both the outdoor and indoor environments. Finally, it must be emphasized that observed indoor values are generally higher than observed outdoor values, and that the ratio of corresponding ambient to indoor values is less than one for at least 80% of the total hours monitored.

Nitric Oxide (NO)

The complexity of the dynamics involved in the establishment of an indoor-outdoor relationship is clearly illustrated in the interpretation of the data base generated for NO. From the perspective of NO indoor variation and under real-life conditions, three types of indoor environments have emerged: 1) houses with electric cooking and heating appliances; 2) houses that are heated by gas furnaces, yet serviced by electric cooking appliances; and 3) houses that are furnished with gas cooking and heating equipment. In houses equipped with gas cooking appliances, observed indoor NO levels are consistently higher than observed outdoor levels. Houses with gas furnaces but electric cooking appliances

display higher NO indoor levels than outdoor levels, most of the time. However, there are time intervals interspersed throughout the monitoring period during which the observed NO outdoor levels surpass corresponding indoor levels. Indoor NO concentrations in totally electric homes are almost always lower than corresponding outdoor concentrations.

Variation of the indoor concentrations of NO_x is associated with emissions from gas stoves. Houses with a regular cooking routine and gas cooking appliances show a strong association between indoor peaks of NO levels and cooking periods; on the other hand such association cannot be made in houses with electric appliances. The observed indoor NO concentrations from totally gas houses are generally higher than the observed indoor NO concentrations in other types of houses; this may be attributed to emissions from gas appliances and possibly faulty gas furnaces. A seasonal impact on the NO indoor levels has been clearly identified only for totally gas houses. During the winter months the residential NO concentrations are higher than the NO levels during the summer months. This seasonal effect may be attributed to the same factors given earlier for a similar behavior observed for the indoor CO concentrations.

The typical range of the observed hourly indoor NO concentrations is 0-300 ppb; the maximum observed indoor hourly NO concentration is 470 ppb. The corresponding levels for the outdoor environment are 1-150 ppb and 300 ppb, respectively. NAAQS for NO do not exist; an 8-h average residential NO standard of 2.5 ppm has been recommended by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE). This indoor standard is not exceeded by the observed NO concentrations. The maximum 8-h average registered by the field program is 285 ppb, well below this standard. Generally, the observed indoor hourly NO concentrations are higher than the corresponding ambient concentrations. The ratio of outdoor to indoor values is less than one for about 50% of the total monitored hours in fully electric houses; the same ratio is less than one for at least 85% of the monitored hours in residences with gas appliances and/or gas furnaces.

Nitrogen Dioxide (NO_2)

The residential environment often provides a shelter from high outdoor NO_2 levels. The three classes of residences identified in the interpretation of the NO data also manifest themselves in the study of NO_2. The data base collected for this project indicates that the hourly average indoor concentrations of NO_2 are almost always lower than the corresponding ambient levels in totally electric houses. Houses equipped with gas furnaces and electric cooking appliances also shelter their occupants, but to a lesser extent during peak ambient NO_2 levels. Totally gas residences do not appear to provide such protection.

In the indoor environment the NO_2 half-life is estimated to be approximately 30 min; this is a relatively short half-life when compared with 2.0 h, the half-life estimated for CO which is considered inert. Thus, the observed low indoor levels of NO_2 may be attributed to the chemical reactivity of this pollutant.

Two major elements seem to determine the indoor NO_2 levels: 1) the variation of outdoor concentrations, and 2) the strength of the indoor sources. A typical pattern of the fluctuations in the ambient NO_2 concentrations has been identified: a broad maximum appears daily between the hours of 0700 and 1000. Due to the high indoor emission rates, only the total gas residences register higher indoor NO_2 levels than the corresponding outdoor levels during these ambient peak periods.

The NAAQS for NO_2 is an annual arithmetic mean of 50 ppb. Typical observed indoor levels fluctuate between 20 and 60 ppb. If the observed indoor concentrations were to maintain the same trend throughout the year, it is likely that the NAAQS would not be exceeded. The highest indoor hourly average NO_2 concentration observed is 180 ppb, which does not exceed an hourly NAAQS currently under consideration. However, 70% of the hourly values obtained from the indoor environment of all gas houses are higher than the corresponding outdoor values.

Sulfur Dioxide (SO_2)

SO_2 concentrations sampled in the residential environment are very low. One or more of the following factors may be contributing to this:

- The observed ambient SO_2 levels, although higher than the corresponding indoor concentrations, are low.
- SO_2 is relatively reactive, and it is absorbed by indoor surfaces.
- The high CO_2 concentrations found in the indoor environment interfere negatively with SO_2 in the monitoring instrument used.

The observed quenching effect of SO_2 by CO_2 in the field instrument is discussed in Section 3. The levels registered indoors are often below or are very close to the detection limits of the instrument; it is therefore impractical to use the correction factor that has been formulated in order to adjust for the experimental errors. Indoor SO_2 concentrations remain lower than corresponding outdoor levels even after the correction factor is applied. Thus, it is concluded that the indoor environment provides a shelter from high outdoor SO_2 levels; this statement, however, must be constrained by the facts that the majority of both ambient and indoor levels was low and that the quenching of SO_2 concentrations was due to instrumentation difficulties. No indoor or outdoor violations of the NAAQS SO_2 standards (24 h: 0.14 ppm; 3-h: 0.5 ppm) have been observed. This can be attributed to the observed low ambient SO_2 levels.

Carbon Dioxide (CO_2)

Observed hourly indoor concentrations of CO_2 are constantly higher than corresponding levels in the ambient environment. The ambient/indoor ratio is less than one for at least 90% of the total monitored hours. The hourly indoor CO_2 concentrations vary between 150 and 2200 ppm; the observed typical range for the ambient CO_2 levels is between 100 and 500 ppm. The ASHRAE-recommended indoor 8-h standard of 500 ppm is violated frequently, often by a factor of three.

Since CO_2 concentrations indoors are a function of the number of inhabitants, the activity period with high indoor levels should correspond to high activity patterns of the residents. Thus, houses with inhabitants who work all day away from the residence should have low readings between the hours of 0900 and 1800, whereas houses that are normally occupied during this time period should display higher levels. Such behavior has been observed. For the same reasons, the activity period with the highest observed indoor CO_2 concentrations is the time interval between 1800 and 2300 hours during which all members of a family are typically indoors.

Ozone (O_3)

Indoor O_3 concentrations are lower than outdoor levels; the ratio value of corresponding hourly ambient over indoor concentrations is greater than one for 95% of the monitored hours. O_3 is the surrogate pollutant for photochemical smog. Ambient O_3 levels are primarily of automotive origin, but other sources include the combustion of fuels for heat and electric power, the burning of refuse, the evaporation of petroleum products, and the handling and use of organic solvents. O_3 is highly reactive and decays rapidly by absorption on indoor surfaces.

The half-life of O_3 is variable because it depends on the surface-to-volume ratio and the material of the furnishings. A 2-min half-life for O_3 has been estimated from the existing data base. This value indicates that O_3 is the most reactive pollutant found in the indoor environment. Owing to its high reactivity, indoor O_3 levels are normally found at levels 50-70% of the corresponding outdoor concentrations.

Ambient hourly O_3 concentrations have been observed at levels higher than the NAAQS of 0.08 ppm. O_3 is not generated indoors in great quantities; however, a few indoor violations of the O_3 hourly NAAQS have been observed. The present data base does not conclusively identify any indoor O_3 sources; however, Hollowell et al. (1976) have attributed small increases in O_3 concentrations to the use of electric stoves. Although electrostatic air precipitators have been identified as possible ozone sources, none of the houses monitored in this program was equipped with such a device. A general ambient daily pattern has been identified: an early morning peak is followed by a second one in the afternoon. Due to the low indoor O_3 levels, there are no identifiable patterns in the residential environment.

Total Nonmethane Hydrocarbons (NMHC)

The ratio of ambient NMHC concentrations over corresponding indoor concentrations is less than one for about 90% of the total monitored hours; that is, the NMHC concentrations observed in the residential environment are almost always higher than the ambient levels. Typical indoor levels vary between 0 and 8.0 ppm while typical ambient concentrations register a range between 0 and 3.5 ppm. The 3-h NAAQS for NMHC (0600-0900) is 0.24 ppm and is often violated in the residential environment. ASHRAE suggests that an indoor residential 8-h standard be 0.10 ppm; this recommended standard is exceeded indoors with the same high frequency that the NAAQS 3-h standard is violated.

Fluctuations in the NMHC indoor concentrations may be associated with cooking, cleaning, and other activities. A general pattern of variation has not been identified; however, the 2-h periods between hours 1200-1400 and 1900-2100 display consistently higher levels in all monitored dwellings. These periods may be associated with cooking and general indoor activity by the occupants.

Total Suspended Particulate (TSP) Matter

In the residential environment TSP is collected on 47-mm glass fiber filter material for a period of 24 h at a sampling rate of 3-4 ft^3/min. In the outdoor environment TSP is collected simultaneously by two different methods: on 47-mm glass fiber filter material as in the indoor environment, and on an 8 x 10 in. glass fiber filter using a conventional high volume air sampler. The outdoor high volume TSP measurements are for comparison with the daily 47-mm (low volume) samplers. Examination of the corresponding daily TSP value from the low and high volume samplers shows that they correlate well with the average correlation coefficient for all residences being 0.86. The ratio of corresponding low volume over high volume daily TSP concentrations varies in the neighborhood of 0.85, with extreme ratio values of 0.68 and 0.96. The data base obtained from the low volume air sampler is used in subsequent data interpretation.

The steady-state TSP model, developed on the data base generated by the project and discussed in detail in Section 3 on Numerical Models, will show the importance of the family activity as an indoor source of TSP matter. Moreover, the data base illustrates that there are no constant ratio values that relate the observed outdoor levels to indoor concentrations. The ratio of observed daily indoor TSP concentrations over corresponding outdoor TSP concentrations varies from 0.3 to 3.6.

The TSP 24-h maximum NAAQS is 260 $\mu g/m^3$. This value must not be exceeded more than once a year. The typical range of observed indoor residential TSP concentrations is between 30 and 100 $\mu g/m^3$, with

a maximum observed level of 500 $\mu g/m^3$. A number of residences, each monitored for a 14-d period, show indoor TSP concentrations that exceed the NAAQS. In addition, the indoor-outdoor data base shows that the NAAQS for particulate matter is exceeded in the indoor residential environment when the corresponding ambient levels are below the standard.

The effect of indoor TSP sources needs further investigation; it is apparent that residential control measures are required in order to protect the indoor environment from levels that are considered hazardous to the public health in the ambient environment. Further examination of the TSP indoor-outdoor relationships appears in Section 3 of this document, while the TSP control measures are discussed in Section 5.

Respirable Suspended Particulate (RSP) Matter

Two samples of RSP matter are obtained daily. One sample is from an indoor location, often the living room, and the other from an outdoor location. The two corresponding RSP concentrations are 24-h average samples collected with the Environmental Research Corporation (ERC) Model #200 Dichotomous Sampler. Particulates with a diameter of 3.5 μm or less are classified as RSP matter.

An effort to formulate a physical model relating the indoor RSP matter concentrations to outdoor levels and to indoor sources was not successful. The available data do not display correlations among the various parameters; the correlation coefficient between indoor and outdoor levels is small, there is no association between the activity index and the indoor RSP levels, and the impact of varying air exchange rates on the indoor RSP concentrations is not significant. Figure 5 shows typical RSP indoor-outdoor levels and illustrates the lack of relationships. Many difficulties are involved in the development of a theoretical relationship between indoor and outdoor RSP concentrations: the deposition rate of respirable suspended particulates is very low and very difficult to quantify, the efficiency of residential filtering devices to remove RSP has not been well established, and the generation rate of RSP by indoor activities is not known. Finally, the data set on RSP indicates that while high activity may lead to high indoor RSP levels, low activity does not necessarily imply low indoor RSP concentrations.

Ambient respirable suspended particulate matter concentrations varied between 1 and 91 $\mu g/m^3$. In the indoor location the concentrations ranged from 1 $\mu g/m^3$ to 260 $\mu g/m^3$. Table 12 summarizes the RSP data obtained from a majority of the residences monitored in the indoor-outdoor project. Each residence is monitored for approximately 2 weeks. The ratio of the arithmetic mean of a 2-week period of indoor daily levels over the corresponding arithmetic mean of outdoor levels separates the residences into two

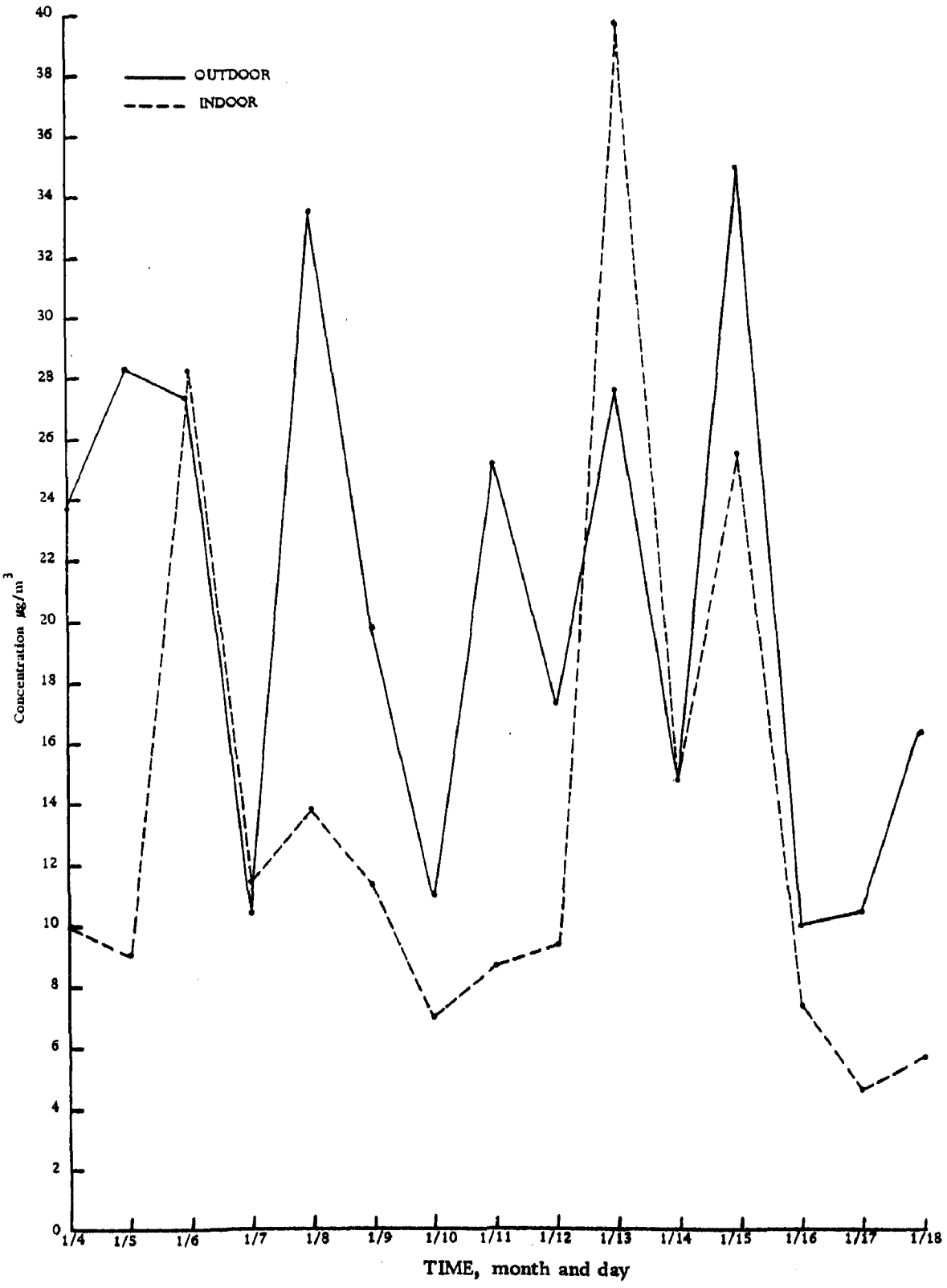


Figure 5. Typical RSP indoor-outdoor levels.

well-defined groups. One group of residences displays higher indoor levels than outdoor, and the second group includes residences with indoor RSP levels lower than outdoor concentrations. The demarcation line is very clear; the $[RSP]_{in}/[RSP]_{out}$ ratio varies from 2.0 to 3.5 for the group with higher indoor levels, and from 0.4 to 1.0 for the residences with lower indoor RSP levels. The houses in each group have two factors in common, and these may be the cause of the observed difference in the ratios. All families in the group with higher indoor RSP levels have children who are of preschool age or in the first or second grades; none of the families who are in the second group have young children. This activity association indicates that young children may keep the matter airborne, while houses without children are likely to have long periods of low activity, thus allowing RSP matter to settle. The smoking-no smoking factor clearly influences the indoor RSP matter levels. All but one of the families in the first group smoke more than 10 cigarettes a day on a regular basis. The families in the second group include no heavy smokers: four families have no smoking members, and the remaining three families have members who smoke less than 10 cigarettes a day, often less than four.

TABLE 12. RESPIRABLE SUSPENDED PARTICULATE (RSP) MATTER INDOOR-OUTDOOR DATA SUMMARY

Residence Identification	Statistics - Values $\mu g/m^3$							Children 7 Years Old or Less	Smoking
	Range		Out		In		In/ Out		
	Out	In	$[\bar{RSP}]$	s. d.	$[\bar{RSP}]$	s. d.			
Baltimore Conventional I	9-54	5-84	23	12	47	17	2.0	Yes	Yes
Denver Conventional	1-40	30-94	23	10	64	20	2.8	Yes	Yes
Pittsburgh Low Rise 1	7-34	26-260	18	9	50	65	2.8	Yes	No
Pittsburgh Low Rise 2	8-34	27-83	18	9	50	17	2.8	Yes	Yes
Pittsburgh Mobile Home 2	16-42	35-210	23	7	82	44	3.5	Yes	Yes
Baltimore Conventional II	7-54	10-86	10	14	46	25	2.5	Yes	Yes
Chicago Experimental I	11-34	6-14	22	6	10	2	0.5	No	<10
Baltimore Experimental II	11-35	5-40	21	8	14	10	0.7	No	No
Pittsburgh Mobile Home 1	37-91	5-60	58	22	21	16	0.4	No	No
Chicago Experimental II	1-35	1-29	19	9	8	7	0.4	No	<10
Pittsburgh High Rise 1	18-62	12-41	36	16	23	9	0.6	No	No
Baltimore Experimental I	11-66	5-56	30	18	18	17	0.6	No	No
Pittsburgh High Rise 2	12-49	1-34	28	14	21	10	0.8	No	No
Pittsburgh High Rise 3	12-76	21-80	36	18	35	16	1.0	No	<10

The above analysis indicates that the combination of young children and regularly smoking adults constitutes an indoor source of RSP matter. Data from houses without young children and regularly smoking members do not display characteristics attributable to indoor RSP sources. This association can be used to estimate indoor RSP levels when the outdoor concentrations are available. Thus, if members of a house include regular smokers and have young children, one can assume that the ratio of indoor over outdoor RSP matter is approximately 2.5; if there are no regular smokers or young children, the ratio may be approximated to 0.8. The demarcation line, obtained from the present set of data, is very definitive; however, more data will be very useful in verifying the relationship outlined and validating the suggested predictive claims.

Few RSP concentrations measured in the indoor environment exceed the NAAQS 24-h maximum particulate matter standard. A few other indoor daily averages come close to the 24-h maximum particulate matter concentration but the corresponding outdoor levels are considerably lower. New studies are required to determine if the observed indoor RSP levels precipitate adverse health effects.

Water Soluble Nitrates (NO_3^-)

Particulate matter collected on the 47 mm glass fiber filter is analyzed by the filtration/brucine laboratory analytical method for water soluble nitrates. Daily concentrations are obtained from the outdoor location and the three indoor sampling sites. The indoor residential levels of nitrates are quite low, and they are mainly driven by the outdoor NO_3^- concentrations. Figure 6 illustrates a typical pattern of the observed nitrate levels. Ninety percent of the observed daily indoor nitrate averages are lower than the corresponding outdoor levels. For over 60% of the total days sampled (over 250 d), the ratio value of corresponding daily indoor NO_3^- levels over the ambient nitrate concentrations is less than 0.3.

The observed daily indoor concentrations of nitrates do not vary significantly and display a small range between 1.0 and 6.0 $\mu g/m^3$, with typical values at the lower end of this concentration interval. The maximum observed daily outdoor concentration is 16 $\mu g/m^3$, and typical values are in the neighborhood of 6.0 $\mu g/m^3$. There are no NAAQS for nitrates; therefore, it is not possible to determine whether the monitored residences register elevated levels of nitrate. It is apparent, however, that the residential environment shelters its occupants from the nitrate levels observed outdoors.

Water Soluble Sulfate - ($SO_4^=$)

Indoor and outdoor sulfate concentrations are obtained from the daily TSP samples. Filtration/methyl-thymol blue is the analytical laboratory

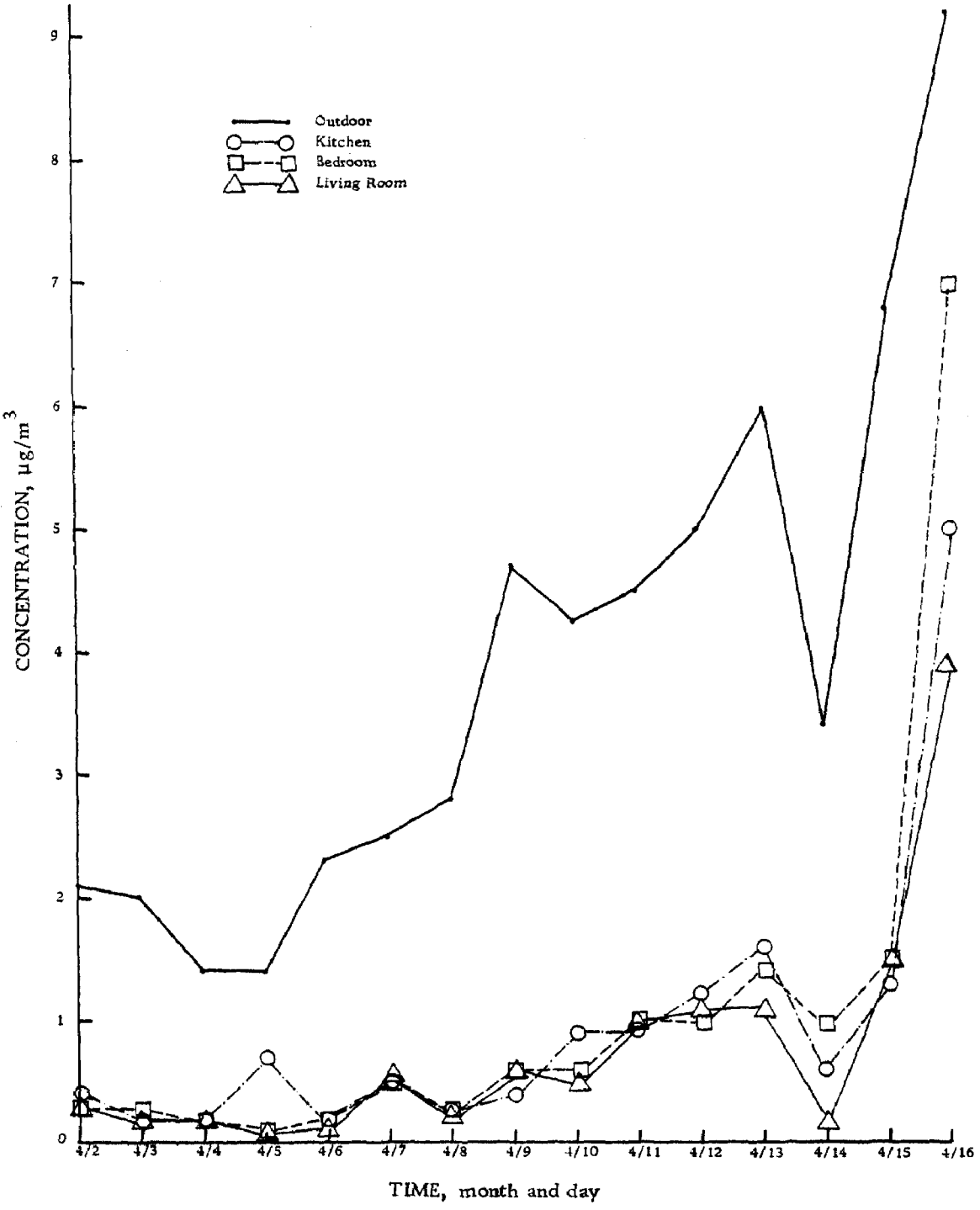


Figure 6. Typical patterns of observed nitrate levels.

method used. Ambient daily sulfate concentrations vary between 1.5 and 48.3 $\mu g/m^3$; the average indoor sulfate concentrations ranged between 1.0 and 41 $\mu g/m^3$. Table 13, the $SO_4^=$ data summary, illustrates the general trends of the collected sulfate data base. Both the indoor and outdoor concentrations vary considerably within each monitoring period. Variations in air exchange rates, indoor temperature, indoor humidity, occupant activity and combinations of these factors do not explain the observed sulfate fluctuations. The TSP removal and reentrainment processes, and the involved chemical conversion mechanisms of sulfur dioxide to sulfates are among the difficulties involved in the development of analytical expressions relating indoor and outdoor sulfate concentrations. It has been concluded that the formulation of a dynamic model for sulfates must await improvement of the state-of-the-art of various closely related scientific questions. The data base generated by the indoor-outdoor project substantially adds to the existing relevant literature on sulfate levels.

Statistical analyses indicate that daily sulfate concentrations are approximately equal in the three indoor sites. Figure 7 is a typical example of the variation of sulfate levels during a 2-week monitoring period; this graphic representation illustrates the similarity of the concentrations at the three indoor sites. Given the uniformity of the sulfate concentrations in the indoor environment, the data analysis is undertaken on the basis of ambient and average indoor concentrations.

The signature parameter used for sulfate data interpretation is the ratio of the indoor daily average concentrations over the corresponding outdoor concentrations. Two categories of houses have been identified with respect to this parameter: the average value of the indoor/outdoor ratio for houses in the first category is 0.46, with 70% of the daily ratio values below a demarcation ratio value of 0.6; the average indoor/outdoor ratio value for residences in the second category is 0.81, with 82% of the daily ratio values above the demarcation ratio value of 0.6. In residences that comprise the first category, electricity or propane is used for cooking and electricity or kerosene is used for heating. The fuel used in residences in the second category is gas.

The indoor-outdoor data base for sulfates shows that the indoor 24-h sulfate concentration is almost always lower than the corresponding outdoor sulfate concentration. The type of fuel used for cooking and heating is an important factor in determining the indoor-outdoor relationship; houses with gas appliances have a slightly higher sulfate indoor/outdoor ratio than houses without gas appliances. Sulfur is added to residential gas appliances for detecting leaks of the otherwise odorless fuel. Hollowell et al. (1976) have determined that approximately 10% of the sulfur added to the residential gas manifests itself as indoor sulfates.

TABLE 13. SULFATE ($SO_4^{=}$) DATA SUMMARY, $\mu g/m^3$

Residence	Fuel Type	Range		Statistics				Correlation Coefficient Between Indoor-Outdoor Daily Concentrations
				Indoor		Outdoor		
		Indoor	Outdoor	Average	Standard Deviation	Average	Standard Deviation	
Pitt. Mobile 1	Kerosene	2.6-10.6	4.2-32.8	5.55	2.42	18.71	7.86	0.937
Pitt. Mobile 2	Kerosene	2.9-8.3	5.8-18.3	4.87	1.50	8.99	3.49	0.024
Balt. Exp. I	Electric	2.6-27.4	3.2-37.4	11.35	8.54	15.42	12.35	0.981
Chic. Exp. I	Electric	1.1-4.9	3.3-10.4	2.53	1.30	5.43	1.84	0.689
Chic. Exp. II	Electric	0.3-5.3	0.6-14.5	2.12	1.55	8.15	4.44	0.767
Balt. Exp. II	Electric	1.5-5.5	2.6-10.1	3.25	1.21	4.94	2.34	0.333
Wash. Exp. I	Gas	2.6-22.0	0.9-30.3	9.09	5.49	11.36	9.23	0.927
Wash. Conv. I	Gas	2.0-5.7	0.9-21.5	3.67	1.09	12.02	5.44	0.678
Chic. Conv. I	Gas	1.5-22.7	1.8-21.9	8.18	6.36	7.78	6.14	0.998
Den. Conv.	Gas	0.9-4.4	0.8-4.4	2.20	0.95	2.20	1.20	0.289
Balt. Conv. I	Gas	2.4-24.8	2.3-21.5	9.50	6.60	10.46	6.44	0.899
Balt. Conv. II	Gas	1.7-5.2	1.8-8.8	3.16	1.06	4.27	2.17	0.789
Pitt. Low-Rise #1	Electric/Gas	3.1-9.5	3.3-16.4	4.47	1.72	8.22	3.95	0.668
Pitt. Low-Rise #2	Electric/Gas	2.2-6.6	3.8-12.5	4.04	1.38	6.83	2.17	0.749
Pitt. Low-Rise #3	Electric/Gas	8.4-20.1	10.8-24.1	12.99	3.37	15.14	3.77	0.494
Pitt. High-Rise #1	Electric/Gas	2.8-18.5	5.1-19.9	8.05	4.36	10.99	4.67	0.741
Pitt. High-Rise #2	Electric/Gas	3.1-17.3	4.1-25.5	8.74	4.76	11.78	6.78	0.967
Pitt. High-Rise #3	Electric/Gas	4.2-48.3	6.0-41.1	14.89	11.81	16.28	9.65	0.983

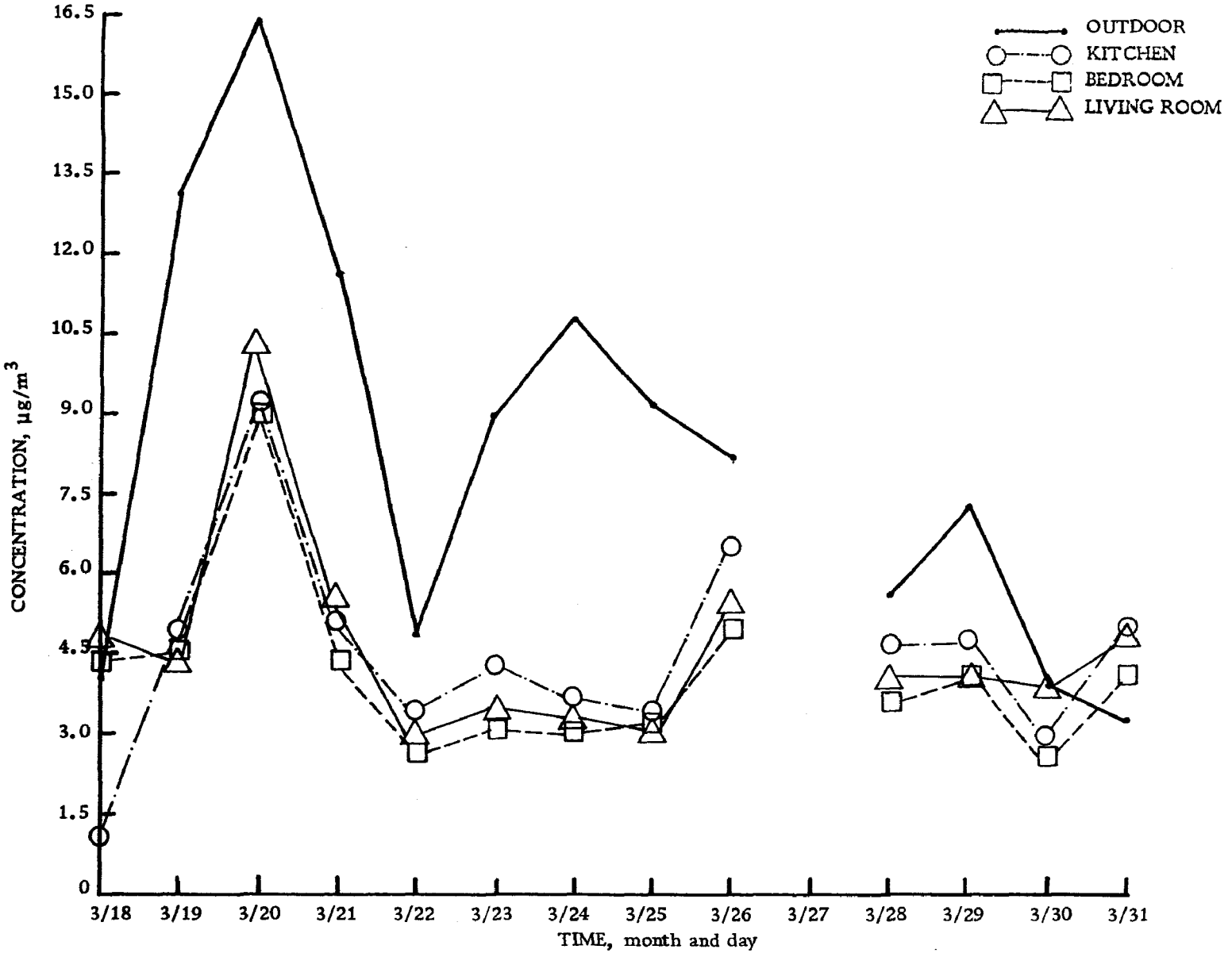


Figure 7. Pittsburgh low-rise #1 $SO_4^=$.

Indoor air quality standards for sulfate concentrations are not available. However, adverse health effects have been associated with ambient levels of sulfates in urban areas. A summary of the ambient sulfate levels by Altshuller (1973), gives the 5-y average concentrations for eastern and western urban centers: the 5-y average of $SO_4^=$ in western urban centers is 6.4 $\mu g/m^3$, and the corresponding 5-y average for eastern urban areas is 13.5 $\mu g/m^3$/ The arithmetic annual average ambient concentration range is 2.4-48.7 $\mu g/m^3$. A daily threshold value of 8-10 $\mu g/m^3$ is suggested by Colucci (1976) who claims that higher indoor sulfate concentrations may lead to adverse health effects in the elderly. If the above levels were to be considered as reference points, the observed indoor sulfate concentrations are often within, and a number of times higher than, this range. Thus, while the indoor daily averages are almost always lower than the corresponding outdoor levels, the observed indoor sulfate concentrations are at levels equivalent to those that have been linked with health problems.

Ammonia (NH_3)

Ammonia (NH_3) experiments were among the few tests staged during this program. Ammonia studies were performed in each residence monitored. The process used to introduce ammonia into the indoor environment was mopping the kitchen floor with a solution of 50 ml of a commercially available cleaning agent, 100 ml ammonia, and 2 gallons of water.* Three 3-h experiments were conducted in each residence. In some residences all experiments were conducted on the same day as one continuous test, while in other residences the experiments were staggered over a 2- or 3-d period. Measurements were taken in the kitchen, bedroom, and living room as soon as the kitchen cleaning activities began.

The collected samples were analyzed using a colorimetric method. Since the ammonia data base is not included in the magnetic tapes, Table 14 provides all information gathered from the staged experiments. As expected, the highest ammonia concentrations occur in the kitchen the first hour following introduction of the pollutant. During the second and third hours, the pollutant is dispersed throughout the residence, and, often by the third hour, ammonia concentrations become low and approximately equal in each location.

The threshold limit value of ammonia for an 8-h day, 5 d per week is 25 ppm (ACGIH, 1976); the ASHRAE-recommended indoor standard is 2.5 ppm. None of the ammonia levels that were observed indoors during the routine floor washing procedure exceeded this level; the highest observed concentration was 1.2 ppm.

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* Before July 1, 1976 only 50 ml NH_3 were used.

TABLE 14. AMMONIA LEVELS, ppm

Location	Run 1				Run 2				Run 3				Ranges		
	Date and Time	Kitchen	Bedroom	Living Room	Date and Time	Kitchen	Bedroom	Living Room	Date and Time	Kitchen	Bedroom	Living Room	Kitchen	Bedroom	Living Room
Pittsburgh Mobile I	2/17 1020-1130	0.033	<0.033	0.11	2/17 1340-1440	0.012	<0.003	<0.003	2/18 1025-1125	0.025	<0.003	0.011	0.003-0.084	0.008-0.008	0.008-0.014
	1131-1231	0.084	0.003	<0.003	1441-1541	<0.003	<0.003	<0.003	1125-1226	0.025	<0.003	0.014			
	1232-1332	<0.003	<0.003	<0.003	1542-1642	0.025	<0.003	<0.003	1227-1327	0.006	<0.003	0.009			
Pittsburgh Mobile II	3/8 1000-1100	0.056	0.027	<0.001	3/10 1200-1300	0.055	0.017	0.011	3/10 1550-1650	0.017	<0.001	<0.001	0.006-0.237	0.001-0.141	0.001-0.073
	1101-1201	0.237	0.141	0.073	1308-1408	0.019	0.001	<0.001	1651-1751	0.006	0.006	0.003			
	1202-1302	0.019	<0.001	<0.001	1411-1411	0.024	<0.001	*	1752-1852	0.024	<0.001	<0.001			
Pittsburgh High Rise 1	5/16 1640-1740	0.776	0.344	0.821	5/16 1956-2056	0.274	0.230	0.383							
	1741-1841	0.265	0.263	0.307	2057-2157	0.692	0.321	0.476							
	1842-1942	0.482	0.354	0.406	2158-2258	0.570	0.377	0.342							
Pittsburgh High Rise 2	5/31 1030-1130	*	0.767	0.332	5/31 1350-1450	0.403	0.153	0.204	5/31 1700-1800	0.148	0.195	0.165			
	1131-1231	*	0.351	0.333	1451-1551	0.136	*	0.125	1801-1901	0.212	0.143	0.119			
	1232-1332	0.198	0.166	0.163	1552-1652	0.252	0.453	0.287	1902-2002	0.342	0.458	*			
Pittsburgh High Rise 3	6/15 1055-1155	0.154	0.049	0.051	6/15 1405-1505	0.339	0.227	0.265	6/16 1030-1130	0.289	0.144	0.201	0.053-0.448	0.049-0.320	0.050-0.369
	1156-1256	0.053	0.052	0.050	1506-1606	0.367	0.320	0.369	1131-1231	0.239	0.273	0.239			
	1257-1357	0.308	0.147	0.178	1607-1707	0.252	0.242	0.127	1232-1332	0.448	0.177	0.171			
Pittsburgh Low Rise 1	3/24 0822-0922	0.207	0.065	0.268	3/24 1132-1232	1.230	0.274	0.067	3/24 1446-1546	0.742	0.082	0.175	0.091-1.230	0.027-0.274	0.023-0.268
	0923-1023	0.136	0.052	0.080	1233-1333	0.205	0.067	0.067	1547-1647	0.185	0.077	0.070			
	1024-1124	0.092	0.027	0.023	1334-1434	0.141	0.046	0.040	1648-1748	1.50	0.52	0.057			
Pittsburgh Low Rise 2	4/5 1100-1200	0.626	0.539	1.04	4/5 1445-1545	0.299	0.087	0.291	4/6 1200-1300	0.691	0.241	0.348	0.299-1.10	0.087-0.945	0.249-1.041
	1200-1300	0.324	0.280	0.663	1545-1645	0.464	0.271	0.649	1300-1400	0.772	0.945	1.00			
	1300-1400	1.04	0.663	0.249	1645-1745	0.659	0.405	0.463	1400-1500	1.10	0.467	0.404			
Washington Conventional 1	7/7 1330-1430	0.184	0.025	0.050	7/8 1200-1300	0.118	0.023	0.039	7/8 1507-1607	0.123	0.027	0.070	0.007-0.184	0.007-0.027	0.007-0.070
	1430-1300	0.056	0.008	0.036	1302-1402	0.029	0.011	0.016	1609-1709	0.016	<0.007	<0.007			
	1530-1630	0.029	<0.007	<0.007	1405-1505	<0.007	<0.007	<0.007	1707-1810	0.053	<0.011	<0.010			
Washington Experimental 1	8/4 0945-1045	0.233	0.033	0.064	8/4 1318-1418	0.984	0.0	0.0	8/4 1636-1736	1.18	0.012	0.012	0.020-0.070	0.0-0.070	0.0-0.14
	1052-1152	0.021	0.0	0.0	1420-1418	0.609	0.072	0.020	1741-1841	0.504	0.012	0.033			
	1154-1254	0.020	0.012	0.0	1525-1625	0.220	0.0	0.012	1849-1949	0.233	0.012	0.064			
Baltimore Conventional 2	2/2 1148-1248	0.978	0.099	0.377	2/2 1451-1551	0.602	0.102	0.186	2/2 1758-1858	0.300	0.086	0.180	0.110-0.041	0.041-0.149	0.113-0.377
	1248-1348	1.207	0.149	0.123	1554-1654	0.176	0.041	0.128	1901-2001	0.179	0.079	0.153			
	1351-1451	0.159	0.067	0.118	1656-1756	1.171	0.125	0.151	2004-2104	0.110	0.075	0.113			
Baltimore Conventional 1	9/8 0965-1055	0.316	0.229	0.153	9/8 1350-1450	0.074	0.155	<0.005	9/8 1702-1802	0.094	0.066	<0.005	0.034-0.316	0.056-0.239	<0.005-0.153
	1057-1157	0.176	0.239	<0.005	1452-1552	0.084	0.066	<0.005	1804-1909	0.135	0.117	0.043			
	1159-1259	0.174	0.155	<0.005	1554-1664	<0.005	0.127	0.014	1906-2006	0.081	0.086	0.055			
Baltimore Experimental 2	1/6 1020-1120	0.285	0.086	0.161	1/6 1331-1431	0.301	0.177	0.221	1/6 1645-1745	0.286	0.233	0.210	0.188-0.301	0.086-0.233	0.151-0.221
	1121-1221	0.223	0.211	0.165	1434-1534	0.205	0.161	0.163	1748-1848	0.262	0.170	0.184			
	1222-1323	0.201	0.174	0.151	1536-1636	0.205	0.165	0.202	1850-1950	0.188	0.155	0.188			

* No sample left in these to rerun.

(continued)

TABLE 14. (continued)

Location	Run 1				Run 2				Run 3				Ranges		
	Date and Time	Kitchen	Bedroom	Living Room	Date and Time	Kitchen	Bedroom	Living Room	Date and Time	Kitchen	Bedroom	Living Room	Kitchen	Bedroom	Living Room
	8/23				8/23				8/25						
Baltimore	1155-1256	0.365	0.260	0.232	1525-1625	0.334	0.270	0.252	0950-1050	0.270	0.239	0.273	0.165-	0.175-	0.132
Experimental 1	1257-1357	0.270	0.378	0.273	1628-1728	0.352	0.388	0.351	1052-1152	0.410	0.400	0.416	0.410	0.400	0.416
	1359-1459	0.365	0.282	0.306	1732-1832	0.313	0.313	0.306	1154-1254	0.165	0.175	0.132			
	7/25				7/26				7/26						
Chicago	1440-1540	0.216	0.070	0.580	0955-1055	0.001	0.162	0.001	1308-1408	0.475	0.001	0.109	0.001-	0.001-	0.001-
Experimental 1	1541-1641	0.251	0.288	0.745	1056-1156	0.874	1.028	0.666	1411-1511	0.330	0.217	0.584	0.874	1.028	0.745
	1642-1742	0.267	0.152	0.284	1157-1257	0.357	0.233	0.172	1513-1613	0.137	0.245	0.326			
	12/16				12/16				12/17						
Chicago	0925-1025	0.005	0.0	0.0	1241-1341	0.009	0.0	0.0	0915-1015	0.080	0.0	0.005			
Experimental 2	1027-1127	0.0	0.0	0.0	1346-1446	0.0	0.0	0.0	1025-1125	0.028	0.0	0.001			
	1132-1232	0.0	0.0	0.0	1450-1550	0.0	0.0	0.0	1129-1229	0.001	0.005	0.001			
	8/3				8/3				8/3						
Chicago	1055-1155	0.674	0.613	0.902	1420-1520	1.017	0.593	0.466	1815-1915	0.854	0.545	0.520	0.342-	0.387	0.436-
Conventional 2	1156-1256	0.825	0.677	1.303	1521-1621	0.522	0.395	0.436	1916-2020	0.342	0.427	0.472	1.017	0.677	1.303
	1257-1357	0.458	0.703	0.561	1622-1722	0.580	0.525	0.463	2021-2124	0.525	0.387	0.503			
	11/30				11/30				11/30						
Chicago	1250-1350	0.293	0.123	0.323	1557-1608	0.031	0.018	0.075	1914-2014	0.091	0.008	0.020	0.022-	0.0-	0.017-
Conventional 1	1351-1451	0.140	0.036	0.352	1659-1759	0.070	0.0	0.016	2016-2116	0.022	0.0	0.074	0.293	0.123	0.357
	1453-1503	0.087	0.081	0.030	1800-1900	0.034	0.0	0.023	2117-2217	0.039	0.012	0.012			
	10/9				10/9				10/10						
Denver	1005-1105	0.609	0.108	0.172	1315-1415	0.791	0.008	0.161	1245-1345	3.085	0.069	0.191	0.006-	0.006-	0.112-
Conventional	1107-1207	0.394	0.322	0.156	1418-1518	0.374	0.008	0.173	1349-1449	0.059	0.008	0.218	3.085	0.322	0.246
	1210-1310	0.368	0.015	0.240	1522-1622	0.238	0.006	0.112	1452-1552	<0.006	0.042	0.198			

The USSR air quality criteria state that human odor perception of ammonia occurs at 0.56 ppm. Levels that exceed this value have been observed in residences in the course of this project. Russian scientists have also found adverse responses of human reflexes when ammonia levels surpass 0.49 ppm (Stern, 1968).

Aldehydes (ALD)

Aldehyde concentrations were measured intermittently. In the outdoor location one 24-h average is obtained daily. In each of the three indoor locations, three 4-h averages were measured each day: the first 4-h period began at 0600 hours, the second at 1000 hours, and the last at 1600 hours. This design takes under consideration the expected low ambient levels; it generates a daily structure and allows for identification of any indoor patterns.

The observed outdoor concentrations of aldehydes were always lower than the indoor levels, typically by a factor of six and quite often by one order of magnitude. Figure 8 is an illustration of the data collected. The observed outdoor concentrations of aldehydes were negligible.

Early in the study of residential aldehyde levels, it was discovered that each dwelling has its own very distinct character and that directly studying the raw data provides the best means of interpreting the observations. Table 15 shows a portion of the aldehyde data collected; Table 16 is an example of the basic descriptive statistic obtained for this set of data. Similar tables were generated for each of the monitored residences.

The data from this study conclusively shows that there are indoor sources of aldehydes. Emanation of aldehydes from chipboard used in the construction of buildings, from pressed board used in mobile homes and furniture may account for the observed high indoor levels.

Daily patterns of aldehyde levels have not been identified; the indoor levels are generally uniform within each day, but they display considerable fluctuations over each monitoring period. Andersen et al. (1975) have formulated a mathematical model that estimates the room air concentration of formaldehyde; this model has been established with the help of chamber experiments. The indoor air pollution study cannot estimate board surface area which has been shown by Andersen to be a crucial parameter involved in estimating the aldehyde concentrations. The temperature and humidity relationships of the Andersen model have been qualitatively verified.

Although the source strengths were not quantified by this study, a series of conclusions were reached.

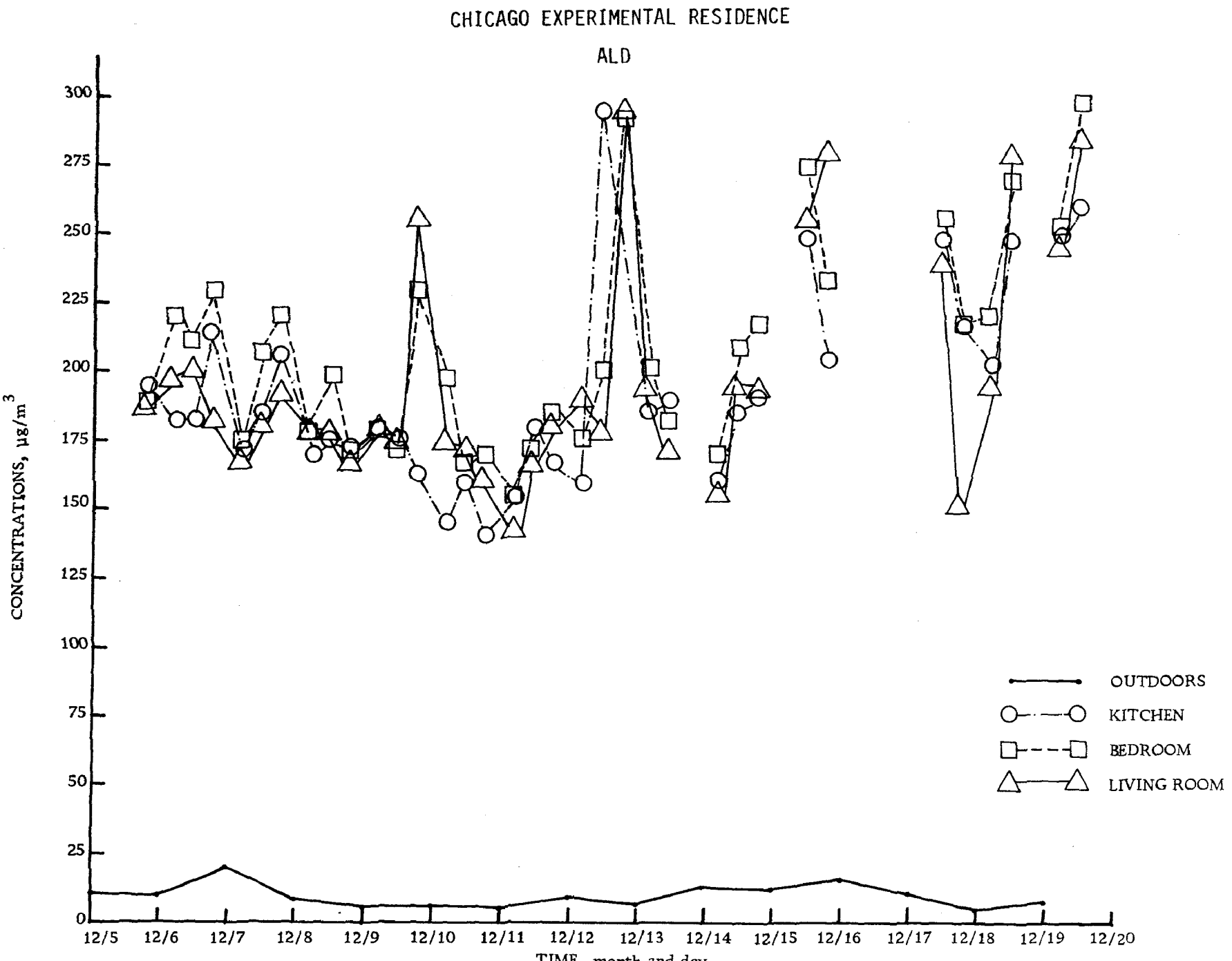


Figure 8. Observed indoor and outdoor aldehyde time (day) variations.

TABLE 15. ALDEHYDE CONCENTRATION IN A SAMPLE RESIDENCE

Site #: 6
Visit #: 2
Pollutant: Aldehydes
Pollutant Units: $\mu g/m^3$

Pollutant concentration values for three 4-h periods beginning at 0600, 1000, and 1600 plus the daily average for each indoor zone

	Kitchen			Bedroom			Livingroom			Daily
Date	0600-1000	1000-1400	1600-2000	0600-1000	1000-1400	1600-2000	0600-1000	1000-1400	1600-2000	Average
77/ 7/13	306.40	298.00	313.80	277.30	219.70	224.60	290.40	255.60	252.40	270.91
77/ 7/14	-1.00*	303.10	-1.00	-1.00	243.90	-1.00	-1.00	215.60	-1.00	254.20
77/ 7/15	-1.00	207.80	555.40	-1.00	277.30	246.90	-1.00	221.70	277.00	297.68
77/ 7/16	302.80	350.70	310.30	262.50	285.00	229.40	224.70	295.20	216.00	275.18
77/ 7/17	377.80	336.10	328.10	252.40	279.70	244.80	226.40	225.10	288.00	284.27
77/ 7/18	409.80	445.20	499.70	309.60	336.20	424.30	371.20	401.60	415.80	401.49
77/ 7/19	-1.00	-1.00	314.70	-1.00	-1.00	320.70	-1.00	-1.00	554.60	396.67
77/ 7/20	450.90	422.10	415.10	400.50	321.70	328.00	412.10	374.60	308.80	381.53
77/ 7/21	369.40	396.60	343.50	352.20	326.30	330.00	317.00	312.80	269.70	335.28
77/ 7/22	216.20	391.10	313.60	393.90	326.60	429.30	362.60	347.20	303.00	342.61
77/ 7/23	390.70	386.40	420.30	316.70	313.00	295.20	305.70	295.20	336.90	340.01
77/ 7/24	427.40	447.40	386.40	332.20	328.80	322.70	315.60	346.70	317.40	358.29
77/ 7/25	339.10	320.50	-1.00	286.80	287.80	-1.00	261.40	241.80	-1.00	289.57
77/ 7/26	-1.00	-1.00	353.00	-1.00	-1.00	257.00	-1.00	-1.00	242.20	284.07
77/ 7/27	346.90	395.20	-1.00	313.10	289.50	-1.00	302.50	277.90	-1.00	320.85

* The designation (-1.0) indicates missing data.

TABLE 16. DESCRIPTIVE STATISTICS CORRESPONDING TO THE ALDEHYDE CONCENTRATION OF TABLE 15

Site #: 6
Visit #: 2
Pollutant: Aldehydes
Pollutant Units: g/m^3

Zone-period statistics

	Kitchen				Bedroom				Livingroom			
	0600-1000	1000-1400	1600-2000	Total	0600-1000	1000-1400	1600-2000	Total	0600-1000	1000-1400	1600-2000	Total
Mean	357.945	361.554	379.492	366.431	317.927	295.039	304.408	305.156	308.145	293.154	315.150	305.067
Sigma	66.347	67.964	80.145	70.357	49.039	35.196	69.395	52.103	58.365	60.970	91.195	70.371

Zone-day statistics

	Kitchen		Bedroom		Livingroom		Daily	
Date	Mean	Sigma	Mean	Sigma	Mean	Sigma	Mean	Sigma
77/ 7/13	306.067	7.905	240.533	31.935	266.133	21.076	270.911	34.637
77/ 7/14	303.100	-1.000*	243.900	-1.000	215.600	-1.000	254.200	44.650
77/ 7/15	381.600	245.790	262.100	21.496	249.350	39.103	297.683	129.377
77/ 7/16	321.267	25.764	258.967	27.968	245.300	43.433	275.178	45.420
77/ 7/17	347.333	26.687	258.967	18.353	246.500	35.946	284.267	53.401
77/ 7/18	451.567	45.287	356.700	60.035	396.200	22.785	401.489	56.980
77/ 7/19	314.700	-1.000	320.700	-1.000	554.600	-1.000	396.667	136.807
77/ 7/20	429.367	18.974	350.067	43.790	365.167	52.292	381.533	50.821
77/ 7/21	369.833	26.553	336.167	14.008	299.833	26.181	335.278	36.275
77/ 7/22	306.967	87.638	383.267	52.169	337.600	30.938	342.611	62.813
77/ 7/23	399.133	18.457	308.300	11.495	312.600	21.689	340.011	46.962
77/ 7/24	420.400	31.097	327.900	4.814	326.567	17.459	358.289	49.940
77/ 7/25	329.800	13.151	287.300	0.718	251.600	13.859	289.567	36.045
77/ 7/26	353.000	-1.000	257.000	-1.000	242.200	-1.000	284.067	60.155
77/ 7/27	371.050	34.153	301.300	16.687	290.200	17.394	320.850	43.430

Monitoring period statistics

Mean	Sigma
325.551	70.502

* The designation (-1.0) indicates missing data.

Table 17 shows two distinct classes of monitored residences one with high indoor levels and the second with lower levels.

TABLE 17. STATISTICAL SUMMARY OF OBSERVED ALDEHYDE LEVELS
(Outdoor levels are very low)

Residence	Observed Range 4-h Concentrations ($\mu g/m^3$)	14-d Monitoring Period	
		Mean Concentrations ($\mu g/m^3$)	Standard Deviation ($\mu g/m^3$)
Denver Conventional	87-615	250	118
Chicago Experimental I	140-300	200	38
Chicago Experimental II	242-555	325	70
Pittsburgh Mobile Home 1	200-938	470	167
Pittsburgh Mobile Home 2	136-934	387	159
Washington Conventional I	21-153	52	31
Baltimore Conventional II	34-150	75	25
Washington Experimental I	10-286	90	78
Baltimore Experimental I	17-162	78	38
Baltimore Experimental II	6-122	48	20
Pittsburgh Low Rise 1	51-152	91	34
Pittsburgh High Rise 1	22-120	56	18
Chicago Conventional I	20-190	54	29
Chicago Conventional II	10-159	47	23
Pittsburgh Low Rise 2	35-149	78	29
Baltimore Conventional I	10-300	144	75
Pittsburgh High Rise 2	76-240	125	27
Pittsburgh High Rise 3	65-234	149	40
Pittsburgh Low Rise 2	20-102	110	32

Table 17 illustrates that the highest levels are observed in the mobile homes; emanation from the pressed board appears to be the primary source. The high aldehyde concentrations in the mobile homes were expected, considering the fact that both structures were almost new. The Denver house, a pre-1940 structure, indicates that emanation from construction material may continue for many years; however, independent research shows that it should decrease with time (Andersen et al., 1975). In view of the fact that all dwellings in the first group register aldehyde levels that exceed the ASHRAE recommended indoor standard of 300 $\mu g/m^3$, the conclusion reached is that further research is warranted on this subject.

It has been suggested that material used to insulate houses emanates formaldehydes. The data base available to this study cannot verify this statement; however, this energy conserving measure and others, which are often taken at the same time, result in a decrease of the infiltration rate of the retrofitted dwelling. Under these conditions, low infiltration rates and possibly high formaldehyde emanation rates, the aldehyde concentrations in the indoor-residential environment will reach high and possibly hazardous levels.

Although high aldehyde levels have been observed in this study, the majority of the dwellings monitored have registered levels below 200 $\mu g/m^3$.

Lead (Pb)

One half of the 47-mm glass fiber filter, used in collecting total particulate matter, is analyzed in the laboratory to determine indoor and outdoor Pb levels. The realization that Pb concentrations do not vary greatly within a residence, combined with the high cost of the analytical method used (atomic absorption spectrophotometry), induced the following change in the experimental design: instead of determining the daily Pb concentrations from all four sites simultaneously, the Pb levels were determined from one site, and the site of measurement was rotated continuously, thus requiring 4 d to estimate levels from all sampling sites.

One of the sampled residences, the Baltimore conventional house, registered Pb ambient levels between 4.0 and 12.5 $\mu g/m^3$; the indoor Pb levels were equally high, varying between 0.1 and 12.0 $\mu g/m^3$. The daily Pb concentrations observed in this house do not surpass the ASHRAE recommended indoor standard of $\mu g/m^3$; however, they are unusually high levels and are a cause of concern.

Table 18, the Pb data collected for this project, shows that the observed Pb levels during the second monitoring period in the same Baltimore Conventional residence varied between 0.1 and 1.8 $\mu g/m3$ in the outdoor environment, and between 0.1 and 0.5 $\mu g/m3$ in the indoor environment. These levels are within the typical observed range of 0.1 to 2.8 $\mu g/m3$. In addition, the Pb levels sampled 2 weeks earlier in an almost identical residence, the Baltimore experimental house, a half mile from the Baltimore conventional dwelling, were within the typical range. Owing to expressed

TABLE 18. Pb CONCENTRATIONS SAMPLED IN 18 RESIDENCES FOR BOTH THE INDOOR AND OUTDOOR ENVIRONMENTS ($Pb, \mu g/m^3$)

Day	Location	Washington Experimental #1	Baltimore Experimental #1	Baltimore Experimental #2	Washington Conventional #1	Baltimore Conventional #1	Baltimore Conventional #2	Denver Conventional	Chicago Conventional #2	Chicago Experimental #1	Chicago Experimental #2	Pittsburgh Low Rise 1	Pittsburgh Low Rise 2	Pittsburgh Low Rise 3	Pittsburgh Mobile 1	Pittsburgh Mobile 2	Pittsburgh High Rise 1	Pittsburgh High Rise 2	Pittsburgh High Rise 3
1	Outdoor	0.9	1.0	0.5	2.6	12.5	0.3	1.7	0.2	0.6	Void	0.1	0.2	2.7	1.2	0.3	0.4	0.8	0.6
2	Kitchen	0.3	0.3	0.2	0.4	1.5	0.1	1.2	0.5	0.2	Void	0.3	0.2	0.9	0.2	0.1	0.4	0.7	0.6
3	Bedroom	0.8	0.3	0.2	0.4	12.0	0.4	0.7	0.1	0.2	0.1	0.3	0.1	0.6	Void	0.1	0.6	0.8	0.1
4	Living Room	0.6	0.2	0.1	0.1	0.2/ 7.3	0.2	Void	0.2	Void	0.1	0.2	0.1	0.8	Void	0.1	0.3	0.3	0.4
5	Outdoor	0.7	0.3	1.5	0.4	4.7	0.4	0.6	0.2	0.2	0.4	0.1	0.4	1.1	0.7	0.7	0.8	0.8	1.3
6	Kitchen	0.9	0.1	0.1	0.3	6.2	0.2	0.6	0.2	0.2	0.1	0.1	0.3	0.4	0.1	0.1	0.5	0.4	0.7
7	Bedroom	0.4	0.3	0.1	1.0	6.7	2.0	0.8	0.1	0.1	Void	0.1	0.1	0.3	0.2	0.1	0.7	0.1	0.2
8	Living Room	0.4	0.4	0.2	0.2	2.2	0.1	0.6	0.2	0.2	0.1	0.1	0.7	0.3	0.1	0.1	0.6	0.1	0.1
9	Outdoor	1.0	1.2	0.3	1.0	10.8	0.3	1.2	Void	0.2	0.3	0.2	0.9	0.7	0.4	0.4	0.9	0.4	Void
10	Kitchen	1.6	0.9	0.3	0.5	5.8	0.1	1.0	Void	0.2	0.1	0.2	0.3	2.1	0.3	0.1	0.4	0.8	0.4
11	Bedroom	0.7	0.4	0.2	0.7	8.2	0.1	0.8	Void	0.3	0.1	0.6	0.3	0.4	0.2	0.1	0.7	0.4	0.5
12	Living Room	0.6	0.4	0.5	0.45	4.8	0.2	1.3	Void	0.1	0.1	Void	0.3	0.8	0.1	0.2	0.5	0.3	0.3
13	Outdoor	0.8	0.7	0.2	2.8	4.0	1.8	2.0	Void	0.5	0.5	0.4	0.6	1.9	0.4	0.9	0.5	0.4	1.1
14	Kitchen	0.5	0.5	0.1	0.4	0.1	0.5	Void	Void	0.5	Void	Void	0.3	0.6	0.2	0.2	Void	0.4	0.3
15	Bedroom	Void	0.1	0.1	0.7	Void	Void	Void	Void	0.1	0.2	Void	0.6	Void	0.5	Void	Void	0.2	Void
16	Living Room	Void	Void	Void	Void	Void	Void	Void	Void	Void	0.2	Void	Void	Void	Void	Void	Void	Void	Void

concern and the consequences of the magnitude of Pb levels observed in this residence, a special effort was undertaken to determine the cause. Unfortunately, the effort was inconclusive, and specific sources were not identified. Therefore, the high ambient Pb levels were attributed to unknown local ambient Pb sources. The possibility of improperly operating sampling instruments or faulty analysis procedures has not been excluded.

The State of California has promulgated a 30-d average Pb standard of 1.5 $\mu g/m^3$. This level is exceeded in only a few instances by the observed 24-h Pb averages. And, it is only in the special case of the Baltimore conventional house that the data base indicated a violation of this standard over the monitoring period.

The observed outdoor Pb concentrations are typically higher than the corresponding (within the 4-d time interval) indoor concentrations; however, there are a few instances of indoor sources. The ratio value of outdoor Pb concentrations over the corresponding indoor averages is shown in Table 19. Only a small percentage of these values is less than one, indicating that the impact of indoor Pb-generating sources is evident only under uncommon conditions; such uncommon conditions are identified in the elemental Pb analysis. (See the discussion on elemental analysis.)

The major surce of outdoor lead is the automobile. A common source of lead in the indoor environment is lead-based wall paint. Such paints are found only in older houses because their use has been recently banned. Titanium-based paint is used in newer residences. It has been recently suggested that indoor residential environments of affluent communities contain high Pb levels of automotive nature. The study of the indoor-outdoor Pb data base verifies only half of the above suggestion: newer houses manifest Pb concentrations of automotive nature; however, the majority of the observed concentrations are low and therefore not hazardous to the public health.

Asbestos

During the performance of this program, 10 air samples were collected on 47-mm Nuclepore filters and analyzed for asbestos fibers. The samples were obtained in two Chicago residences during the summer monitoring period in 1977. Five samples were collected at the experimental residence, and five were collected at the conventional residence.

For analysis, the filters were divided into eight sections. Each of six sections per filter was examined by dispersion staining microscopy at 100X magnification for one of the six principal asbestos minerals. The six mineral types are chrysotile, amosite, crocidolite, anthophyllite, actinolite, and tremolite.

Dispersion staining uses a liquid of specific refractive index for each asbestos type. As polarized light passes through asbestos fibers surrounded by the liquid, they appear in color. The color observed

TABLE 19. RATIO VALUES OF OUTDOOR Pb CONCENTRATIONS WITH CORRESPONDING INDOOR AVERAGES

	1st 4-d Cycle			2nd 4-d Cycle			3rd 4-d Cycle			4th 4-d Cycle		
	Outdoor	Indoor Average	Out/In	Outdoor	Indoor Average	Out/In	Outdoor	Indoor Average	Out/In	Outdoor	Indoor Average	Out/In
Washington Experimental I	0.9	0.63	1.4	0.7	0.57	1.2	1.0	0.97	1.0	0.8	0.5	1.6
Baltimore Experimental I	1.0	0.27	3.7	0.3	0.27	1.1	1.2	0.57	2.1	0.7	0.3	2.3
Baltimore Experimental II	0.5	0.17	2.9	1.5	0.13	0.3	0.3	0.33	0.91*	0.2	0.10	2.0
Washington Conventional	2.6	0.30	8.7	0.4	0.50	0.8*	1.0	0.48	2.1	2.8	0.37	2.4
Baltimore Conventional I	12.5	5.3	2.4	4.7	5.0	0.94*	10.8	6.3	1.7	4.0	0.1	40.0
Baltimore Conventional II	0.3	0.23	1.3	0.4	0.17	2.4	0.3	0.13	2.3	1.8	0.5	3.6
Denver Conventional	1.7	0.95	1.8	0.6	0.67	0.89*	1.2	1.0	1.2	2.0	-	-
Chicago Conventional II	0.2	0.27	0.74*	0.2	0.17	1.2	-	-	-	-	-	-
Chicago Experimental I	0.6	0.2	3.0	0.2	0.17	1.2	0.2	0.2	1.0	0.5	0.3	1.7
Chicago Experimental II	-	0.1	-	0.4	0.1	4.0	0.3	0.1	3.0	0.5	0.2	2.5
Pittsburgh Low Rise 1	0.1	0.27	0.37	0.1	0.1	1.0	0.2	0.4	0.24*	0.4	-	-
Pittsburgh Low Rise 2	0.2	0.13	1.5	0.4	0.37	1.1	0.9	0.3	3.0	0.6	0.45	1.3
Pittsburgh Low Rise 3	2.7	0.76	3.6	1.1	0.33	3.33	0.7	1.1	0.64*	1.9	0.6	3.2
Pittsburgh Mobile 1	1.2	0.2	6.1	0.7	0.13	6.2	0.4	0.2	2.0	0.4	0.35	1.1
Pittsburgh Mobile 2	0.3	0.1	3.0	0.7	0.1	7.0	0.4	0.13	3.1	0.9	0.2	4.5
Pittsburgh High Rise 1	0.4	0.43	0.93*	0.8	0.6	1.3	0.9	0.53	1.7	0.5	-	-
Pittsburgh High Rise 2	0.8	0.6	1.3	0.8	0.2	4.0	0.4	0.5	0.8*	0.4	0.3	1.3
Pittsburgh High Rise 3	0.6	0.37	1.6	1.3	0.33	3.9	-	0.4	-	1.1	0.3	3.7

* Indoor source.

depends on the type of asbestos and whether the fiber is parallel or perpendicular to the plane of the polarized light. For example, amosite in liquid refractive index 1.67 appears magenta when aligned with the polarized light and yellow when perpendicular to it.

The seventh section of each filter was examined by the Analytical Method for Detection of Asbestos Fibers (Federal Register, 1972) to obtain a quantitative analysis of asbestos fibers. This method uses phase contrast microscopy at 400X magnification to make filters appear distinct from their background. A portion reticle with a field area of 3.08×10^{-3} mm^2 was used; 100 fields were examined on each filter section.

The minimum detection limit of fibers in the air sampled was determined as follows:

Usable area of filter = 1320 mm^2
Area of 1 field = 3.08×10^{-3} mm^2
Area of 100 fields = 0.308 mm^2

$$\text{Detection limit, fibers/cm}^3 = 1 \text{ fiber} \times \frac{1320 \text{ mm}^2}{0.308 \text{ mm}^2} \times \frac{10^{-6}}{\text{air volume, m3}}$$

The eighth section (1/4 of the filter) was retained as a reserve.

No fibers of any of the six asbestos forms were found during the dispersion staining examinations. No asbestos form fibers were found by the Federal Register method count. Table 20 below lists the filters, the air volumes samples, and the detection limits.

TABLE 20. ASBESTOS COUNT RESULTS

Residence	Site	Location	Date	Sampling Time (hours)	Air Volume (m^3 at STP)	Detection Limit (Fibers/cm^3)
Chicago Experimental	1	Ambient	7/22/77	8	23.7	1.81×10^{-4}
	4	Living Room	7/22/77	8	23.5	1.82×10^{-4}
	4	Living Room	7/23/77	8	17.8	2.41×10^{-4}
	4	Living Room	7/25/77	8	23.8	1.80×10^{-4}
	4	Living Room	7/26/77	8.5	25.8	1.66×10^{-4}
Chicago Conventional	1	Ambient	7/31/77	8	47.4	0.90×10^{-4}
	4	Living Room	7/31/77	8	28.7	1.49×10^{-4}
	4	Living Room	8/1/77	7	24.7	1.74×10^{-4}
	4	Living Room	8/2/77	7.3	26.2	1.64×10^{-4}
	4	Living Room	8/3/77	8	28.1	1.53×10^{-4}

All filters had fiber counts below the detection limit. The detection limits are well below the 8-h time-weighted average of two fibers/cm^3 of air allowed by the U.S. Department of Labor for occupational exposure (Federal Register, 1972).

Elemental Analysis

Aerosol samplers used in this study are continuous Nuclepore filter devices which provide a smoothly varying sample streak by a sliding, sucking orifice (Nelson, 1977). Elemental analysis is carried out in a stepwise fashion using proton-induced X-ray emission, PIXE (Johansson et al., 1975), providing a record with 2-h time resolution of the time variability in elemental concentrations of the suspended particulate matter. Samples were collected throughout the indoor-outdoor field monitoring program, for a number of residences monitored early in the program; a total of 84 2-hourly analyses of each sample were performed by PIXE for S, Cl, K, Ca, Ti, Mn, Fe, Cu, Zn, Br, and Pb. Five samples were collected for elemental analysis; three indoors (in the kitchen, living room, and bedroom) and two outdoors (one in front of the house and the other in the back). For a variety of technical reasons, analysis for each residence was undertaken only on representative sites. The results of time variability of aerosol composition from three residences are presented in this section.

During the first visit at the Baltimore experimental residence, the indoor concentration of Pb fluctuated synchronously with the corresponding outdoor concentrations. The air exchange rate is essentially instantaneous within the time resolution of the experiment--2 h. A similar correspondence in the optimal points of Pb levels is observed in the Baltimore conventional residence. A small filtering effect observed in this residence may indicate that the ambient site is not representative. The location of the ambient sites with respect to the house is of greater importance in aerosol considerations than in gas pollutants. The correspondence of the maximum concentrations indicates that the indoor sources of lead, if any, are not substantial.

The Denver single family house illustrates that under certain conditions indoor Pb sources may exist. Indoor sources of lead are attributed to reentrainment of particulate matter caused by the daily activity in the house. Outdoor concentrations of most elements sampled in this residence were high during the first 40 h of sampling, then low for a 4-d period, and again high during the final 30 h, apparently reflecting weather changes during the sampling period. Of special interest are Pb and Br, both derived primarily from automotive exhaust, which during the middle 4 d had higher indoor concentrations than outdoor (see Figure 9). The concentration units used in Figure 9 and all subsequent figures illustrating measurements by PIXE correspond to ng/m^3 absolute concentration to a significance of a factor of two depending on the flow rate calibration of the experimental arrangement. Indoor sources of Pb,

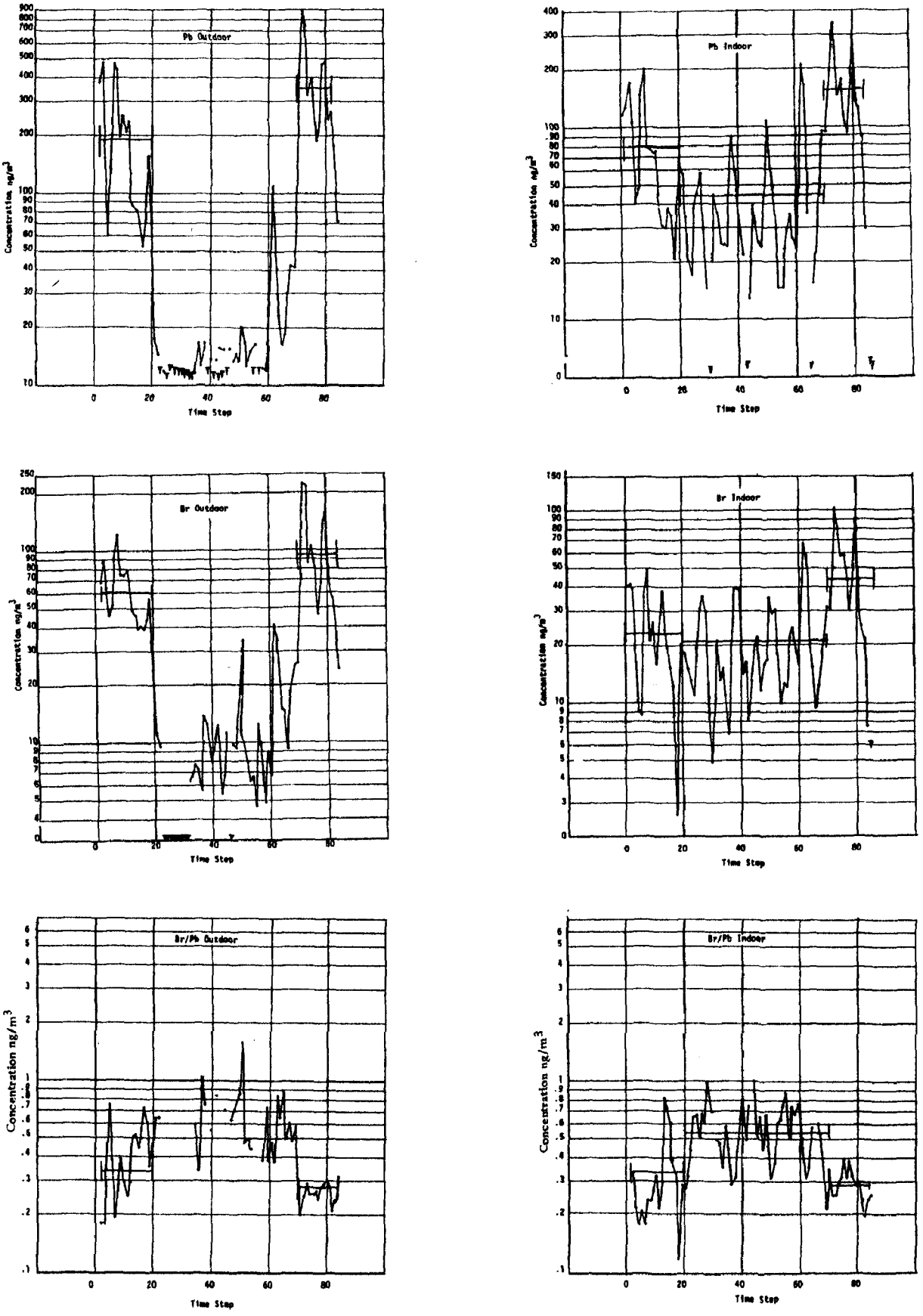


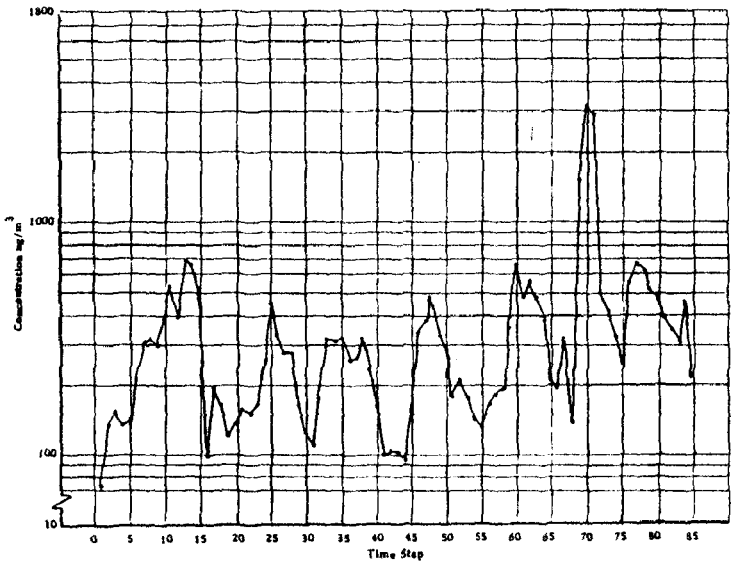
Figure 9. Time variation of Pb and Br concentrations and Br/Pb ratio in Denver single-family dwelling. Time steps represent 2-hour sampling intervals, starting and ending at 1600 hours October 5-12, 1976. Mean values Pb, Br, and Br/Pb for each of three time periods are indicated by horizontal bars, with their standard deviations as vertical bars.

with Br/Pb = 0.6, predominated in the middle period. Infiltration from outside sources having Br/Pb = 0.3 predominated in the initial and final periods. A simple mixing model for indoor- and outdoor-generated Pb and Br within this residence leads to an estimate of 0.3 as the factor by which outdoor lead is reduced in concentration during its penetration indoors (Moschandreas et al., 1977). Owing to the prevailing meteorological conditions, the Denver concept does not apply in the two Baltimore residences; therefore, it has not been tested. However, a general agreement is manifested among the residences when similar weather conditions and ambient lead concentrations are observed.

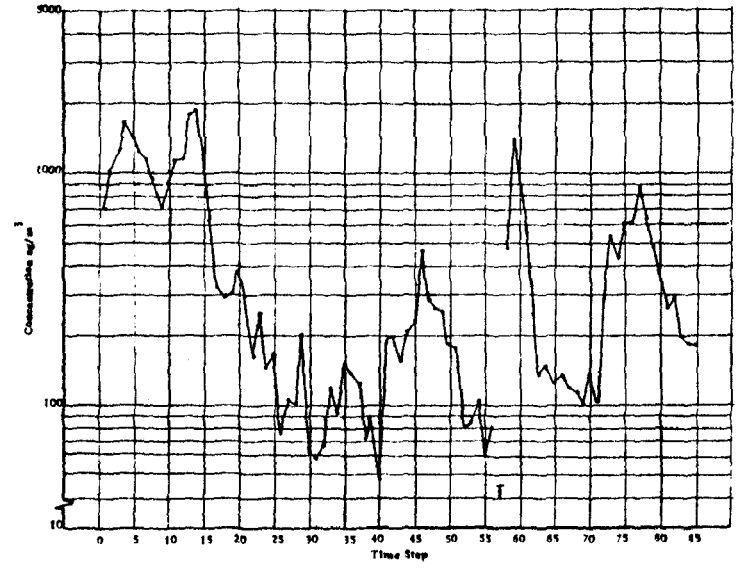
Potassium is associated with organic materials. Indoor sources include cooking, smoking, emissions from wood, and general human activity. It is not considered hazardous to residential occupants, but its behavior as an indoor-generated element is of interest. Potassium fluctuations are associated with indoor activity in various indoor sites. Potassium levels increase at times of cooking and when large numbers of people are gathered for such activities as card games and parties. Concentrations of potassium fluctuate indoors independently from the corresponding outdoor variation; the variation of the indoor potassium concentrations within each residence is connected with the life style of the inhabitants. The unusual diurnal variations observed in the Baltimore experimental residence (Figure 10) show peaks early in the morning; this variation may be explained by the fact that a member of the family is a nurse who does some routine activities such as cooking and eating shortly after midnight when she returns from work. Similar but not as clearly identifiable associations between household activity and potassium concentrations have been observed in all residences.

Iron is associated with relatively large particulate size soil dust. Figure 11, illustrating the iron fluctuations in the Baltimore experimental residence, shows that Fe concentrations are lower indoors than outdoors; it also shows that optimal levels do not correspond. The overall trends within each residence are similar. This lack of indoor-outdoor correspondence is attributed to the large size of the Fe particles. It is of interest to note that the ambient Fe concentrations in the Denver residence display a three-step fluctuation similar to the one observed for Pb concentrations, but the corresponding indoor Fe concentrations do not display fluctuations that may be explained by an indoor source. The difference in the indoor fluctuations between Pb and Fe may be attributed to the size of the particulates; the larger particulate matter is heavier and therefore does not remain airborne as long as the finer Pb particles.

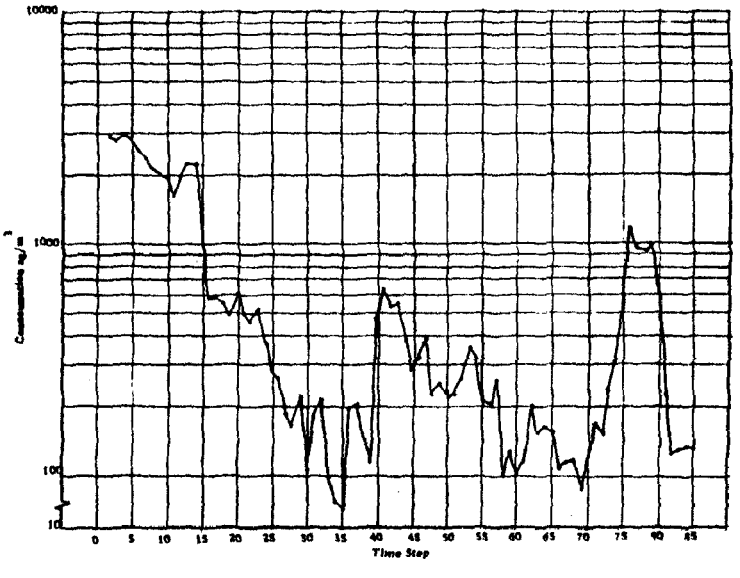
Finally, the indoor structure observed for elemental sulfur follows the trends of the outdoor behavior. Figure 12, illustrating the Baltimore conventional residence, but representative of all houses monitored, shows that outdoor levels are higher than indoor in all residences. Thus, it can be concluded that the sulfur found indoors is of outdoor origin. The Denver conventional residence and the Baltimore conventional residence have gas cooking and heating equipment: the indoor/outdoor sulfur ratio appears



(a) Outdoor

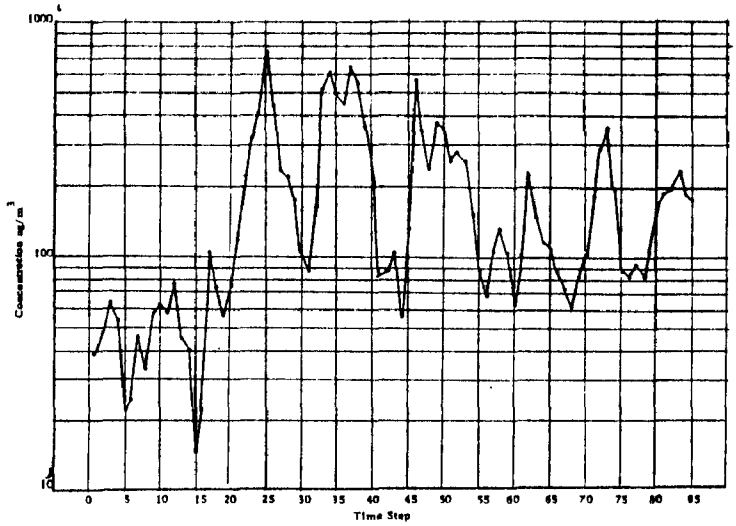


(b) Kitchen

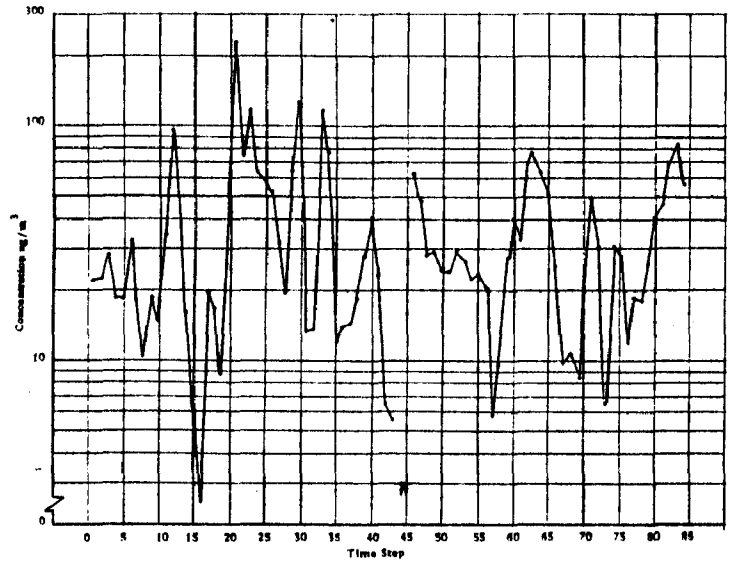


(c) Bedroom

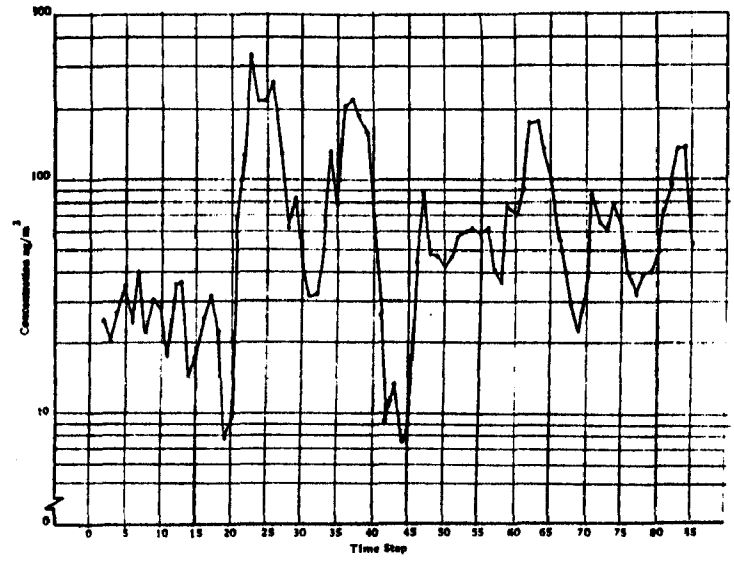
Figure 10. Time variation of potassium (K) concentrations in Baltimore experimental residence. Time represents 2-h sampling interval.



(a) Outdoor

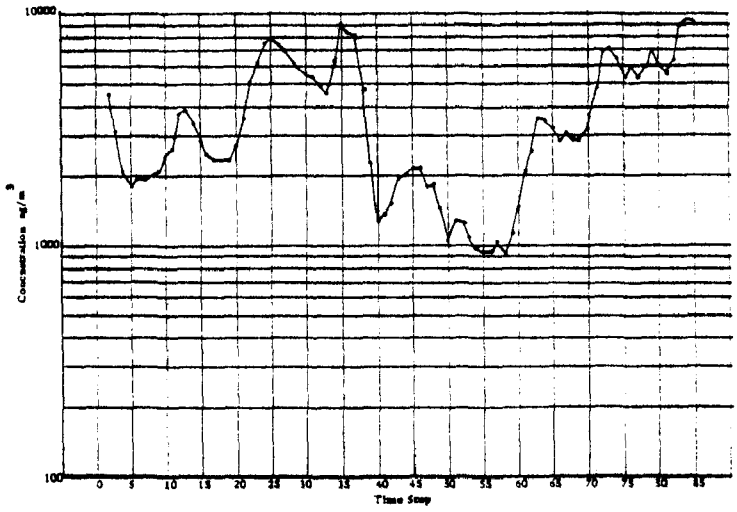


(b) Kitchen

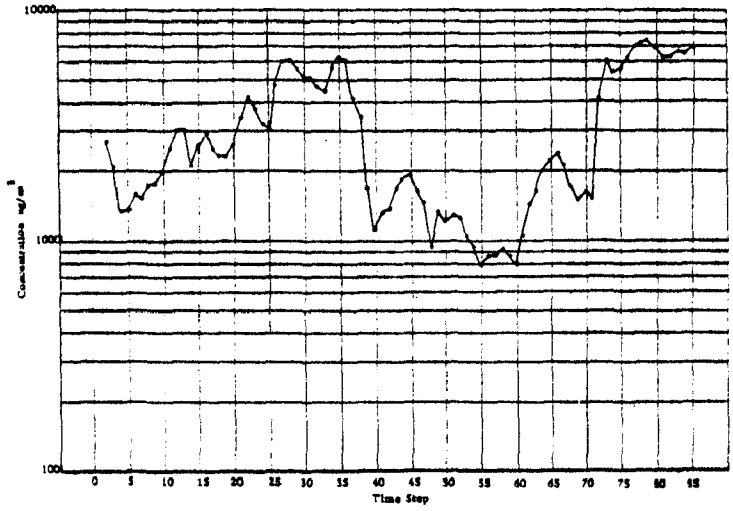


(c) Bedroom

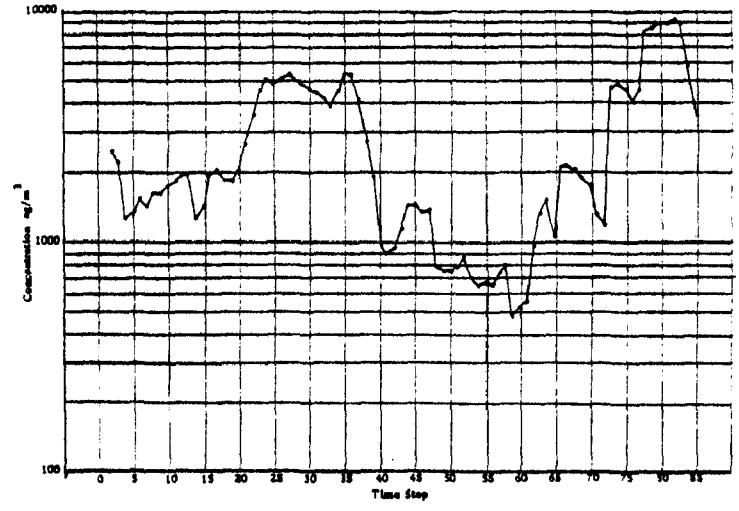
Figure 11. Time variation of iron (Fe) concentrations in Baltimore experimental residence. Time step represents 2-h sampling intervals.



(a) Outdoor



(b) Kitchen



(c) Bedroom

Figure 12. Time variation of sulfur (S) concentrations in Baltimore conventional residence. Time step represents 2-h sampling intervals.

to be higher in these two residences but it remains less than one. Similar analyses can be carried out for the remaining elements--Al, Si, Cl, Ca, Cu, and Zn--but this has not yet been done.

Episodic Pollutant Release

The objective of this series of experiments is twofold; the first objective is to continue testing the methods developed by IIT Research Institute under the direction of Dr. A. Dravnieks (1977) for collecting samples of organic contaminants; the second objective is to determine a time history of aerosol pollutants introduced into the indoor environment by an episodic release. As this is the beginning of a scientific effort in this specialized air pollution field (episodic release in indoor environments), we must not expect to totally resolve all problems; however, we will seek to answer some of the major questions.

The sources selected to simulate episodic releases were an oven spray cleaner, an aerosol anti-perspirant, and a spray furniture polish. Locations for release of these sources were the kitchen to simulate oven cleaning, the bathroom to represent morning activities, and the living room as prime area for house cleaning activities. Each of the three Pittsburgh high-rise apartments was used for a different episodic release experiment.

From the simulated releases the major contaminants found to originate in the apartments were terpenes, especially limonene; some chlorinated and Freon-related organic compounds such as dichlorobenzene; and oxygenated organic compounds including acetone and ethanol. These contaminants are associated with the episodic releases as components of the odorant, propellant, or solvent. As such they were found in measurable concentrations in the indoor samples, while in the outdoor ambient samples little or no concentrations were detected for these contaminants.

Pollutant distribution was investigated by collecting samples at designated time intervals, generally 15 min, in the location of release and one adjacent area, plus continuous 1-h samples in other locations away from the source. In general, peaks occurred in the area of the source and the adjacent locations during the second samples, 15 to 30 min after release. In other locations within the residence, the contaminants were detected but generally at concentrations slightly lower than those at or near the source locations. This indicates that pollutant distribution was accomplished throughout the entire residence.

Similar results were obtained with an episodic release of the SF_6 tracer gas. Figure 13 shows the measured SF_6 concentrations plotted against time. The source location is the living room, and the adjacent locations are the kitchen and hall. Since SF_6 is an inert gas, a requirement for a tracer, it does not react in the same manner as the components released in the other episodic experiments. For this reason peak concentrations in source and adjacent locations occur within 2 min. From this experiment, it is shown that SF_6 tracer gas reached all areas in the residence

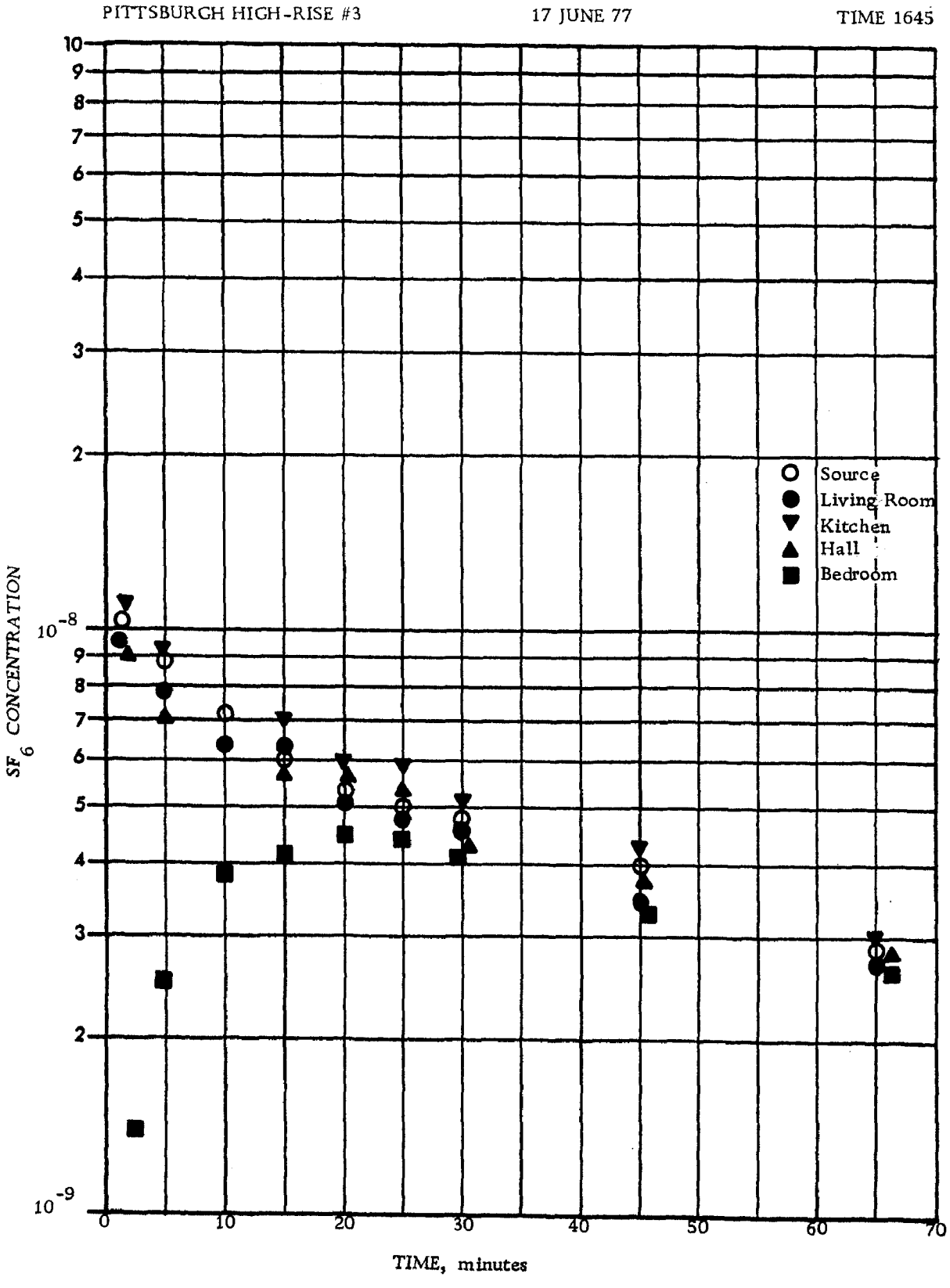


Figure 13. Episodic release of SF_6 gas.

and accomplished complete mixing in about 30 min, at which time all locations obtained approximately identical concentrations.

The other objective of this study was to test a method, developed by Dr. A. Dravnieks, for collecting samples of organic contaminants from the air without the use of air-contaminating electrical devices. The method Dr. Dravnieks developed allows for the transfer of samples to a gas-chromatographic/mass-spectrometric system for identification of contaminants. The data collected in this study substantiates Dr. Dravnieks findings that this technique is suitable for detecting organic contaminant species at parts per billion (ppb) concentration levels.

Data reports prepared by the IIT Research Institute in Chicago, Illinois, are shown in Chapter 2 (Volume II) of this final report.

Questionnaire-Activity Index

An activity scale was developed to rate household activity in each of the residences monitored. Information for the development of this scale was drawn from the family daily log. The questionnaire, answered by the head of each household, provided a record of the daily occupant activity. The original and the revised version of this questionnaire are shown as Figures 14 and 15, respectively.

A point scale, Table 21, was developed to interpret the information made available by the family daily logs. The summation of these point values for all activities denotes the daily activity index (daily totals); the mean of the daily totals is the average daily index. A typical day is identified when the observed daily index falls within a range of 4-8 points. Those days when the activity index falls within this range are considered "typical" or "routine." Days when the activity index exceeds 8 points are considered "active days," and days when the activity index falls below 4 points are considered "inactive." On a daily basis, the distribution of the activity index shows that 24% of the days observed are rated inactive, 56% typical, and 20% active.

The average daily index also enables a characterization of each family as either typical, active, or inactive with regard to their average daily activity pattern. Table 22 shows that seven of the families questioned are inactive, seven are typical, and two are active. This distribution is constrained by the integrity of the responses by the residents to the questionnaire.

This activity index is an important element in determining the mode of operation of indoor sources. The activity index and its relationship to indoor TSP levels are discussed in Section 3 with reference to the TSP steady state model.

Site I.D.: Location:
Date: Day of Week:

	Yes	No	Comments
1. Did you cook breakfast? What time?			
2. Did you cook lunch? What time?			
3. Did you cook dinner? What time?			
4. Did you have guests? What time? If yes, how many?			
5. Did you cook anything special which took more cooking time?			
6. Did you do any cleaning? If yes, what kind of cleaning material did you use?			
7. Did you use any air freshener? If yes, what kind (brand)?			
8. Did you use any aerosols? If yes, what kind (brand)?			
9. Did you open the windows? If yes, between what hours?			
10. Did you vacuum? If yes, what time?			
11. Did you turn on the range hood fan while cooking?			
12. Was there any period of time that nobody was home; what hours?			
13. Did you use the bathroom exhaust fan? If yes, how many times?			
14. Did you do the laundry today?			
15. Did you use the clothes dryer? If yes, how long did you run the dryer?			
16. Did you, family, or guest smoke? What was smoked and how many? During what period?			
17. Did you use a fireplace? What kind and for what period?			
18. Other activities that were unusual.			

Figure 14. Daily activity record.

DAILY ACTIVITY RECORD

Daily activity record of the_____residence for the day of_____.

1. Did you cook breakfast? Yes( ) No( )
   What did you cook? _____
   What time did you start?_____How long did you cook?_____

2. Did you cook lunch? Yes( ) No( )
   What did you cook? _____
   What time did you start?_____How long did you cook?_____

3. Did you cook dinner? Yes( ) No( )
   What did you cook?_____
   What time did you start?_____How long did you cook?_____

4. Did you cook or bake anthing other than regular meals? Yes( ) No( )
   What did you cook or bake?_____
   What time did you start?_____How long did you cook?_____

5. Did you turn on the range hood fan while cooking? Yes( ) No( )
   What time did you turn it on?_____off?_____

6. Did you wash dishes today? Yes( ) No( )
   At what times?_____For how long?_____

7. Did you have any guests today? Yes( ) No( )
   How many guests did you have? _____
   What time did they arrive? _____Leave?_____

8. Was there any period of time that nobody was home? Yes( ) No( )
   What time? From_____to_____

9. Did you, your family or any of your guests smoke? Yes( ) No( )
   What was smoked? cigarettes ( ) cigar ( ) pipe ( )
   How many or how often? _____ What times? _____ _____ _____
   In what rooms? _____ _____ _____ _____ _____

10. Did you do any cleaning today? Yes( ) No( )
    What rooms did you clean?_____
    What time did you start? _____Stop_____
    Was cleaning continuous? ( ) Intermittent? ( )
    List cleaning materials used _____

11. Did you vacuum clean today? Yes( ) No( )
    At what time did you start? _____Stop?_____
    Was vacuuming continuous? ( ) Intermittent? ( )
    What rooms did you clean? _____

12. Did you do the laundry today? Yes( ) No( )
    What time did you start? _____Stop?_____
    How many loads did you do? _____

13. Did you use the clothes dryer? Yes( ) No( )
    What time did you start? _____Stop?_____
    Did the dryer run continuous? Yes( ) No( )

14. Did you use any air freshener today? Yes( ) No( )
    At what time?_____What brand did you use?_____
    In what room did you use it?_____

15. Did you use any aerosols today? Yes( ) No( )
    At what time?_____What brand did you use?_____
    In what room did you use it?_____

16. Did you open any windows today? Yes( ) No( )
    At what time were they opened?_____Closed?_____
    In what rooms were they opened?_____

17. Did you use a fireplace? Yes( ) No( )
    What time did you use it? Start_____Stop_____

18. Please list any additional activities that may have taken place in the house that have not been listed. This would include activities related to hobbies, repairs, painting, etc. A short description of the activity, any materials used if any, room in which the activity had taken place, and time of starting and ending should be included. If there are any questions on what should be included please ask the PEDCo personnel for assistance.

_____
_____
_____
_____

Activity record completed by_____Date_____
Activity record checked by_____Date_____

Figure 15. Revised version of daily activity record.

TABLE 21. ACTIVITY POINT SCALE

Preparation of Meals	1 pt. per meal
Use of Bathroom Exhaust	-1 pt.
Use of Range Hood Fan	-1 pt.
Additional People in Dwelling	1-3 people = 1 pt. 4-6 people = 2 pts. 7-9 people = 3 pts. 10+ people = 4 pts.
Housecleaning Activity	1 pt.
Use of Cleaning Agents	1 pt. per agent
Use of Aerosols/Air Fresheners	1 pt. per agent
Open Windows	1 pt.
Vacuuming	1 pt/30 min
Doing Laundry	1 pt. per load
Use of Clothes Dryer	1 pt. per 30 min
Cigarette Smoking	1 pt. for 1st pack 2 pts. for over 1 pack
Empty House	-1 pt. for time over 2 h -11 pts. for days when house is empty 72 h
Special Activities	1 pt. per activity
GEOMET Test	1 pt.

TABLE 22. CHARACTERIZATION OF FAMILY TYPE

Residence	Average Daily Rating	Category
Denver Conventional	3.4	Inactive
Baltimore Experimental II	3.4	
Pittsburgh High-Rise Apt. 1	3.5	
Baltimore Conventional I	3.5	
Pittsburgh High-Rise Apt. 2	3.6	
Pittsburgh Low-Rise Apt. 1	3.7	
Pittsburgh Mobile 1	3.8	
Pittsburgh Mobile 2	4.7	Typical
Baltimore Experimental I	5.0	
Baltimore Conventional II	5.1	
Washington Conventional I	5.2	
Chicago Experimental I	5.6	
Pittsburgh High-Rise Apt. 3	6.6	
Pittsburgh Low-Rise Apt. 3	6.8	
Pittsburgh Low-Rise Apt. 2	8.9	Active
Washington Experimental I	9.5	

SF_6 Tracer Gas Experiments

Air infiltration in residences is an important factor in energy consumption as related to the comfort control of the indoor environment. Indoor air quality characteristics are related to the rates of air infiltration by the introduction of outdoor air pollutants and the distribution of indoor-generated pollutants. The investigation of residential energy consumption and indoor-outdoor air quality relationships are discussed in other sections of this report. An important element of these investigations is the determination of a structure's representative air exchange rate. The purpose of the tracer studies is to experimentally measure the rates of air exchanges and their associated dependencies in other factors. The primary objectives of these experiments are as follows:

- Experimental determination of each structure's air exchange rate under normal real-life conditions
- Investigation of parameters affecting air exchange rates such as meteorological conditions, human activity patterns, and structural and mechanical parameters
- Investigation of pollutant distribution potential.

This section discusses the experimental design used in the tracer studies and the results and conclusions derived from over 60 such experiments.

To determine a representative air exchange rate for each residence, sulfur hexafluoride (SF_6) was used as a tracer gas. The tracer was released in the residence and monitored throughout the structure. The decrease rate of the SF_6 concentrations is a measure of the air exchange rate. To monitor the distribution and flow of the SF_6 tracer gas, two sampling techniques were employed.

One procedure collected samples through a network monitoring system. Sample probes were located in three major indoor activity areas. These areas were generally selected as the living room, kitchen, and master bedroom. Samples were drawn through teflon lines at recorded time intervals into the mobile laboratory adjacent to the structure under investigation. Concentrations were determined by electron capture gas chromatography.

A second technique developed to estimate air exchange rates with SF_6 tracer gas investigated all individual areas within each structure. Researchers obtained 30 cm^3 disposable plastic syringes with the needle cap cut and sealed to make the instrument air tight. Samples were collected by hand at recorded time intervals with numbered syringes in designated areas of the residence. In general these areas were rooms, halls, stairwells, and foyers. Syringe samples and coded forms were sent to the California Institute of Technology (Caltech) for analysis of SF_6 concentrations.

The Caltech facility consists of 16 electron capture gas chromatographs (constructed in-house), the output signals of which are processed through two digital integrators (Spectra Physics-System I Integration). A stainless steel coaxial electron capture detector, electronically insulated with Teflon and Nylon plugs, is pulsed periodically with a -25 V, 1- μs pulse every 200 μs. The radioactive source used is a 200 mCi H^3 source bonded to a titanium substrate (U.S. Radium Corp., Parsippany, New Jersey). Analysis for SF_6 was achieved using a stainless steel column (39" x 0.25" o.d., 0.18" i.d.) packed with 5A 80-100 mesh molecular sieve (Alltech Assoc., Arlington Heights, Illinois). The columns were conditioned at 300 °C overnight with N_2 flowing continuously. Using prepurified N_2 at 60 cm^3/min as the carrier gas, SF_6 was eluted in 18 s and O_2 in 45 s. A typical calibration curve is shown in Figure 16. Note that the linear range is from 10^{-8} to 10^{-12}; at 10^{-12} the signal-to-noise ratio is still better than 3 to 1.

Three categories of physical data were monitored in the course of the SF_6 tracer experiments. The first data set consists of the physical characteristics unique to each structure. This data set contains information on the type and quality of each structure and its building components, along with their physical dimensions. Table 23 summarizes the portion of this data set relevant to the infiltration studies.

The second data set consists of the meteorological parameters monitored during the tracer studies. The average indoor/outdoor temperature and relative humidity differences, along with average wind speed and direction, are also shown in Table 23.

A third category of data contains information obtained from daily family activity logs. These logs were investigated to determine the impact of occupant activity on the air exchange rate for each residence. Information obtained from this data consisted of the number, duration, and approximate size of window and door openings.

To determine the total air exchange rate of each different structure the tracer dilution technique was employed. An instantaneous release of a known quantity of SF_6 tracer gas was injected into the forced air ventilation system just ahead of the blower fan. The blower fan was initially turned on for 20 min to insure a uniform distribution throughout the structure. Dilution of the tracer concentration occurs with the introduction of infiltrated air. The decay in the tracer concentrations was found to be exponential as shown by the following equation:

$$C = C_o e^{-\nu t}$$

where: C = tracer concentration at time t

C_o = tracer concentration at time $t = o$

t = time in hours

ν = air changes per hour.

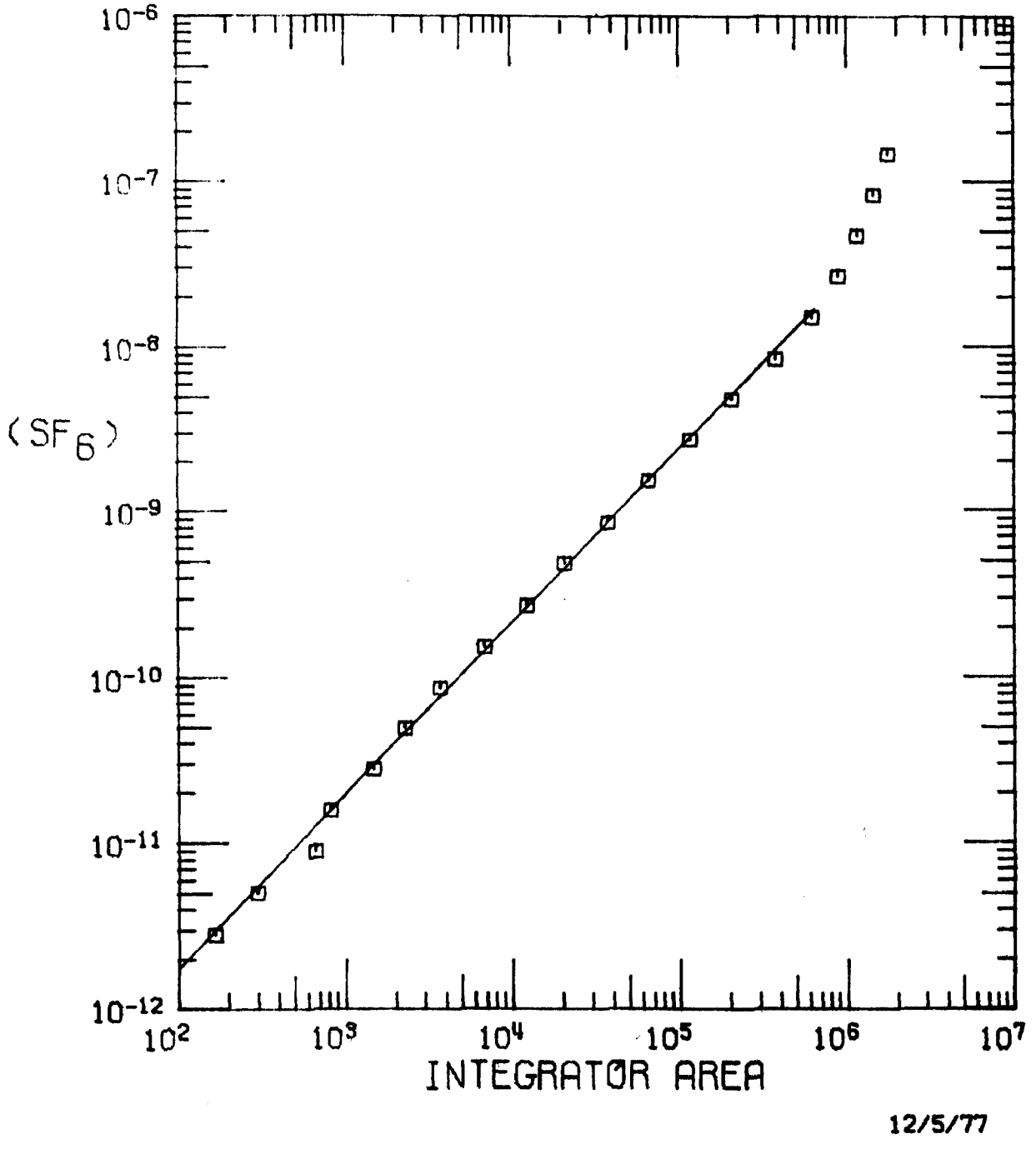


Figure 16. Typical calibration curve for SF_6.

TABLE 23. PHYSICAL AND METEOROLOGICAL PARAMETERS

Residence	Physical			Meteorological			
	Structural Type	Volume (ft^3)	Date	Average ΔT (F^o)	Average WS (mph)	Wind Sectors	Average ΔRH (%) Range
Washington Conventional	Detached	21,585	July, 1976	0 - 14	1 - 2	SW, NE	10 - 21
			January, 1978	37 - 42	3 - 6	NW - E	8 - 66
Washington Experimental	Detached	19,880	August, 1976	4 - 5	2 - 5	N	3
			December, 1977	22 - 35	3 - 10	E - SW	47 - 53
Baltimore Experimental	Semidetached	11,650	August, 1976	0 - 11	3 - 5	E - S	5 - 10
			January, 1977	47 - 57	2 - 17	SSE, NW	15 - 37
Baltimore Conventional	Semidetached	13,575	September, 1976	2 - 3	3 - 5	NW - N	10 - 18
			January, 1977	42 - 55	5 - 20	S - NW	24 - 31
Denver Conventional	Detached	20,100	October, 1976	0 - 16	1 - 5	NE, S	9
Chicago Conventional	Detached	18,170	November, 1976	52 - 62	N/A	N/A	1 - 23
			August, 1977	3 - 4	1 - 5	S - W	3 - 21
Chicago Experimental	Detached	26,330	December, 1976	33 - 39	0 - 8	SE - N	9 - 33
			July, 1977	5 - 8	5 - 16	NW - NE	5 - 7
Pittsburgh Mobile 1	Mobile	6,380	February, 1977	35 - 55	5 - 12	S - N	5 - 15
Pittsburgh Mobile 2	Mobile	6,850	March, 1977	9 - 36	2 - 12	S - W	10 - 26
Pittsburgh Low-Rise 1	Low-Rise Apt.	6,460	March, 1977	1 - 30	6 - 22	SW - NW	3 - 31
Pittsburgh Low-Rise 2	Low-Rise Apt.	6,460	April, 1977	7 - 30	10 - 19	W - N	3 - 23
Pittsburgh Low-Rise 3	Low-Rise Apt.	6,460	May, 1977	10 - 20	8 - 11	W	20 - 40
Pittsburgh High-Rise 1	High-Rise Apt.	7,240	May, 1977	2 - 12	5 - 11	NW - NE	12 - 17
Pittsburgh High-Rise 2	High-Rise Apt.	7,240	June, 1977	5 - 21	7 - 13	W - NE	20 - 53
Pittsburgh High-Rise 3	High-Rise Apt.	7,240	June, 1977	1 - 9	5 - 19	S - NW	5 - 10

The building air exchange rate is obtained from the slope of a semilog plot of the natural logarithm of the tracer concentrations versus time; the calculated air exchange rate is a comprehensive one, it includes infiltration rate, mechanical ventilation rate and recirculation rate. Figure 17 shows a typical tracer curve from which the air exchange rate is estimated. The experimentally determined ranges of air exchange rates are shown for each residence in Table 24.

Additionally, diluted SF_6 gas was released continuously for periods of 3 to 4 h. A known concentration of the tracer is emitted at a constant rate and monitored as it disperses throughout the residence. The objective of this release is to experimentally determine the time required for a pollutant generated by a single source, often in the kitchen, to disperse in the residence, and to reach a constant level as illustrated in Figure 18.

The determination of a structure's air exchange rate requires that the indoor and outdoor tracer concentrations are zero. This was verified by collecting samples both indoors and outdoors before the tracer was released.

The findings reported in this discussion are based on data obtained from tracer experiments performed in inhabited residences under real-life conditions. During these conditions the measurable parameters are in a constant state of flux and what appears to be a predominant factor in one experiment has minimal effects during another. For this reason the effect on the structure's air exchange rate directly attributable to any one particular parameter is difficult to quantify. However, certain relationships became apparent and are presented in the following discussion.

Differences between indoor and outdoor temperatures have been considered as one of the major causes for air infiltration in structures. From the investigation of average indoor/outdoor temperature differentials for structures less than three stories in height, a definite relationship with the rates of air exchange was observed. Figure 19 is a graph of average temperature differentials plotted against measured air exchange rates. As differences between indoor and outdoor temperatures increase, there is a corresponding increase in the air exchange rates. This relationship is represented by the following equation:

$$\nu = 0.235 + 0.013\ \Delta T\ .$$

This relationship can also be seen in Table 25 where variations in air exchange rates associated with seasonal changes are shown. One can conclude that during the colder winter months, when indoor/outdoor temperature differences are relatively high, there is a corresponding increase in infiltration rates within a particular structure. In comparison, low temperature differentials during summer seasons are associated with lower air exchange rates.

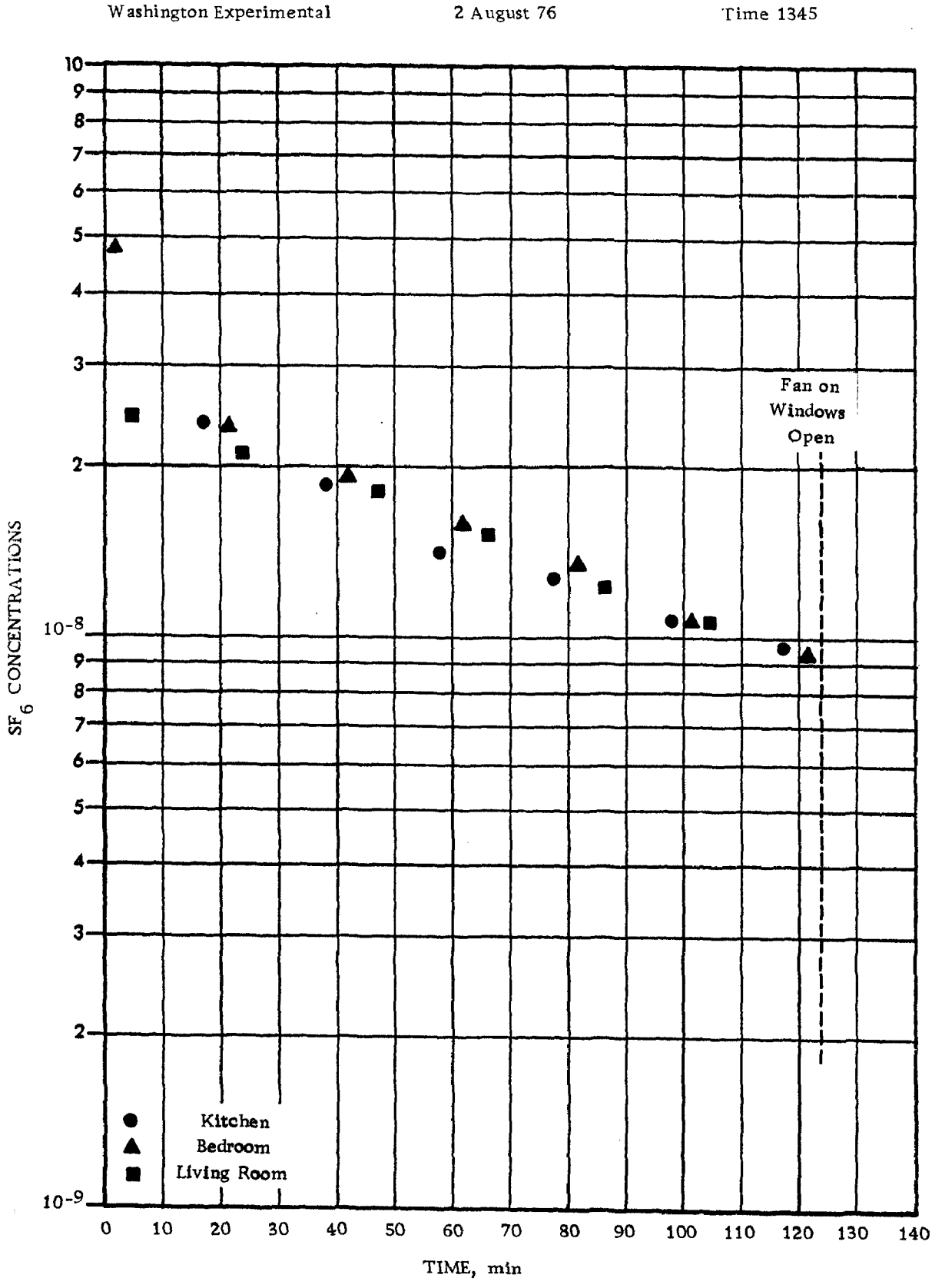


Figure 17. Instantaneous release.

TABLE 24. EXPERIMENTALLY DETERMINED AIR EXCHANGE RATES

Residence	Air Changes Per Hour
Washington Experimental (s)*	0.6
Washington Experimental (w)	0.5-1.0
Washington Conventional (s)	0.6-0.8
Washington Conventional (w)	0.2-0.4
Baltimore Experimental (s)	0.5-0.7
Baltimore Experimental (w)	0.8-1.2
Baltimore Conventional (s)	0.6-0.8
Baltimore Conventional (w)	0.9-2.0
Denver Conventional	0.8-1.0
Chicago Conventional (s)	0.6-0.8
Chicago Conventional (w)	0.8-1.0
Chicago Experimental (s)	0.1
Chicago Experimental (w)	0.2-0.3
Pittsburgh Mobile 1	0.4-1.0
Pittsburgh Mobile 2	0.3-1.1
Pittsburgh Low-Rise 1	0.3-0.8
Pittsburgh Low-Rise 2	0.7-1.4
Pittsburgh Low-Rise 3	1.6-1.7
Pittsburgh High-Rise 1	0.9-1.4
Pittsburgh High-Rise 2	0.9-1.4
Pittsburgh High-Rise 3	0.9-1.2

* (s) = summer
(w) = winter

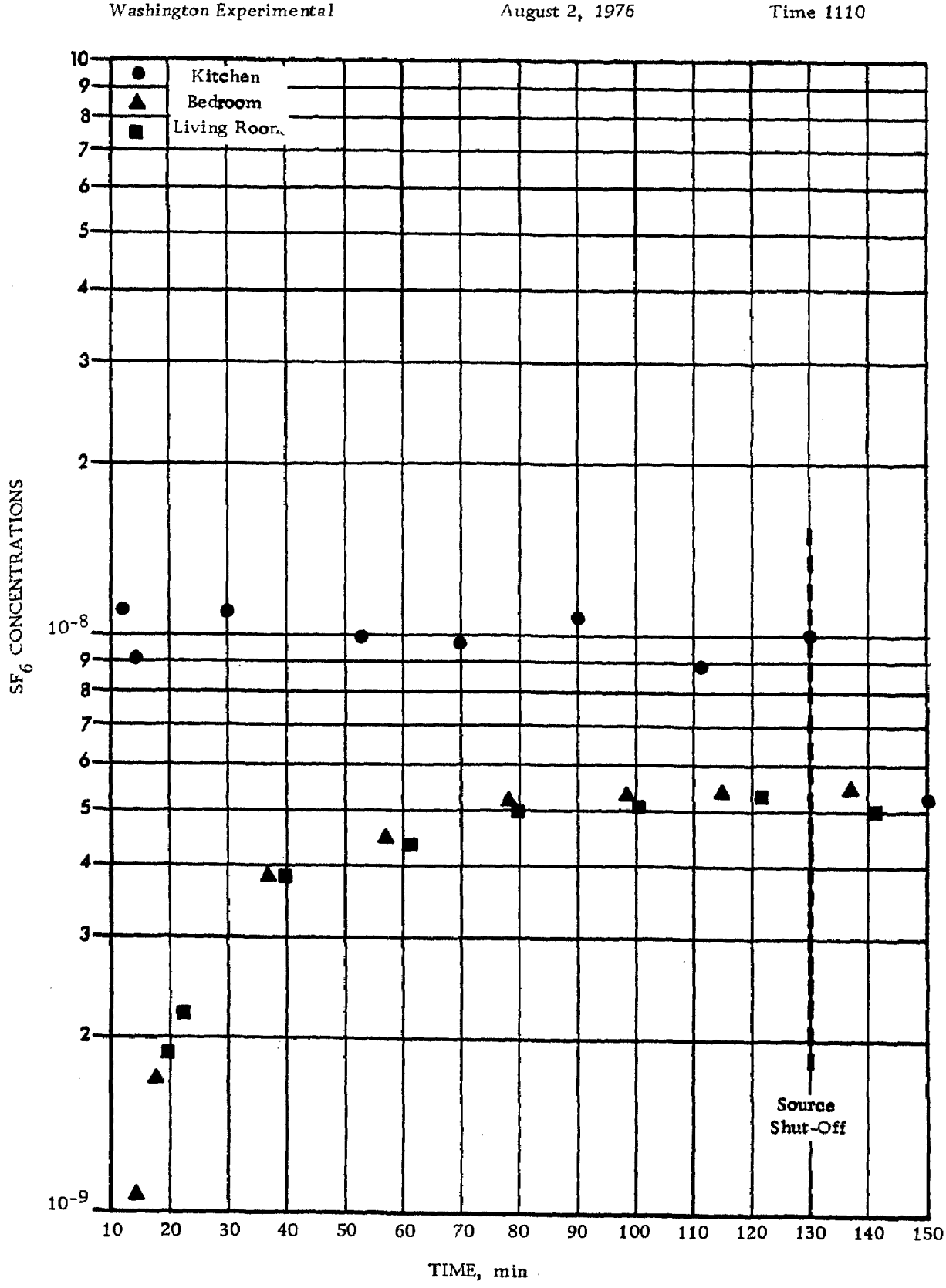


Figure 18. Continuous release.

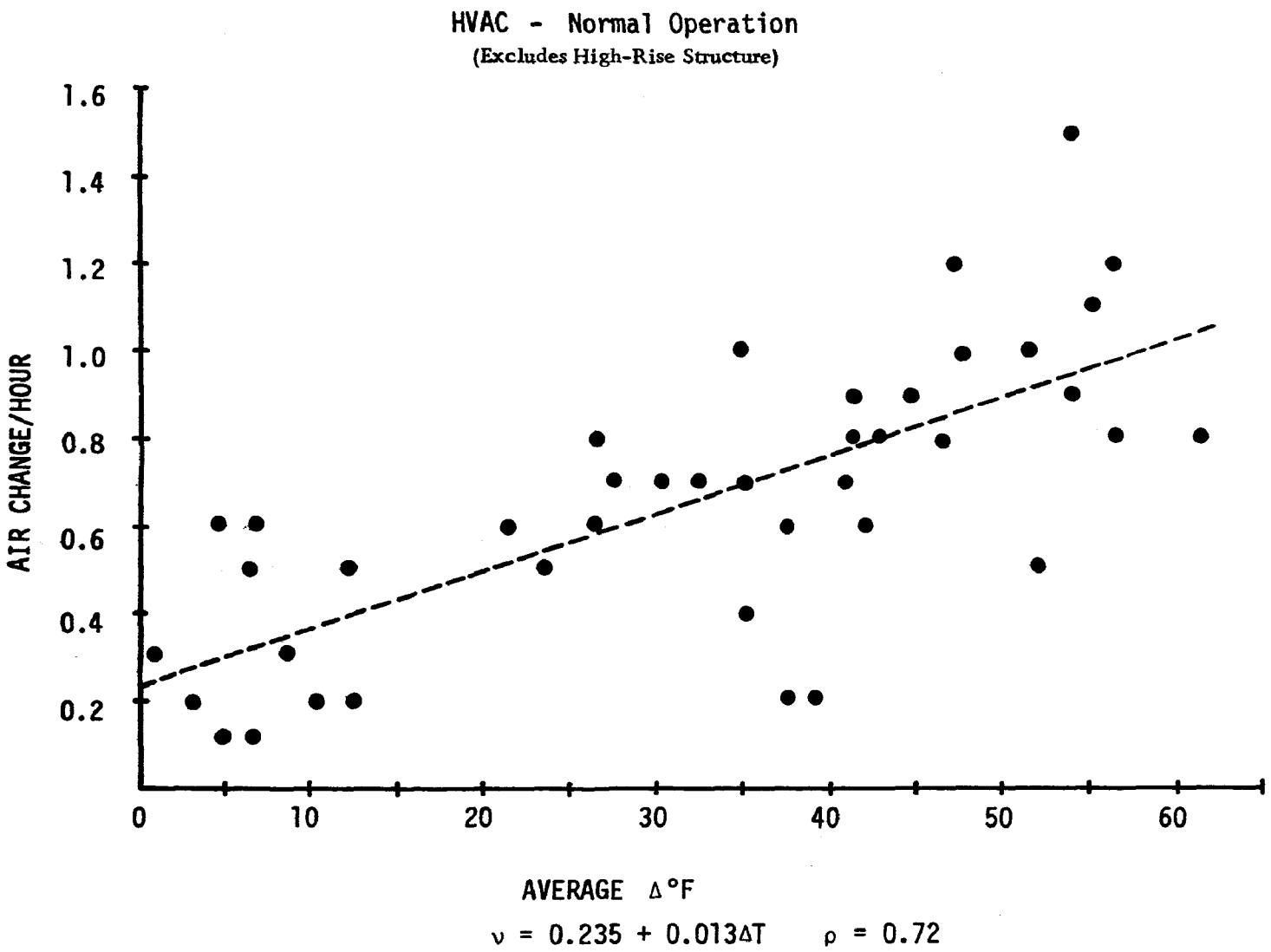


Figure 19. Effect of temperature on infiltration.

TABLE 25. SEASONAL VARIATION IN AIR EXCHANGE RATES

Residence	Air Changes Per Hour	
	Summer	Winter
Washington Experimental	0.6	0.5-1.0
Washington Conventional	0.2-0.4	0.6-0.8
Baltimore Experimental	0.5-0.7	0.8-1.2
Baltimore Conventional	0.6-0.8	0.9-2.0
Chicago Experimental	0.1	0.2-0.3
Chicago Conventional	0.6-0.8	0.8-1.0

A parameter that exerts an effect on the air exchange rate of a structure is the forced infiltration associated with the operation of the heating, ventilating, and air conditioning (HVAC) system. To show the relative effect of HVAC operation, several tracer experiments were performed with the air blower recirculation fan in a continuous operating mode and in a normal mode as determined by the thermostat setting. Figure 20 shows a tracer experiment where the blower fan was turned on to continuous operation after several hours of normal HVAC operation. The forced circulation of indoor air increases the infiltration of outdoor and a corresponding increase in the number of air changes per hour is measured. Table 26 shows a similar relationship for the experiments performed in other residences.

TABLE 26. EFFECT OF HVAC OPERATION

Residence	Air Changes Per Hour	
	Normal HVAC Operation	Continuous HVAC Operation
Washington Conventional	0.2-0.3	0.4
Baltimore Experimental	0.5-0.6	0.7
Chicago Experimental	0.2	0.3
Pittsburgh Mobile 2	0.3-0.5	0.8-1.1
Pittsburgh High-Rise 1	0.8	1.1-1.3
Pittsburgh High-Rise 2	0.9-1.1	1.1-1.4
Pittsburgh High-Rise 3	0.9-1.0	1.2

PITTSBURGH MOBILE 2 MARCH 10, 1977 TIME 1200

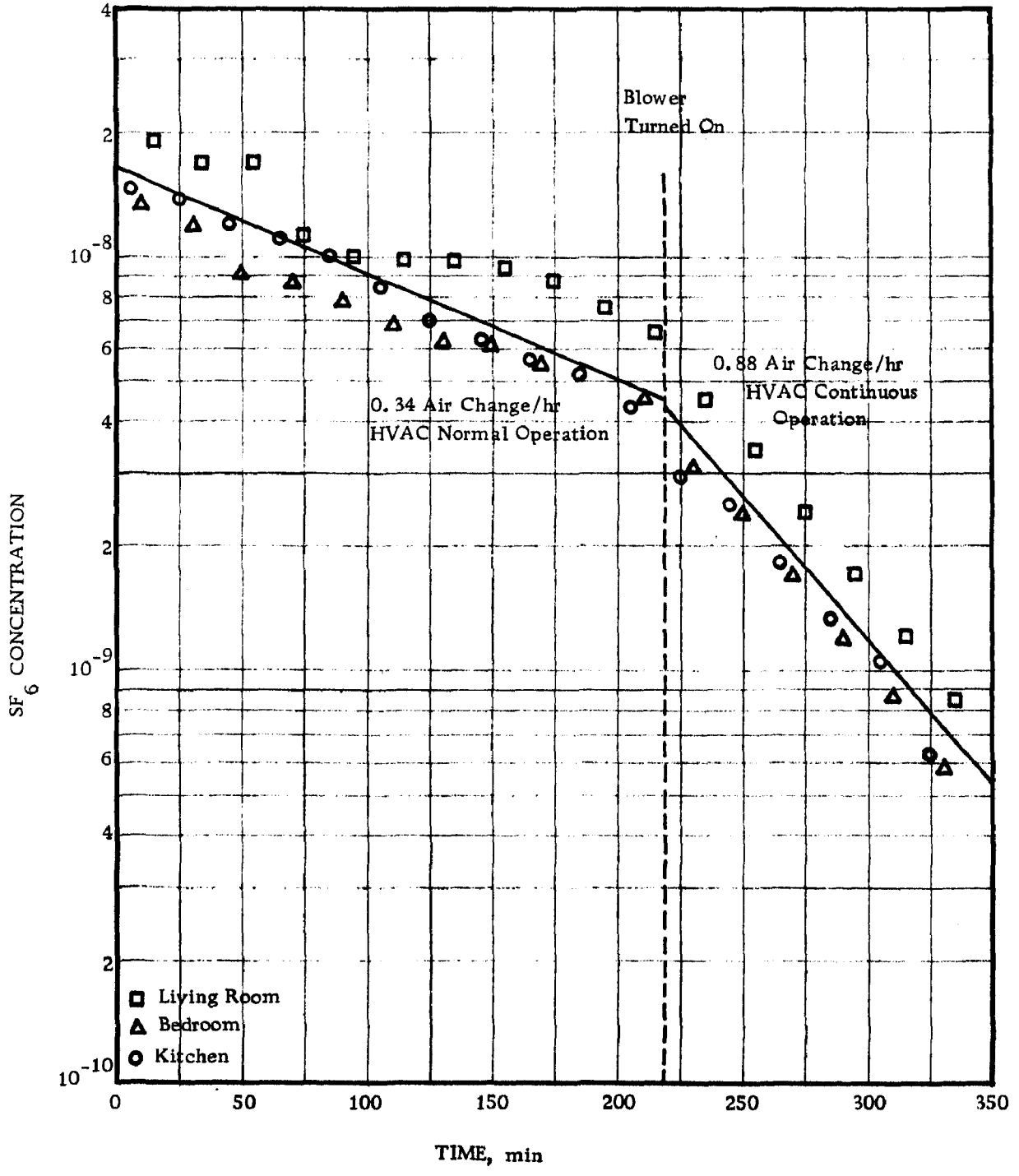


Figure 20. Effect of HVAC operation on residential air exchange rates.

Notice that the HVAC operating mode has a greater effect on the air exchange rates of the mobile home and apartments than on the single family structure. The volume of air in the mobile home and apartments is smaller than single family dwellings. Thus, under forced circulation the infiltration of outside air has less conditioned inside air to mix with. This creates an increased dilution rate of the tracer concentration and higher air exchange rates are evident.

During periods of SF_6 tracer experiments the occupants' activities, such as door and window openings, were recorded. The effect of human activity was difficult to quantify with respect to measured air exchange rates. However, there is evidence, as shown in Figure 21, that the occupants' activity has a noticeable effect and can be verified by data from the tracer studies. This figure shows a continuous release tracer experiment performed on a semidetached residence. During this experiment, two door openings occurred within the residence at different locations. Investigation of this illustration shows that the tracer concentrations reached an equilibrium level in about 60 min. The first door opening, shortly after equilibrium was obtained, occurred in the basement and remained open throughout the test. The opening disrupted the equilibrium and concentrations began to fluctuate for approximately an hour before equilibrium was again obtained. Next, a door was opened in the living room, this time for only a short duration, and again the equilibrium was upset. The experiment was ended before a new equilibrium was reached. This example shows the effect that occupant activity can have on the air flow patterns within a residence.

An attempt to investigate the effects of wind velocity and direction on air exchange rates proved to be a difficult task. In several instances these parameters displayed suggested relationships, but in an equal number of cases no relationships were shown. The short duration of the experiment (3-5 h) may be one reason why significant relationships could not be investigated. Additionally, the obstacles and barriers surrounding each structure varied greatly from site to site. This variation made representative comparisons impossible.

The results of these tracer studies show that the air exchange rates of residential structures are affected by many different parameters. When experimenting under real-life conditions it becomes a difficult task to separate the effects among these parameters. This discussion has attempted to quantify several of the most important factors.

In conclusion, it is observed that environmental factors play an important role in determining average residential air exchange rates. Of particular importance are the effects from indoor/outdoor temperature differences. This does not exclude other parameters such as wind direction and relative humidity from having some effect on air exchange rates, but these factors are not evident in this investigation.

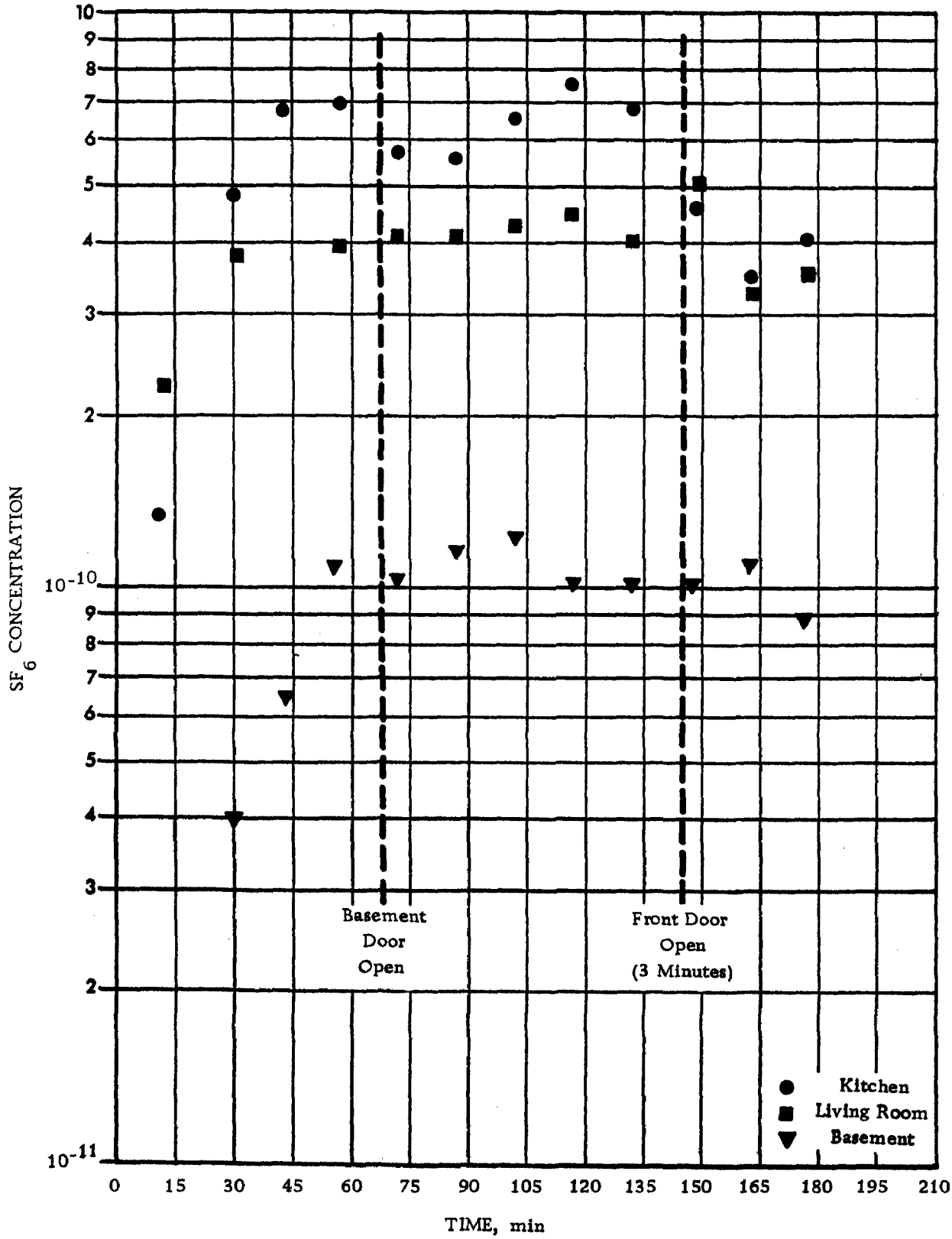


Figure 21. Effect from occupant activity.

The high-rise apartment structures react differently than low-rise or single family structures. This is particularly true for the effects of HVAC operation where the volumes of the high-rise units are low and display high air exchange rates during HVAC operation. The operation of the HVAC systems has significant effects on the air exchange rates. Studies on the impact of temperature differences in high-rise apartment units were inconclusive.

This study has shown that a broad range of air exchange rates exists for various types of residential structures. The variation in measured air exchange rates during this study ranged from 0.1 to 2.0 air changes per hour. Much of the variation was found to be dependent upon several variables, making the prediction of structure's exact air exchange rate a difficult task. However, evidence indicates that residential structures with similar characteristics have similar rates and that estimates can be made to determine a structure's "representative" seasonal air exchange rate.

SECTION 3

NUMERICAL MODELS

THE GEOMET INDOOR-OUTDOOR AIR POLLUTION (GIOAP) MODEL

Introduction

Numerical simulation is considered among the most practical tools in estimating indoor air pollutant levels as a function of the outdoor pollutant levels plus other parameters. While its potential use has been realized by many scientists in the field, its application has been rather restricted, because the indoor-outdoor numerical models require inputs not readily available to the researcher. The extensive field program of the EPA-GEOMET project on the "Indoor Air Pollution Assessment Control and Health Effects" has provided a large data base. Using this information we have formulated the GEOMET Indoor-Outdoor Air Pollution (GIOAP) model.

The objective of the GIOAP model is to predict the indoor air pollution levels by simulating a series of complex interactions involving outdoor pollutant levels, structural characteristics of the examined dwellings, and behavioral patterns of the inhabitants.

The motivation for the formulation and application of the numerical model arises from the scientific recognition that measures to conserve energy within buildings, through the introduction of new energy transfer systems and the reduction of building ventilation rates, will result in changes in the indoor air quality characteristics. These changes may affect air quality either adversely or beneficially. Simulation of a large variety of indoor conditions will quantify these effects. In addition, the validated GIOAP model can be coordinated with an epidemiological study to determine the health effects of indoor air pollution.

The approach followed in the generation of the GEOMET model is a two-step procedure: 1) mathematical formulation, and 2) model validation. Each of these steps will be discussed in detail in the balance of this section.

The impact of a validated indoor-outdoor air pollution model will be substantial in identifying the optimum scenario that meets the national policy toward energy conservation measures in residential buildings without endangering the health of the segment of the population that spends a large portion of its time in the indoor residential environment. The last subsection discusses the conclusions and impact of the GIOAP model.

General Principles

The numerical simulation model formulated by GEOMET for assessing air quality in the indoor residential environment follows the general principles of a mass balance equation. In the sense that the GIOAP model specifically addresses residential environments (detached dwellings, row buildings, mobile homes, and apartments), it is different from the general models which include terms that are not applicable in the nonworkplace environment.

Air pollution in an enclosure may be of either outdoor or indoor origin, or both. If of outdoor origin, it enters through infiltration and ventilation. If of indoor origin, it is generated from pollutant sources within the enclosure. Regardless of source, air pollutants diffuse in the enclosure. They are removed over varying periods of time by exfiltration and ventilation to the outdoors and/or through indoor decay processes.

Air infiltration is defined as the change of air within a structure without the interference of the inhabitants. Thus, the ambient air entering an enclosure through cracks in its walls is infiltrated air which, whether clean or contaminated, influences the indoor pollution levels. Ambient pollutants may also be introduced indoors through the ventilation process, which may be defined as air changes induced by the occupants of an enclosure; this can be natural ventilation through closing and opening of doors and windows, or can be forced ventilation through the operation of attic fans, air conditioning or heating systems. Air exfiltration is the opposite of air infiltration, in which indoor air leaves an enclosure through structural cracks.

Exhaust ventilation moves air from indoors to outdoors through the vents of a forced circulation system as well as through door and window openings. Pollutants are introduced into the indoor environment by means of sources such as fireplaces, stoves, smoking, and cleaning devices. Finally, pollutants may be removed from the indoor air environment through indoor decay processes such as chemical transformation, settling, and absorption and adsorption by walls and furnishings (collectively termed pollutant sinks), and by filtering procedures in the makeup air or in the recirculated air.

To characterize time-dependent aspects of pollutant behavior, it is useful to deal with rates of change of air pollution within enclosures, rather than simply with absolute amounts of pollution. Mass balance principles require that the rate of change of an air pollutant quantity within an enclosure equals the sum of the rates of all pollutant introduction and removal processes that operate upon the enclosure.

Mathematical Formulation

The GIOAP model illustrates the above general principles by specifically simulating procedures present in residential environments. The GIOAP model is based upon the following mass balance equation:

$$V \frac{dC_{in}}{dt} = V\nu C_{out} + S - V\nu C_{in} - VDC_{in} \qquad (1)$$

where

C_{in} = the indoor pollutant concentration, mass/volume

C_{out} = the outdoor pollutant concentration, mass/volume

V = the volume of the building, volume

ν = the air exchange rate of the building, air exchange/time

S = the indoor source strength rate (rate of indoor pollutant emission), mass/time

D = the decay factor, $time^{-1}$.

The term on the left-hand side of Equation (1) denotes the rate of change of the indoor pollutant mass. The first two terms on the right-hand side of the equation represent the rate by which the pollutant is introduced indoors, by infiltration of air ($V\nu C_{out}$) from outdoors, and by indoor pollutant generation due to indoor sources (S). The last two terms represent the pollutant removal rate due to exfiltration of indoor air ($V\nu C_{in}$), and due to indoor sinks, such as decay processes (VDC_{in}). The factor ν, the air exchange rate, appearing in the first and third terms of the right-hand side in Equation (1) is a total rate; it is the sum of the infiltration, exhaust, and ventilation rates.

A series of approximations are necessary before the GIOAP model can be applied to estimate the indoor air pollution levels. Over short time intervals simulated, the outdoor pollutant concentration is approximated by a straight line (an approach used by Shair and Heitner (1974)). The line is given by:

$$C_{out} = m_{out}t + b_{out} \tag{2}$$

where m_{out} is the slope, t is the time, and b_{out} is the y-intercept. It is further assumed that the parameters ν, S, and D are constant during the time interval that is being modeled.

Thus, the model equation becomes:

$$V\frac{dC_{in}}{dt} = V\nu(m_{out}t + b_{out}) - V\nu C_{in} + S - VDC_{in} \qquad t_0 \leq t \leq t_f \tag{3}$$

$$C_{in_0} \equiv C_{in}(t_0)$$

where C_{in_0} is the initial condition.

The estimations of the indoor pollutant concentrations are obtained from the solution to the initial value problem described by Equation (3). The closed-form solution to Equation (3) is given below:

$$C_{in}(t) = \left[C_{in_0} - m_{out}\left(\frac{\nu}{D+\nu}\right)t_0 - \left(\frac{1}{D+\nu}\right)\left(\nu b_{out} + \frac{S}{V} - \frac{m_{out}\nu}{D+\nu}\right)\right] e^{-(\nu+D)(t-t_0)}$$

$$+ \left(\frac{1}{D+\nu}\right)\left(\nu b_{out} + \frac{S}{V} - \frac{m_{out}\nu}{D+\nu}\right) + m_{out}\left(\frac{\nu}{D+\nu}\right)t \qquad t_0 \leq t \leq t_f \quad . \qquad (4)$$

This is the equation used for numerical simulations of indoor air pollution levels.

The subject of relating the outdoor and indoor levels is relatively recent, and research emphasis has been placed on field measurements of contaminant levels rather than the development of numerical models. Several scientists have attempted to formulate models employing relationships similar to the one expressed by Equation (3); Milly (1953), Calder (1957), Turk (1963), Hunt et al. (1971), Shair and Heitner (1974), and others have used more or less complex versions of the equation. The GIOAP model is specifically designed to simulate residential conditions. The assumptions concerning elements of the right-hand side of Equation (3) (S, ν, and D are constant over the time period being modeled, and C_{out} can be approximated by a straight line over the time period being modeled) are consistent with those made for other models. Previous studies have emphasized and simulated steady-state conditions; however, the GIOAP approach includes the transient portion of the solution to Equation (3). As a result, it is possible to model both short- and long-term intervals.

When Equation (4) is used in this study to model indoor air pollutant concentration levels, several additional assumptions are required. These assumptions are as follows:

1. The air exchange rate ν remains constant for at least one hour.

2. The internal pollutant source rate S remains constant for at least one hour.

3. The indoor pollutant removal procedure is modeled as a first-order decay term with the decay factor $D = \ln 2 / t_{\frac{1}{2}}$, where $t_{\frac{1}{2}}$ is the half-life of the pollutant considered. For stable pollutants with long half-lives D is approximated by zero. A list of the decay factors used in this study is given in Table 27.

The GIOAP model is capable of simulating any time interval, because the principles involved do not constrain this aspect. However, the time unit of the generally available ambient pollution data has led us to specify one hour as the time resolution of the model. Finally, one hour is the smallest interval that is appropriate for comparison to NAAQS.

TABLE 27. DECAY FACTORS (PER HOUR) USED IN THE GEOMET INDOOR AIR POLLUTION STUDY

Pollutant	Decay factor (per hour)
CO	0.00
SO_2	1.04
NO	0.00
NO_2	1.39
O_3	34.66
CH_4	0.00
THC	0.00
CO_2	0.00
THC-CH_4	0.00

In order to model the indoor air pollutant behavior over the time interval $[t_0, t_f]$, the interval must be decomposed into the set of subintervals

$(t_0, t_1], \ldots (t_{n-1}, t_n]$ where $t_n = t_f$, and $t_i - t_{i-1} = 1$ h. As a result, Equation (3) becomes

$$C_i = \left[C_{i-1} - m_i \left(\frac{\nu_i}{D_i+\nu_i}\right) t_{i-1} - \left(\frac{1}{D_i+\nu_i}\right)\left(\nu_i b_i + \frac{S_i}{V} - \frac{m_i \nu_i}{D_i+\nu_i}\right)\right] e^{-(\nu_i+D_i)(t_i-t_{i-1})}$$

$$+ \left(\frac{1}{D_i+\nu_i}\right)\left(\nu_i b_i + \frac{S_i}{V} - \frac{m_i \nu_i}{D_i+\nu_i}\right) + m_i \left(\frac{\nu_i}{D_i+\nu_i}\right) t_i \qquad (5)$$

where

C_i = the indoor pollutant concentration level at time t_i, $i = 1, \ldots, n$

$C_{out}(t)$ = the outdoor pollutant concentration level at time t

$m_i = [C_{out}(t_i) - C_{out}(t_{i-1})]/(t_i - t_{i-1})$, $i = 1, \ldots, n$

$b_i = C_{out}(t_i) - m_i t_i$, $i = 1, \ldots, n$

S_i = internal source rate over the interval $(t_{i-1}, t_i]$, $i = 1, \ldots, n$

ν_i = air exchange rate over the interval $(t_{i-1}, t_i]$, $i = 1, \ldots, n$

V = volume of the building

D_i = decay factor over the interval $(t_{i-1}, t_i]$, $i = 1, \ldots, n$.

MODEL VALIDATION

Introduction

The problem of estimating indoor air pollution levels involves both physical and behavioral parameters; the outdoor levels vary as a function of the local meteorology and other factors, while the indoor source strengths (indoor pollutant generation rates) and air exchange rates depend on the meteorology and the activity of the occupants. The combination of all inputs results in complex conditions which are either rarely repeated or very expensive to duplicate in the laboratory. Numerical models enable scientists to simulate these complex conditions, to stage specific incidents, and most importantly to estimate values for the indoor pollutant concentrations.

Two essential stages determine the predictive capability of the GIOAP model:

1. Initial model validity. Do the predicted concentrations reflect observed data?

2. Model sensitivity. How do the predicted concentrations change in relation to changes in input parameter values?

An intrinsic element of these two stages is the ability to demonstrate the validity of the model using "best" estimates of the input model parameters. We have formulated a parameter estimation procedure that enables us to estimate the values of indoor source strengths and air exchange rates from the raw outdoor and indoor pollutant data. Recurring modes of pollution behavior, episodes, are of extreme importance in the EPA-GEOMET indoor air pollution project. Numerically, a new episode is defined each time a new initial condition is introduced. It is our objective to associate each episode with stratified levels of indoor activity so that in the future we can estimate the indoor pollutant concentrations from outdoor pollution concentrations and indoor activity levels. The validity of these estimates will be studied in the balance of this section.

A three-step evaluation design will be followed in the assessment of the GIOAP model: we begin by estimating "best" values for input parameters, continue with statistical validation studies which include tables and input/output graphs, and conclude with a section on parameter sensitivity. This design takes advantage of the extensive data base available to this project.

Parameter Estimation Procedure

In order to estimate the indoor pollution levels using the GIOAP numerical model, all parameters associated with the model must be given numerical values. The monitoring data from the field studies of the indoor air pollution project constitutes a unique source of information for assigning numerical values to the relevant parameters. Some parameter values, such as initial indoor concentration and the volume of the structure, are easily determined; others, such as the air exchange rate ν of the building investigated and the internal pollutant generation source strength S, are more difficult to obtain.

The validity of the GIOAP model obviously depends on the values given to these difficult-to-quantify parameters. Since the model is to be validated under "best" conditions, we must obtain the best possible values for ν and S; the methodology used to obtain these values is the Parameter Estimation Procedure described in this section.

Theoretical Approach--

Recall Equation (4):

$$C_{in}(t) = \left[C_{in_0} - m_{out}\left(\frac{\nu}{D+\nu}\right)t_0 - \left(\frac{1}{D+\nu}\right)\left(\nu b_{out} + \frac{S}{V} - \frac{m_{out}\nu}{D+\nu}\right)\right] e^{-(\nu+D)(t-t_0)}$$

$$+ \left(\frac{1}{D+\nu}\right)\left(\nu b_{out} + \frac{S}{V} - \frac{m_{out}\nu}{D+\nu}\right) + m_{out}\left(\frac{\nu}{D+\nu}\right)t \qquad t_0 \le t \le t_f \ . \qquad (4)$$

Also, consider the following function of S and ν:

$$f(S,\nu) = \sum_{i=1}^{n} [C_i(S,\nu) - CM_i]^2 \qquad (6)$$

where

n = number of points

CM_i = i^{th} measured value; $i = 1, \ldots, n$

$C_i(S,\nu)$ = i^{th} computed value via Equation (4) corresponding to CM_i .

The fundamental problem in parameter estimation is to find value(s) of ν and S that minimize Equation (6). Two points must be made: 1) in the case of indoor air pollution studies, the parameters ν and S are constrained to lie within certain intervals specified by the nature of the investigated dwelling and the particular pollutant and source examined; 2) Equation (4) is not linear in ν. These two points combine to make the problem of estimating values for ν and S difficult.

A parameter estimation technique appropriate for the present problem is the grid search method. Although this process is easily constrained, it is lengthy, and its accuracy strongly depends on the number of grid points. Because $f(S,\nu)$ is a function of two variables, it is not possible to obtain the required minimum by the technique used for finding extreme values of functions of one variable taught to all students of beginning calculus. This technique is easily constrained over a given interval, but it cannot be applied to $f(S,\nu)$ because it minimizes only functions of one variable. However, the Parameter Estimation Procedure used in this study is a cross between the grid search and the optimization technique for a function of one variable. A sequence of five steps must be followed in the Parameter Estimation Procedure.

1. Define the constraints on ν and S; i.e., $\nu_l \leq \nu \leq \nu_u$ and $S_l \leq S \leq S_u$, where subscripts l and u define the lower and upper values of the parameter intervals.

2. Determine $\Delta\nu = (\nu_u - \nu_l)/k$, where k is the number of intervals.

3. For a given $\nu_i = \nu_l + (i-1)\,\Delta\nu$, $i = 1, \ldots, k+1$, find the points S_{0_i} for which

$$\left.\frac{df(S,\nu)}{dS}\right|_{(S,\nu) = (S_{0_i},\nu_i)} = 0 \quad .$$

4. Determine S_{m_i} as the value of S which gives

$$\min \{f(S_l,\nu_i),\ f(S_{0_i},\nu_i),\ f(S_u,\nu_i)\}$$

5. The required estimates of ν and S are the values that give

$$\min \{f(S_{m_i},\nu_i): i = 1, \ldots, k\}.$$

The theoretical approach used in deriving this Parameter Estimation Procedure is provided below. Owing to step 3 of the above sequence, all

equations below refer to a given fixed value of the parameter ν. Equation (4) can be rewritten as follows:

$$C = \left[\frac{1 - e^{-(\nu+D)(t-t_0)}}{V(D+\nu)}\right] S$$

$$+\left[C_0 - m\left(\frac{\nu}{D+\nu}\right) t_0 - \left(\frac{1}{D+\nu}\right)\left(\nu b - \frac{m\nu}{D+\nu}\right)\right] e^{-(\nu+D)(t-t_0)}$$

$$+ \left(\frac{1}{D+\nu}\right)\left(\nu b - \frac{m\nu}{D+\nu}\right) + m\left(\frac{\nu}{D+\nu}\right) t \qquad (7)$$

where

$C = C_{in}(t)$

$C_0 = C_{in_0}$

$m = m_{out}$

$b = b_{out}$

or as

$$C = \alpha S + \beta \qquad (8)$$

where

$$\alpha = \frac{1 - e^{-(\nu+D)(t-t_0)}}{V(D+\nu)}$$

and

$$\beta = \left[C_0 - m\left(\frac{\nu}{D+\nu}\right) t_0 - \left(\frac{1}{D+\nu}\right)\left(\nu b - \frac{m\nu}{D+\nu}\right)\right] e^{-(\nu+D)(t-t_0)}$$

$$+ \left(\frac{1}{D+\nu}\right)\left(\nu b - \frac{m\nu}{D+\nu}\right) + m\left(\frac{\nu}{D+\nu}\right) t \ .$$

From Equation (6) we have

$$f(S,\nu) = \sum_{i=1}^{n} (\alpha_i S + \beta_i - CM_i)^2 \qquad (9)$$

where

α_i is computed @ $t = t_i$ and $t_0 = t_{i-1}$

β_i is computed @ $t = t_i$ and $t_0 = t_{i-1}$ and $C_0 = CM_{i-1}$.

Equation (9) becomes

$$f(S,\nu) = S^2 \sum_{i=1}^{n} \alpha_i^2 + 2S \sum_{i=1}^{n} \alpha_i(\beta_i - CM_i) + \sum_{i=1}^{n} (\beta_i - CM_i)^2$$

$$f(S,\nu) = AS^2 + 2BS + C \qquad (10)$$

where

$$A = \sum_{i=1}^{n} \alpha_i^2$$

$$B = \sum_{i=1}^{n} \alpha_i (\beta_i - CM_i)$$

$$C = \sum_{i=1}^{n} (\beta_i - CM_i)^2 \quad .$$

Equation (10) indicates that $f(S,\nu)$ is parabolic in S. The critical point is found by taking the derivative of f with respect to S:

$$\frac{df}{dS} = 2AS + 2B \quad . \qquad (11)$$

Setting $df/dS = 0$, it is seen that $-(B/A)$ is a critical point; in order to determine whether $-(B/A)$ is a maximum or a minimum, the second derivative of f with respect to S is taken:

$$\frac{d^2f}{dS^2} = 2A \quad . \tag{12}$$

Since A is a sum of squares, $A > 0$, which means that

$$\left.\frac{d^2f}{dS^2}\right|_{S = -\frac{B}{A}} > 0$$

thus $S = -(B/A)$ minimizes $f(S,\nu)$.

Completion of the square in Equation (10) leads to the same conclusion:

$$f(S,\nu) = A\left(S + \frac{B}{A}\right)^2 + \left(C - \frac{B^2}{A}\right) \quad . \tag{13}$$

Again, since $A > 0$, the vertex $S = -(B/A)$ is the desired minimum.

The parameter S, representing the indoor pollutant generation rate, must be constrained to lie in a physically meaningful interval $[S_1, S_u]$. Thus, while $S = -(B/A)$ is an absolute minimum, $-(B/A)$ may not be within the interval $[S_1, S_u]$. Hence, in addition to computing $-(B/A)$, a test must be made to determine if $-(B/A)$ lies in the interval (i.e., if $-(B/A) \in [S_1, S_u]$); if not the end points of the interval must be examined. The three cases to be considered are illustrated in Figure 22. They are:

Case 1: $S_{m_1} < S_1$

Case 2: $S_1 \leq S_{m_2} \leq S_u$

Case 3: $S_u < S_{m_3}$.

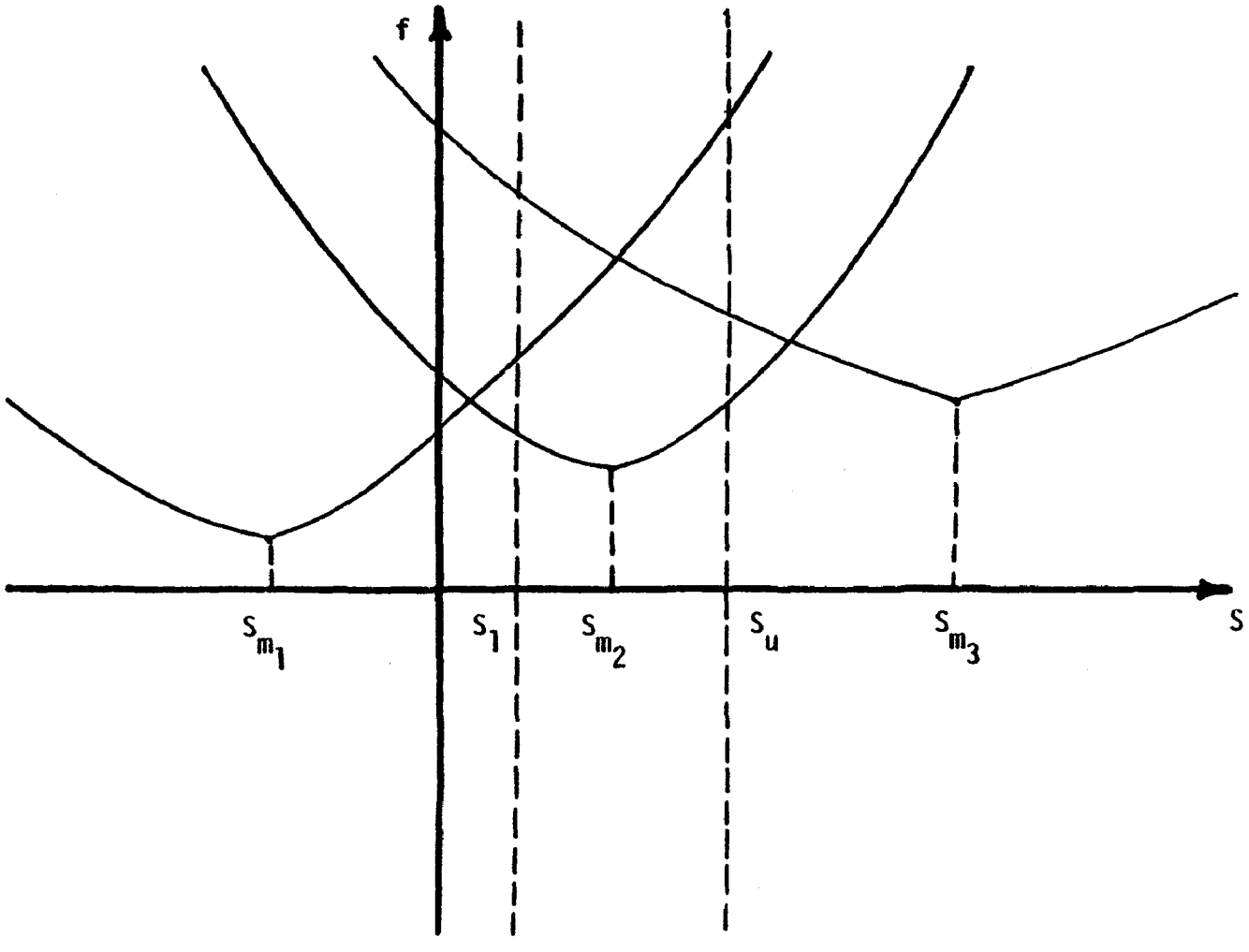


Figure 22. Graphical illustration for the three cases of constraints on interval source rate.

In Case 1, the constrained minimum occurs at S_1; in Case 2, the constrained minimum occurs at S_{m_2}; and in Case 3, the constrained minimum occurs at S_u.

Application of the Parameter Estimation Procedure to the Indoor Air Pollution Data Base--

In order to apply the Parameter Estimation Procedure to the indoor air pollution data base, the problem of degrees of freedom must be considered; i.e., the fact that the number of observations used to estimate a set of parameters must be greater than the number of parameters being estimated. Thus, as a means of increasing the amount of data available for use in the Parameter Estimation Procedure, the instantaneous outdoor values and instantaneous indoor averages for each 20-min segment of each hour were used because at this time the entire house is being modeled instead of individual zones.

Hourly values of ν and S are desired; however, there is a problem in applying the Parameter Estimation Procedure to obtain hourly estimates of ν and S. The problem involves degrees of freedom. Even though three values are available for each hour to be used in the estimation, one of these is the initial value, which means that only two values can actually be used in the estimation procedure. As a result, the number of parameters to be estimated equals the number of points to be used, which means that no degrees of freedom are left for the estimation procedure.

The problem mentioned in the previous paragraph is resolved as follows: 2-h estimates of ν are calculated from the data of a "nonreactive pollutant;" then, using these estimates of ν, hourly estimates of S are found for all pollutants. The "nonreactive" pollutant chosen was CO. If any of the 12 CO values (6 indoor and 6 outdoor over a 2-h period) are missing, ν is estimated using NO data; however, if both CO and NO data are missing for a given 2-h period, neither ν nor any of the pollutant source rates for that period are computed. Finally, if, for a given pollutant for a given hour, any values are missing, the corresponding source rate is not computed.

Essentially, we are using CO as a tracer to estimate theoretical values of air exchange rates for each of the investigated dwellings. As part of the field monitoring program of the indoor air pollution project,

the air exchange rate of each residence is determined experimentally. The tracer used for the experimental determination of the air exchange rate is SF_6; the monitoring protocol calls for three or four different 4-h experiments per residence. The theoretical and experimental values for the air exchange rate agree in most of the investigated periods, and, in those cases of disagreement, the difference between the two values is not appreciable. Table 28 shows a comparison between the estimated and experimental values for the air exchange rates.

The estimated indoor source strength value S in mg/h is an "effective" pollutant production rate; i.e., the internal source is treated as though it operates for the entire 1-h period. The estimated indoor source is also comprehensive; that is, if two indoor sources are generating a pollutant simultaneously, the calculated theoretical value will be the sum of the individual source strengths. Using the daily logs kept by the occupants of the residences we monitored, we are often able to isolate a single source; the estimated theoretical values due to isolated indoor sources compare favorably with the available literature values.

TABLE 28. AIR EXCHANGE RATES

Residence	Air exchange rates	
	Estimated	Experimental
Chicago experimental I	0.40	0.23
	0.30	0.22
	0.20	0.26
Pittsburgh low-rise apt I	0.64	0.60
	0.58	0.84
	0.60	0.63
Pittsburgh mobile home I	0.98	1.05
	0.44	0.52
Denver conventional	1.10	1.02
Washington experimental I	0.10	0.60
Washington conventional I	0.6	0.24
	0.4	0.2
	0.4	0.43
Baltimore conventional I	1.2	0.75
Baltimore experimental I	0.64	0.72

Statistical Studies

The objective of the statistical studies performed on the GIOAP model is to define its ability to estimate indoor air pollution levels. In this document we evaluate the results from a sample of eight residences; this is a comprehensive review of the predictive power of the model.

In the first section we describe the procedure followed and outline the motivation and the objectives of each step. The section on the statistical assessment includes response graphs, statistical tables, and scatter diagrams. In addition, it contains comments and conclusions on the model for each gaseous pollutant monitored. The final section provides theoretical details on sensitivity coefficients and includes a series of simulations that illustrate the errors introduced by not using the "best" estimated value for any given input parameter.

Statistical Procedure and Methodology--

The strength of a theoretical or numerical method to predict air pollution levels has often been demonstrated with graphical illustrations. This has been the case in many studies with a small data base. Figure 23 presents a sample of indoor values estimated by the GIOAP model against the observed indoor values for a number of pollutants during a 2-week monitoring period. While this randomly chosen set of illustrations indicates the predictive power of the model, it does not allow for general conclusions. In order to validate the GIOAP model, a statistical approach is required.

A statistical analysis is performed on data sets consisting of pairs of hourly estimated and observed indoor air pollutant concentrations. A statistical approach is preferred to judgments made on the basis of comparing corresponding estimated and observed indoor air pollutant concentrations for two reasons. First, the GIOAP model simulates a variety of conditions for a number of pollutants and generates a large number of data sets, each of which contains many points (over 300). Second, direct comparison of estimated and observed values involves difficult judgments in deciding when the estimated

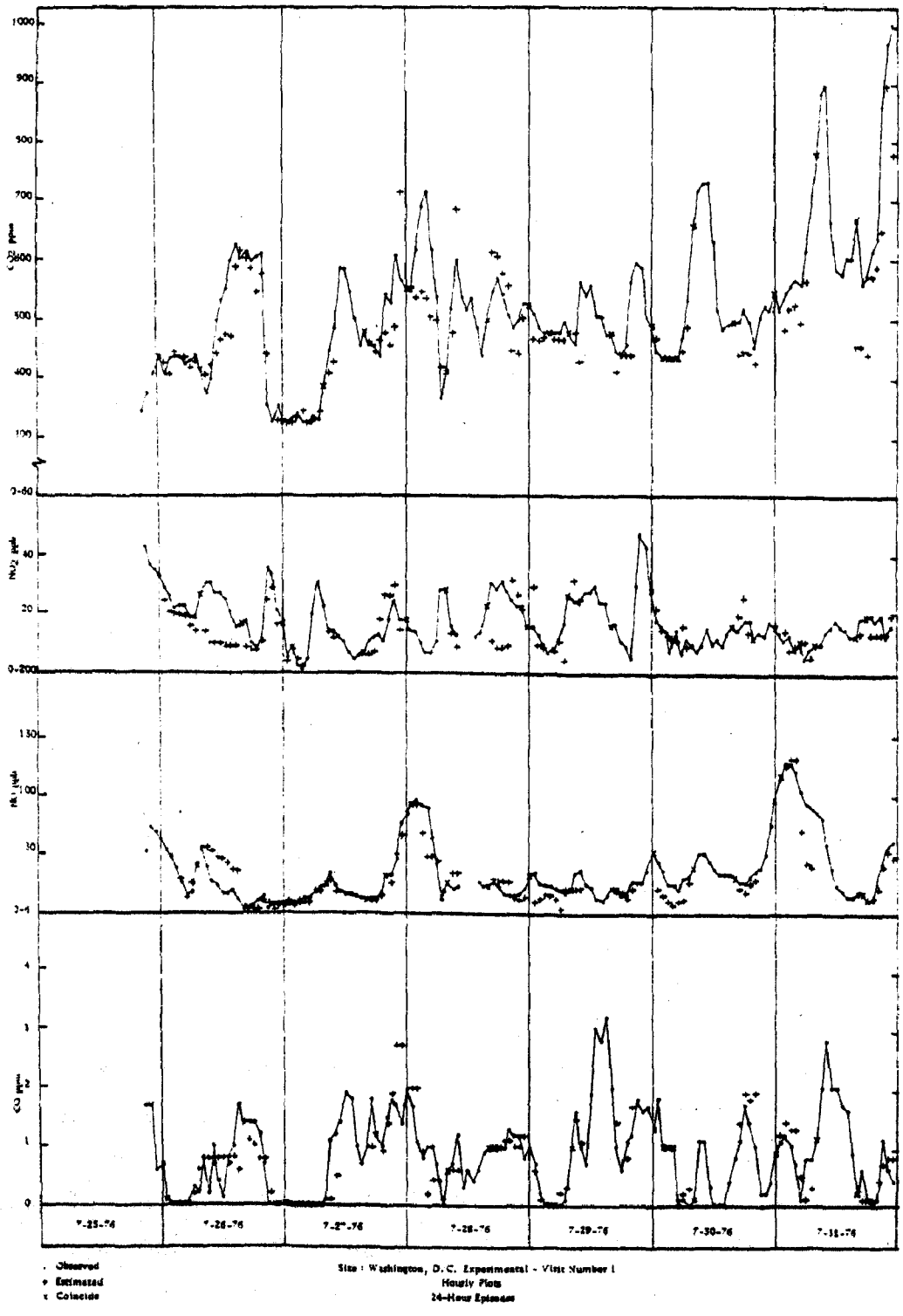


Figure 23. Estimated vs. observed pollutant concentrations for 7 consecutive days.

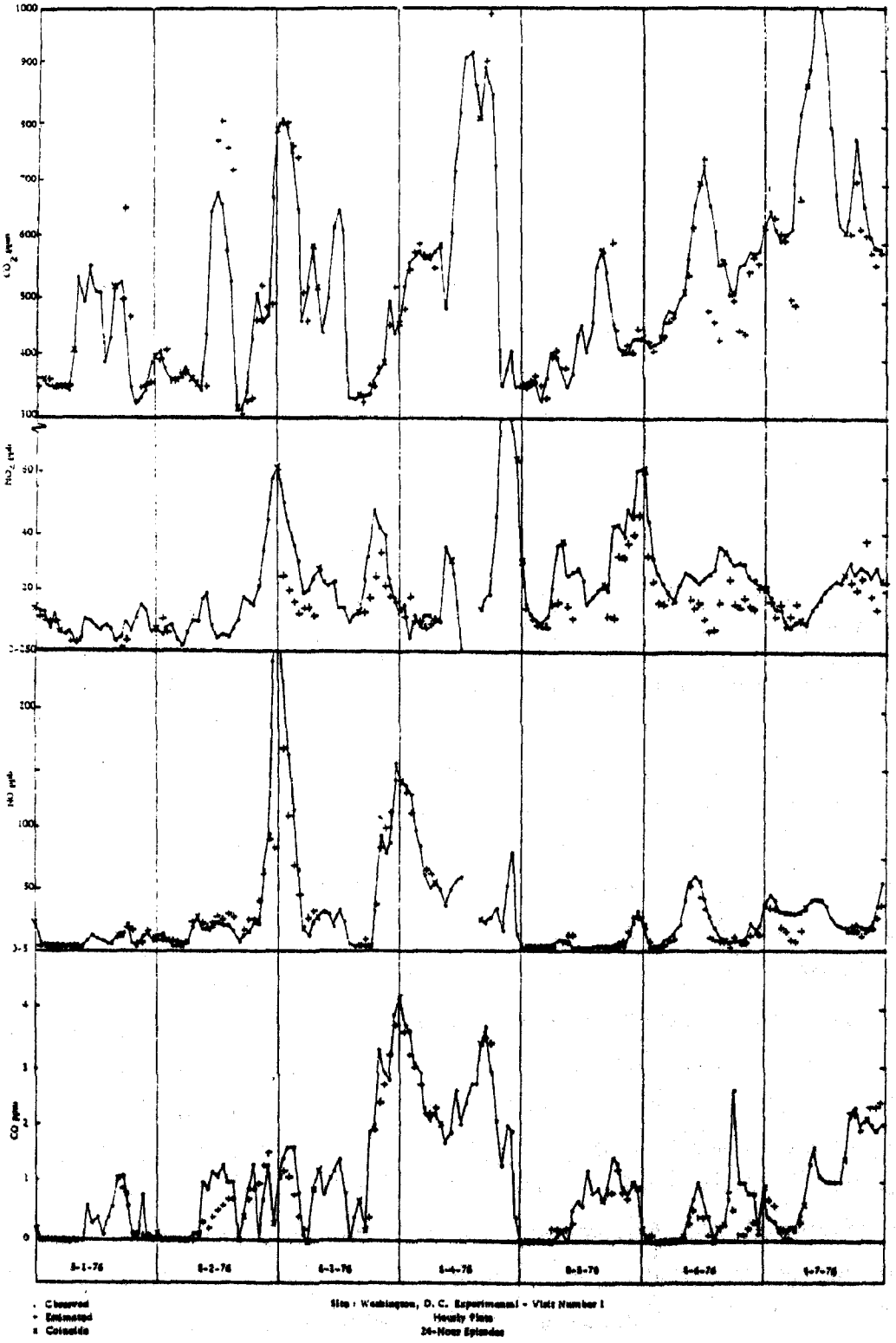


Figure 24. Estimated vs. observed pollutant concentrations for 7 consecutive days.

value falls within an acceptable range of the observed value. Under such conditions statistical techniques provide fast, efficient, reliable methods for assessing the data, and make the judgements much less subjective.

The statistical analysis used to validate the GIOAP model is based on the principle that if the model simulates realistically the involved complex conditions, a plot of the estimated versus observed values would fall on or near a line with a slope of one and intercept of zero.

The problem of measuring the association between the observed and estimated values is divided in the following three sequential steps:

1. The degree of linearity in the relationship between the pairs of estimated and observed values is established. Linearity is required to proceed to step 2.

2. The slope and intercept of the line expressing the linear relationship between the observed and estimated values are determined. Criteria on the proximity of the slope and intercept to one and zero, respectively, are established and must be met before proceeding to step 3.

3. The degree of dispersion about the line defined by the slope and intercept in step 2 is calculated and must meet certain acceptability criteria.

The statistical methods used in each of the three steps will be discussed in the remainder of this subsection.

The Pearson product-moment correlation coefficient is calculated in order to determine whether or not a linear relationship exists between the pairs of estimated and observed values. The calculated correlation coefficient must be close to +1; if that is not the case, it should be concluded that the numerical model does not realistically simulate the processes involved.

The second step requires that the relationship be linear. A line is characterized by calculating the regression parameters (slope and intercept) of the plot of observed versus estimated values. In addition, the calculated slope and intercept values are tested for statistical significance. Each of

the following hypotheses is statistically tested by a two-tailed t-test 1) the slope is +1, and 2) the intercept is 0. In the following section it will become apparent that this statistical procedure will reject numerical estimations well within the accuracy limits of the input values. Thus, it is necessary to ease the limits that strict adherence requires by establishing a set of less restrictive criteria.

The final step is necessary only if a linear relationship exists between the estimated and observed values, and if the regression line meets the established criteria. This step determines how well the line fits the data points. In order to estimate the dispersion of the data points from the regression line, the Standard Error of Estimate (SEE) is calculated. If the SEE is small, the model data set is acceptable; if the SEE is large, it indicates that the points are widely scattered about the regression line and that the modeled set should be rejected.

If a data set meets all these criteria, then it is concluded that the GIOAP model adequately represents the simulated event.

Statistical Assessment of the GIOAP Model--

The statistical procedure outlined in the last section will be applied to eight sets of data corresponding to continuous monitoring from eight dwellings, each set consisting of seven gaseous pollutants. The model predicts the average indoor pollutant concentration for three different time periods (episodes), 3 h, 8 h, and 24 h. The model performance is evaluated for all days of the monitoring period.

The statistical information generated for each pollutant, each episode, and each residence is presented in tabular form (for example, see Table 29). The first column identifies the residence investigated, the column labeled t_{epis} indicates the duration of each episode. The column labeled r contains the correlation coefficient; b is the intercept of the regression line corresponding to the plot observed versus estimated values, and m is the slope of this line. The null hypothesis that the intercept is zero is tested against the statistic t_b, while the null hypothesis that the slope equals

TABLE 29. STATISTICAL DATA SUMMARY

Residence	t_{epis}	r	b_i	m	t_b	t_{in}	Range of Indoor Observ. Value	SEE	No. of Observ.	Comments
	3-hr.									
	8-hr.									
	24-hr.									
	3 hr.									
	8-hr.									
	24-hr.									
	3-hr.									
	8-hr.									
	24-hr.									
	3-hr.									
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	3-hr.									
	8-hr.									
	24-hr.									
	3-hr.									
	8-hr.									
	24-hr.									

one is tested against the statistic t_m. The column to the right of t_m contains the range of the average pollutant concentration observed indoors; this range provides a value against which the calculated standard error of estimate can be judged. The next to the last column presents the number of observations which are used for estimating the various statistics; it must be noted that this number is not always the total number of possible pairs because of either missing observed values and/or missing calculated values due to the lack of the initial value, the air exchange rate, and/or the effective source strength.

Based on the information included in these columns, a conclusion is reached on how well the model predicts the indoor observed values. Three classes of acceptance or rejection comments are generated: Class I describes the simulations that satisfy all predetermined tests; Class II refers to numerical estimation of the indoor pollutant concentrations which, although not statistically acceptable, are judged to meet predetermined criteria which will be described below; and Class III refers to model estimations that do not meet any of the above requirements and must be rejected because they do not realistically simulate the observed indoor values.

The investigation of the model performance for each pollutant will be presented in the balance of this section. However, it is essential to begin by stating a set of rules for each of the classes outlined in the previous paragraph. Since there are varying degrees of linearity, a decision must be made on the cutoff level of the correlation coefficient. Figures 25 through 28 are scatter diagrams with four different correlation coefficients; their values are $r = 0.96$, $r = 0.82$, $r = 0.72$, and $r = 0.66$, respectively. The cutoff value chosen for this study for the correlation coefficient is $r = 0.7$; thus, if r is below 0.7, the relationship between the observed and estimated value is considered nonlinear for the purposes of this study.

For Class I acceptance the criteria on b and m are set by the two-tailed statistical t-test. For a significance level of 0.01, the t value $t_{0.005,\infty} = 2.576$ (the number of degrees of freedom is considered to be infinite because in this project it is almost always larger than the maximum finite degrees of

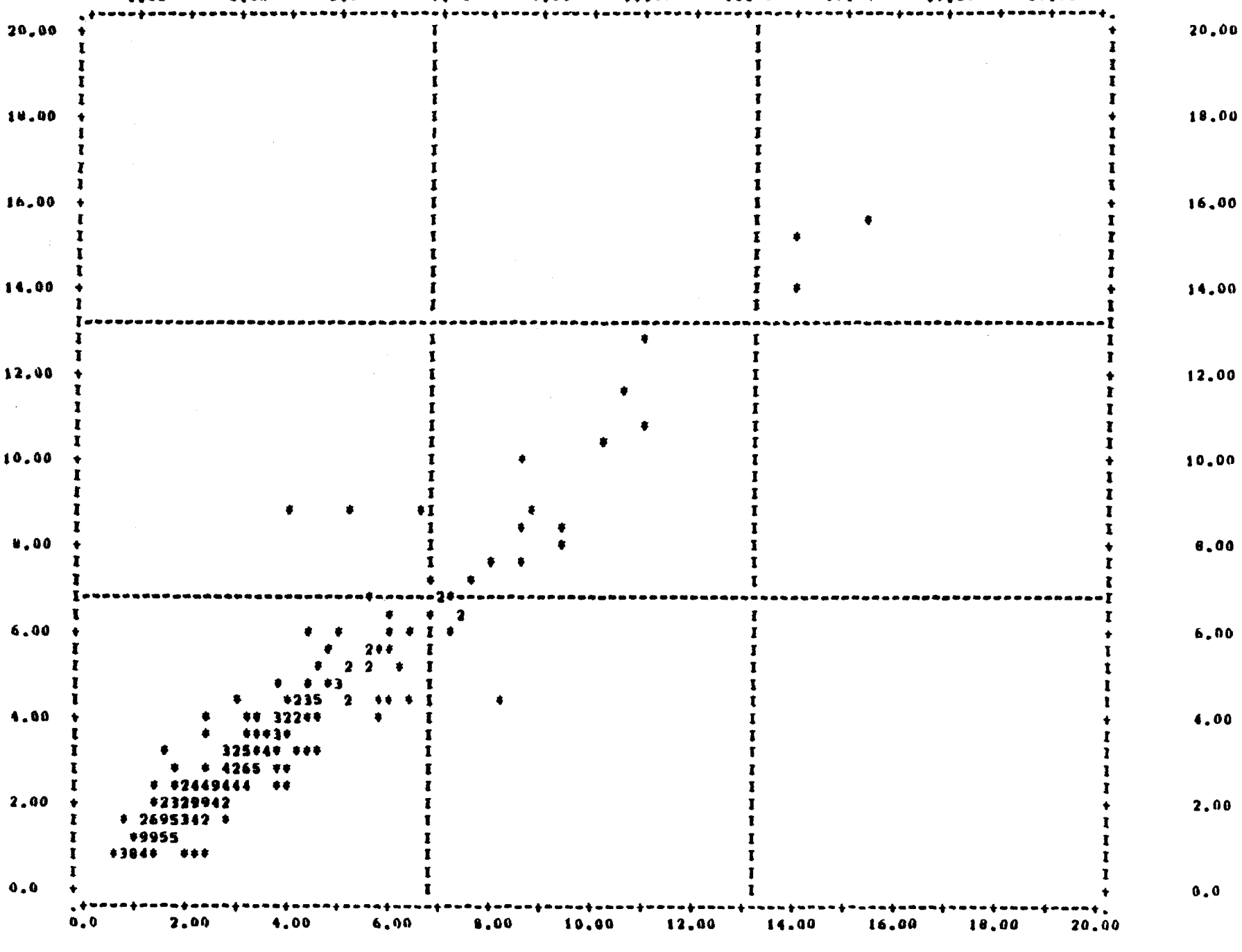

Figure 25. Scatter diagram with r = 0.96.

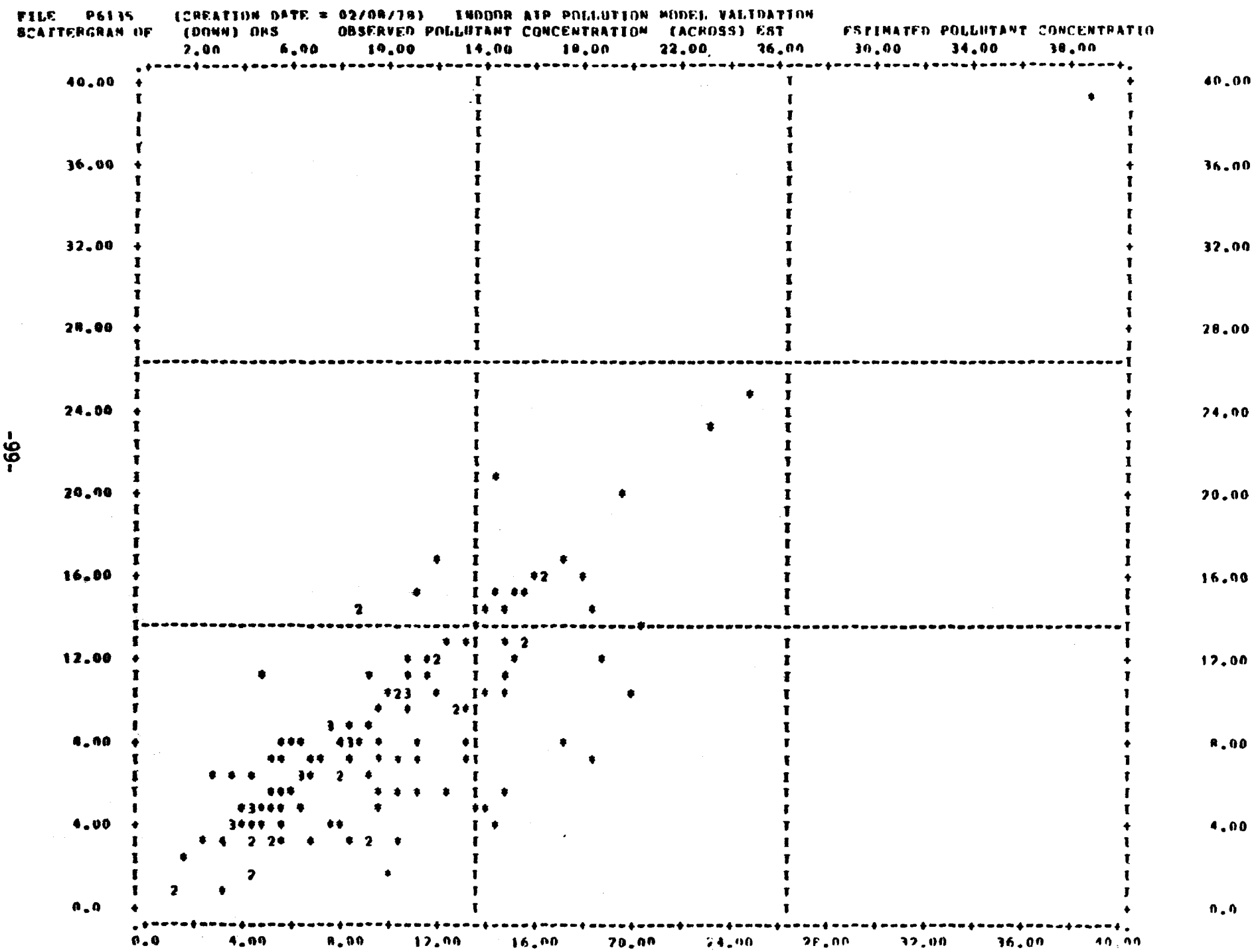

Figure 26. Scatter diagram with r = 0.82.

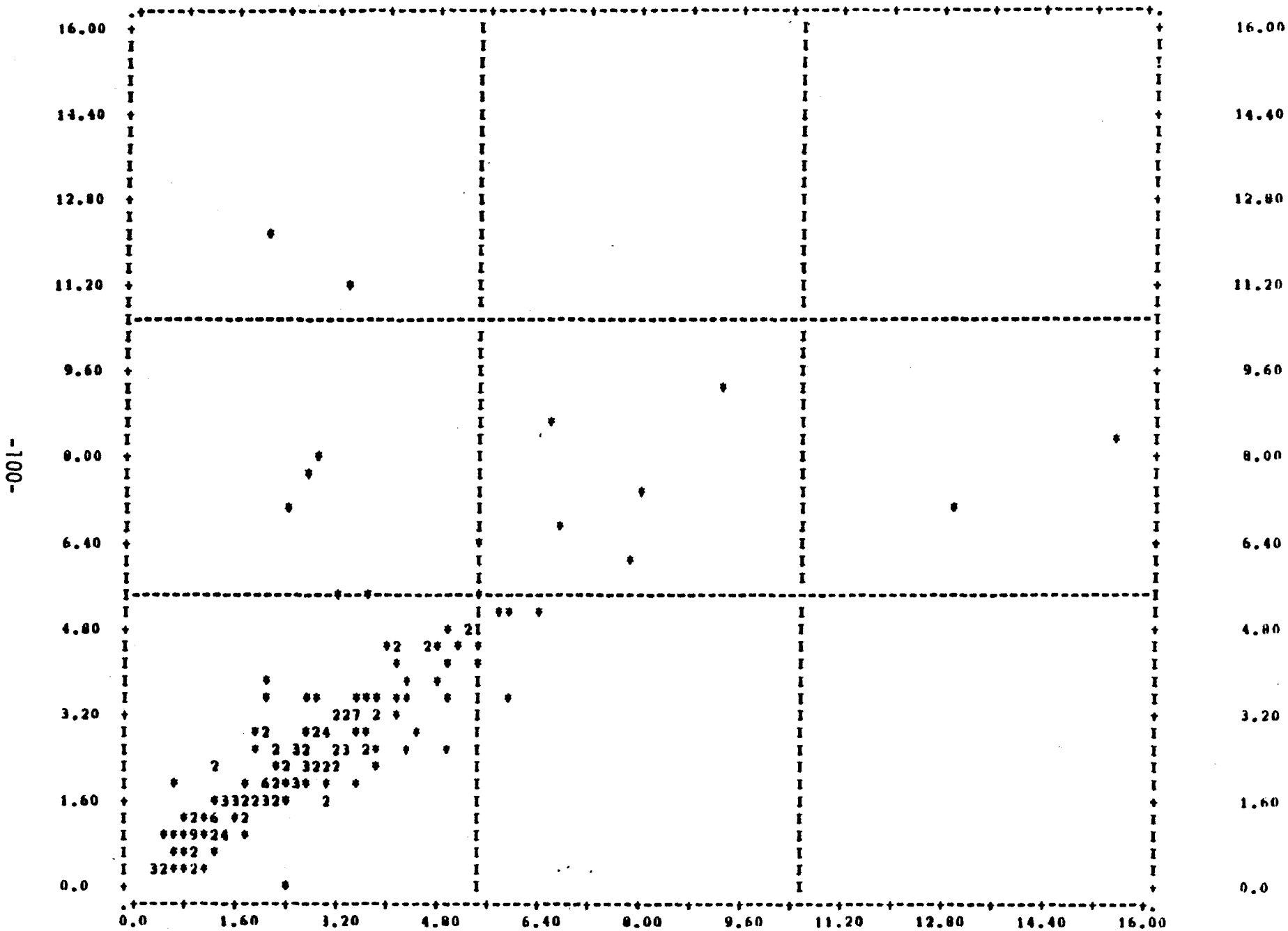

Figure 27. Scatter diagram with r = 0.72.

FILE P6135 (CREATION DATE = 02/08/78) INDOOR AIR POLLUTION MODEL VALIDATION
SCATTERGRAM OF (DOWN) OBS OBSERVED POLLUTANT CONCENTRATION (ACROSS) EST ESTIMATED POLLUTANT CONCENTRATIO

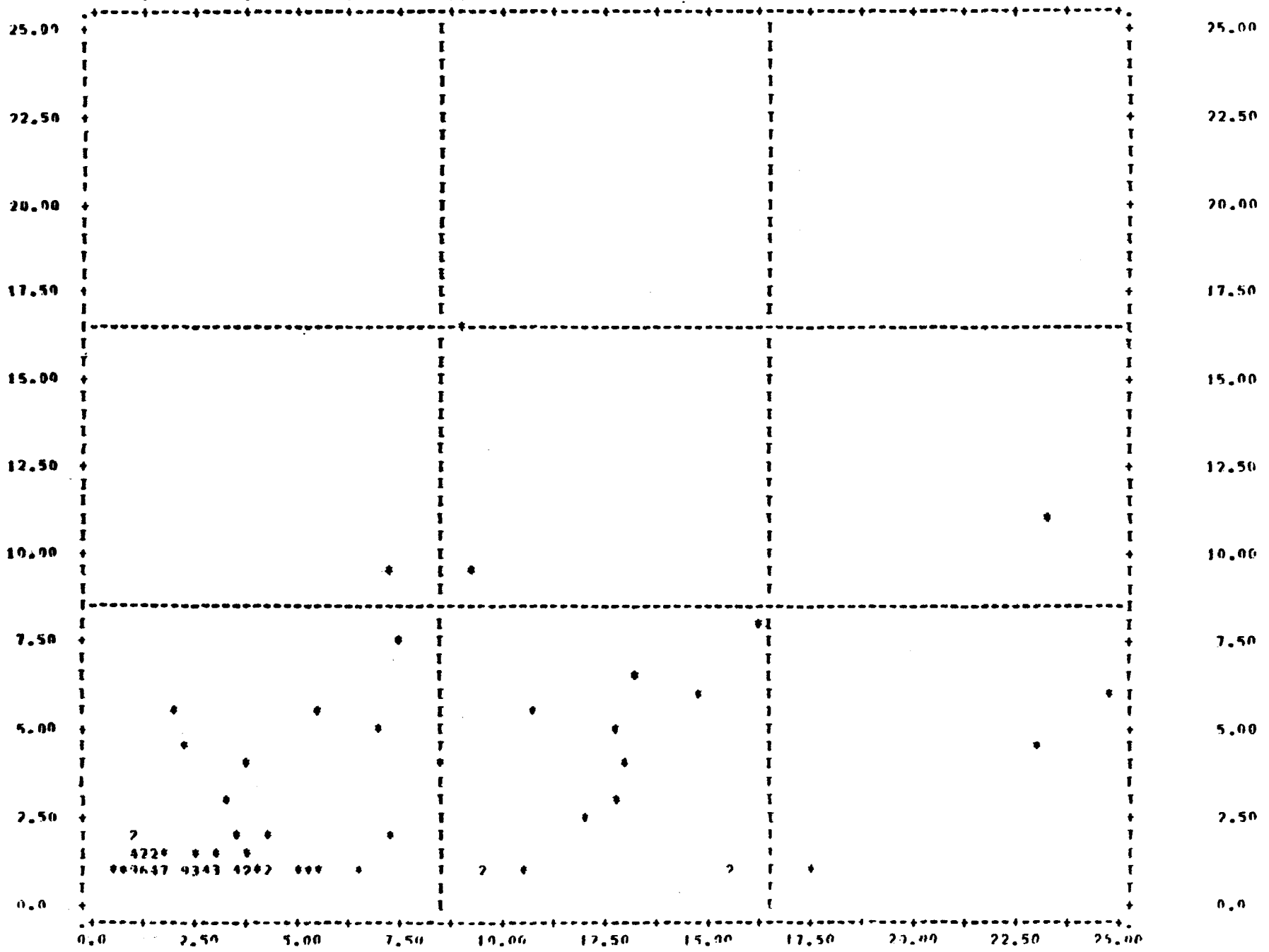

Figure 28. Scatter diagram with r = 0.62.

freedom specified in the statistical tables); thus if either t_b or t_m is outside the interval $-2.576 \leq t \leq 2.576$, the estimated indoor pollutant concentrations do not fall into Class I.

For Class II, predetermined acceptability limits can be placed on the slope m for all pollutants. However, limits on the intercept must be determined on a case basis since the proximity to zero of the intercept crucially depends on the range of the observed values which varies from pollutant to pollutant. In Class II, slope values within the closed interval [0.7, 1.3] are acceptable. In addition, values of the intercept that have magnitude greater than 15% of the maximum observed pollutant concentration are rejected. The last criterion for acceptance in Class II requires that the Standard Error of Estimate (SEE) is less than or equal to 10% of the maximum observed value.

When examining the tables containing the statistical validation data for each pollutant (i.e., Tables 30 through 33 and 36 through 38), it will be seen that the following phenomenon occurs several times: for a given set of conditions the 3- and/or 8-h episodes will be Class II, but the corresponding 24-h episode will be Class I. Further examination will reveal that the 24-h episode statistical data is based on fewer observations the either the 3- or 8-h episode data. The reason for this is that, when missing data are encountered, the model calculations cease whether or not the end of the episode has been reached. Thus, some episodes span fewer hours than indicated by the headings, which results in less overall variation and gives better statistical data.

In the balance of this section each pollutant will be examined individually.

Carbon Monoxide (CO)--Table 30 provides all the statistical information obtained by the previously outlined steps for CO. In all cases investigated an acceptable degree of linearity ($r \geq 0.821$) exists, the intercept is uniformly close to zero, and the slope is outside the prescribed interval only once ($m = 1.336$ for the 24-h episode in the Pittsburgh low-rise apt. I);

TABLE 30. STATISTICAL DATA SUMMARY FOR CARBON MONOXIDE (CO ppm)

Residence	t_{epis}	r	b	m	t_b	t_m	Range of Indoor Observ. Value	SEE	No. of Observ.	Comments
Pittsburgh Mobile Home I	3-hr.	0.943	0.174	0.911	4.779	-5.039	0.0-6.2	0.310	337	II
	8-hr.	0.900	0.242	0.874	4.810	-5.096		0.389	293	II
	24-hr.	0.912	0.173	0.919	3.119	-2.553		0.268	174	II
Denver Conventional	3 hr.	0.970	0.041	0.980	0.744	-1.471	0.89-15.9	0.570	320	I
	8-hr.	0.959	0.018	1.006	0.259	0.333		0.683	291	I
	24-hr.	0.949	-0.024	0.993	-0.286	-0.285		0.549	168	I
Chicago Experimental I	3-hr.	0.947	0.289	0.943	5.768	-3.004	0.33-6.33	0.352	282	II
	8-hr.	0.888	0.683	0.862	9.350	-4.616		0.520	224	II
	24-hr.	0.920	0.70	0.796	9.293	-6.890		0.462	133	II
Pittsburgh Low-Rise Apt. I	3-hr.	0.884	-0.029	1.128	-5.90	3.40	0.0-7.0	0.519	253	II
	8 hr.	0.821	0.023	1.218	0.348	3.778		0.652	217	II
	24-hr.	0.878	-0.105	1.336	-1.378	5.143		0.571	126	III
Baltimore Experimental I	3-hr.	0.967	0.001	1.005	0.264	0.308	0.0-2.0	0.077	235	I
	8-hr.	0.969	0.004	1.096	0.709	5.062		0.075	213	II
	24-hr.	0.960	-0.003	1.034	0.525	1.419		0.067	162	I
Washington Conventional I	3-hr.	0.961	0.040	0.972	1.222	-1.913	0.0-5.2	0.396	360	I
	8-hr.	0.938	-0.003	0.949	-0.068	-2.543		0.487	305	I
	24-hr.	0.912	0.019	1.004	0.390	0.130		0.475	200	I
Baltimore Conventional I	3-hr.	0.851	0.107	0.778	3.683	-8.038	0.0-4.56	0.389	305	II
	8-hr.	0.876	0.036	0.882	1.178	-3.734		0.349	240	II
	24-hr.	0.916	0.034	0.894	1.235	-3.363		0.271	154	II
Washington Experimental I	3-hr.	0.930	0.080	0.942	3.224	-2.740	0.0-4.22	0.314	313	II
	8-hr.	0.889	0.117	0.883	3.594	-4.175		0.391	265	II
	24-hr.	0.895	0.087	0.948	2.50	-1.427		0.358	169	II

this is the only Class III case simulated. Let us investigate this Class III case in more detail. The following points can be made:

1. Frequency distribution tables show that 91% of the sampled values fall in the half-open interval [0, 2.8).
2. Straightforward calculations using the following relationship,

   Observed Value = Intercept + (Slope) (Estimated Value),

   indicate that the approximate maximum difference between observed and estimated values is 22% of the observed value.

A similar analysis applied to a randomly chosen Class II case gives an approximate maximum difference between observed and estimated values of 2% of the observed CO value. Analyses of this nature for a Class I case provide similar or better results. It is concluded that the model predicts indoor values acceptably.

Nitric Oxide (NO)--Table 31 illustrates a strong linear correlation between observed and estimated values, $r \geq 0.875$. Similarly, the slopes of the calculated regression lines lie within the predetermined interval. As a first observation, the magnitude estimated for the intercept and the standard estimates of error may seem large; however, after comparisons with the indicated ranges of the monitored values, they are put in proper perspective and are judged acceptable. Thus, 21 cases are accepted as Class II, while the remaining 3 cases are accepted as Class I.

In order to provide a perspective on the model performance, an approximate estimate of the percent difference between observed and estimated values will be calculated. The Denver conventional residence is chosen because it was one of the extreme cases considered. Let us investigate the 8-h episode simulations. The relevant statistics are $r = 0.875$, $b = 10.135$, and $m = 0.793$. Frequency distributions of observed indoor averages generated for the data interpretation task of this study show that 94% of the hourly values fall within the half-open interval [0, 120). Following the thinking

TABLE 31. STATISTICAL DATA SUMMARY FOR NITRIC OXIDE (NO ppb)

Residence	t_{epis}	r	b	m	t_b	t_m	Range of Indoor Observ. Value	SEE	No. of Observ.	Comments
Pittsburgh Mobile Home I	3-hr.	0.970	6.873	0.962	2.377	-2.912	77-467	22.295	335	II
	8-hr.	0.941	5.192	0.990	1.159	-0.480		29.690	274	I
	24-hr.	0.917	12.541	0.931	2.213	-2.366		29.452	193	I
Denver Conventional	3 hr.	0.909	8.307	0.798	4.304	-9.899	2.1-409	25.288	323	II
	8-hr.	0.875	10.135	0.793	4.072	-8.203		31.605	305	II
	24-hr.	0.911	1.236	0.912	0.543	-2.550		18.175	147	I
Chicago Experimental I	3-hr.	0.987	1.907	0.941	3.531	-6.753	0.0-256	6.513	320	II
	8-hr.	0.970	3.479	0.913	3.720	-6.003		10.281	251	II
	24-hr.	0.976	4.733	0.836	4.642	-10.686		8.947	151	II
Pittsburgh Low-Rise Apt. I	3-hr.	0.982	-1.135	1.034	-2.03	3.014	4.11-300.1	7.233	316	II
	8 hr.	0.982	-2.355	1.066	-3.525	5.101		7.805	258	II
	24-hr.	0.993	-2.235	1.048	-3.603	4.775		5.717	155	II
Baltimore Experimental I	3-hr.	0.939	1.231	1.026	3.656	1.202	0.0-87.2	5.334	300	II
	8-hr.	0.948	1.740	1.042	5.270	1.958		4.983	221	II
	24-hr.	0.946	2.402	1.039	6.239	1.596		5.327	221	II
Washington Conventional I	3-hr.	0.986	5.542	0.975	5.325	-2.619	18.6-279	9.101	303	II
	8-hr.	0.966	15.105	0.919	7.784	-4.711		14.303	210	II
	24-hr.	0.953	25.878	0.809	8.988	-7.957		15.482	117	II
Baltimore Conventional I	3-hr.	0.906	2.314	0.841	2.328	-7.159	1.0-224.1	14.139	316	II
	8-hr.	0.954	0.706	0.927	0.960	-3.969		9.235	252	II
	24-hr.	0.961	0.207	0.931	0.256	-3.421		8.657	177	II
Washington Experimental I	3-hr.	0.935	1.120	1.058	1.085	2.527	0.0-283.8	13.320	312	II
	8-hr.	0.918	2.052	1.052	1.560	1.829		15.818	263	II
	24-hr.	0.906	1.841	1.066	0.924	1.721		19.272	169	II

expressed for CO, we conclude that for this case, within the specified interval, the approximate maximum difference between observed and estimated values is 15% of the observed value; or within this interval the statistical model value is at most 1.15 times the observed value.

This specific analysis is of course an example; however, we feel that the model realistically simulates indoor average concentration for NO.

Nitrogen Dioxide (NO_2)--Numerical simulations of indoor NO_2 concentrations require the use of a first-order decay term. The half-life used for these simulations is 30 min; this value is suggested by observations of the indoor instantaneous NO_2 values of this project as well as by C. Hollowell (1977) (private communication) and Wade et al. (1975). The use of first-order chemical decay terms, instead of the zero-order rate, which was used originally, has substantially improved the predictive power of the model. Six cases are rejected, 3 cases are accepted as Class I, and 15 cases are accepted as Class II. The cases that have been rejected are in residences without indoor NO_2 sources; the indoor concentrations are persistently low with very little variation. In cases like this the model may overestimate the indoor NO_2 concentrations by as much as 50%. However, the model performs well for a total of 18 cases (out of 25) (see Table 32). The maximum difference between the statistical model value and the observed value is 16%. This conclusion is reached by the process described for CO, and it refers to a specific example; however, the general assessment is that the GIOAP is realistically simulating indoor average concentrations for NO_2.

Sulfur Dioxide (SO_2)--The nature of the SO_2 data is a source of the model's apparent inability to estimate the observed indoor values (see Table 33). Table 34 shows portions of the indoor average concentration frequency distribution for SO_2. Note that the instrument used, a Meloy AO-185-2A commercial detector, has a limit of detection of 0.005 ppm. It is apparent that almost all SO_2 values observed indoors are at or below the instrument's lower limit of detection.

TABLE 32. STATISTICAL DATA SUMMARY FOR NITROGEN DIOXIDE (NO_2 ppb)

Residence	t_{epis}	r	b	m	t_b	t_m	Range of Indoor Observ. Value	SEE	No. of Observ.	Comments
Pittsburgh Mobile Home I	3-hr.	0.834	1.093	0.838	1.961	-5.326	0.0-75.3	5.770	334	II
	8-hr.	0.773	1.265	0.832	1.712	-4.045		6.616	272	II
	24-hr.	0.708	2.630	0.718	2.943	-5.451		6.662	193	II
Denver Conventional	3 hr.	0.875	8.045	0.803	6.696	-7.919	11-138	8.604	321	II
	8-hr.	0.744	12.349	0.711	7.249	-7.773		11.256	298	II
	24-hr.	0.835	6.012	0.837	3.371	-3.429		5.578	137	II
Chicago Experimental I	3-hr.	0.651	6.106	0.725	13.324	-5.757	0.0-39.3	5.058	316	III
	8-hr.	0.487	7.558	0.677	13.148	-4.196		6.072	251	III
	24-hr.	0.475	7.684	0.868	9.623	-0.999		6.779	151	III
Pittsburgh Low-Rise Apt. I	3-hr.	0.918	-0.400	0.946	-1.635	-2.312	0.0-31.1	2.646	315	I
	8 hr.	0.871	-0.317	0.873	-0.938	-4.142		3.222	257	II
	24-hr.	0.839	-0.255	0.837	-0.606	-3.732		3.103	155	II
Baltimore Experimental I	3-hr.	0.750	2.779	0.661	8.549	-9.963	0.0-41.1	3.755	295	III
	8-hr.	0.679	3.448	0.571	10.035	-11.074		3.937	255	III
	24-hr.	0.570	4.176	0.492	10.850	-10.229		3.915	206	III
Washington Conventional I	3-hr.	0.847	0.192	0.925	0.469	-2.051	0.0-38.8	3.113	253	I
	8-hr.	0.823	0.567	0.809	1.085	-4.090		3.005	144	II
	24-hr.	0.773	0.856	0.739	1.086	-3.223		2.424	58	II
Baltimore Conventional I	3-hr.	0.758	7.398	0.707	7.099	-8.452	1-130.6	10.039	309	II
	8-hr.	0.836	5.574	0.764	6.075	-7.224		7.085	237	II
	24-hr.	0.925	1.879	0.934	2.458	-2.269		4.988	177	I
Washington Experimental I	3-hr.	0.854	3.492	0.968	4.902	-0.934	0.0-95.2	6.637	296	II
	8-hr.	0.728	5.981	0.888	5.583	-1.984		7.756	224	II
	24-hr.	0.758	4.372	0.939	3.594	-0.861		7.246	131	II

TABLE 33. STATISTICAL DATA SUMMARY FOR SULFUR DIOXIDE (SO_2 ppb)

Residence	t_{epis}	r	b	m	t_b	t_m	Range of Indoor Observ. Value	SEE	No. of Observ.	Comments
Pittsburgh Mobile Home I	3-hr.	0.491	4.848	0.142	16.172	-60.011	3.0-29.1	4.028	314	III
	8-hr.	0.488	4.346	0.130	12.044	-59.732		4.262	258	III
	24-hr.	0.517	3.963	0.152	7.916	-44.596		4.682	176	III
Denver Conventional	3 hr.	0.692	0.725	0.361	8.575	-30.321	1.0-16	1.262	321	III
	8-hr.	0.619	0.778	0.277	9.021	-35.481		1.253	300	III
	24-hr.	0.713	0.696	0.259	7.091	-37.442		1.055	168	III
Chicago Experimental I	3-hr.	0.603	1.342	0.489	9.946	-14.083	2-19.8	1.089	320	III
	8-hr.	0.464	1.789	0.341	11.292	-15.973		1.214	252	III
	24-hr.	0.574	1.350	0.449	7.235	-10.652		1.012	155	III
Pittsburgh Low-Rise Apt. I	3-hr.	0.511	0.414	0.226	4.002	-35.463	0.0-110	1.463	304	III
	8 hr.	0.505	0.398	0.166	3.417	-45.249		1.455	240	III
	24-hr.	0.514	0.488	0.159	3.246	-40.140		1.548	164	III
Baltimore Experimental I	3-hr.	0.0	2.0	0.0	0.0	0.0	2.0-4.2	0.0	299	III
	8-hr.	0.948	1.740	1.042	5.270	1.958		4.983	269	III
	24-hr.	0.946	2.40	1.039	6.239	1.596		5.327	221	III
Washington Conventional I	3-hr.	0.945	-0.169	1.113	-1.705	5.506	3-9.7	0.744	357	II
	8-hr.	0.919	-0.474	1.231	-3.487	7.582		0.874	301	II
	24-hr.	0.906	-0.800	1.326	-4.366	7.413		0.896	200	III
Baltimore Conventional I	3-hr.	0.704	1.127	0.448	15.164	-20.740	1.8-114	0.668	290	III
	8-hr.	0.627	1.384	0.329	15.933	-24.627		0.809	228	III
	24-hr.	0.825	1.006	0.472	11.709	-20.109		0.630	154	III
Washington Experimental I	3-hr.	0.140	1.920	0.041	57.273	-58.279	1.4-2.5	0.063	313	III
	8-hr.	0.051	1.985	0.008	92.926	-96.717		0.060	264	III
	24-hr.	0.050	1.993	0.007	89.566	-95.012		0.061	168	III

TABLE 34. SO_2 FREQUENCY DISTRIBUTION

Residence	Percentage	SO_2 Range in ppb
Pittsburgh Mobile Home I	44.2%	3.00 - 5.60
	35.2%	5.60 - 8.20
Denver Conventional	90.5%	1.00 - 2.50
Chicago Experimental I	80.0%	2.00 - 3.80
	15.6%	3.80 - 5 60
Pittsburgh Low-Rise Apt. I	60.9%	0.00 - 1.00
	20.7%	1.00 - 2.00
Baltimore Experimental I	99.7%	2.00 - 2.20
Washington Conventional I	60.5%	3.70 - 4.40
	28.8%	7.90 - 8.60
Baltimore Conventional I	94.9%	2.00 - 2.90
Washington Experimental I	98.8%	2.00 - 2.12

Three factors influence these low levels of SO_2: 1) the observed SO_2 outdoor levels are generally low; 2) the pollutant is a moderately reactive gas, so the indoor levels are lower than the outdoor levels; and 3) the flame photometric principle of detection, employed in the commercial instrument used in the field operations, is subject to negative interference from CO_2. The instrument, although "approved" by EPA for sampling in the outdoor ambient environment, is subject to quenching by CO_2, which is present in high levels in the indoor environment. The extent of the negative CO_2 interference on the SO_2 levels is illustrated in Table 35, which shows the results of four tests performed by the field team of this project. In each case the same correction factor is calculated; however, we have not undertaken such corrections because the observed levels are almost always close to very low, unreliable levels.

TABLE 35. NEGATIVE CO_2 INTERFERENCE ON SO_2 LEVELS*

Test No.	$[CO_2]$ Introduced into the SO_2 Monitor	$[SO_2]$ Output by the Instrument	$[SO_2]$ Introduced into the Instrument
1	300	0 33	0. 33
	813	0. 265	0. 33
	1460	0. 205	0. 33
	1975	0. 165	0. 33
2	300	0. 23	0. 23
	833	0. 18	0. 23
	1450	0. 14	0. 23
	1975	0. 115	0. 23
3	308	0. 095	0. 095
	850	0. 075	0. 095
	1500	0. 055	0. 095
	2037	0. 045	0. 095
4	312	0. 050	0. 050
	872	0. 040	0 050
	1525	0. 030	0. 050
	2088	0. 023	0. 050

* All concentration levels in ppm.

The point here is that while the model does not simulate the observed SO_2 concentrations, both the estimated values and the observed values are too low and too close to zero to justify employment of correction factors. It is concluded that the model's ability to correctly estimate SO_2 values has not been tested by the available data. SO_2 levels have been found to be low in the indoor environment not only by the present study but in all similar studies. SO_2 concentrations decay at rates similar to NO_2; thus, it is expected that the GIOAP model would realistically simulate higher and more variable indoor levels.

Ozone (O_3)--An ozone table similar to the statistical summary tables for the other pollutants would indicate that the model does not satisfy the predetermined criteria. However, it is misleading to consider the model performance as

unsatisfactory since the majority of the estimated values are within 2 ppb of the observed values; this difference is smaller than the monitor's precision. The observed ozone levels in the indoor environment are low and often constant for long time periods. The small variations in the predicted values weigh heavily in the estimation of correlation coefficients and other statistics that assess the power of the model to predict. The performance of the GIOAP model to predict indoor ozone levels is judged adequate and not unsatisfactory because it gives a realistic picture of the ozone variation indoors. Finally, the linear dynamic model (Shair and Heitner, 1974) has been utilized to predict higher indoor levels, and its use in conjunction with the GIOAP model is recommended.

Nonmethane Hydrocarbons(NMHC)--The model simulates the majority of the investigated cases well. The model requires knowledge of the molecular weight of the pollutant examined; in the case of hydrocarbons we had to use an average molecular weight representing the hydrocarbons most often sampled. Thus, the uncertainty introduced may have caused some of the Class III judgments. In spite of this uncertainty, Table 36 indicates that the GIOAP model estimates the indoor nonmethane hydrocarbon levels satisfactorily in the majority of the cases examined.

Methane(CH_4)--Table 37 illustrates that the model estimates the indoor methane values realistically. As always, 24 cases are run. For this pollutant, 2 are judged Class III, 17 are accepted as Class II, and 5 are classified as Class I. Following the techniques used in previous pollutant analysis, we estimate a maximum difference of approximately 30% between the statistically estimated CH_4 concentration and its corresponding observed value. This is one of the largest percent differences found in Table 37.

TABLE 36. STATISTICAL DATA SUMMARY FOR NONMETHANE HYDROCARBONS (THC-CH_4 ppm)

Residence	t_{epis}	r	b	m	t_b	t_m	Range of Indoor Observ. Value	SEE	No. of Observ.	Comments
Pittsburgh Mobile Home I	3-hr.	0.819	1.036	0.585	10.996	-18.596	0.0-13	1.189	338	III
	8-hr.	0.745	0.884	0.665	6.752	- 9.451		1.365	285	III
	24-hr.	0.721	0.765	0.718	4.511	- 5.690		1.368	196	II
Denver Conventional	3 hr.	0.817	0.030	0.851	0.707	- 3.831	0.0-5.33	0.402	239	II
	8-hr.	0.792	0.120	0.714	2.408	- 7.448		0.393	209	II
	24-hr.	0.662	0.186	0.542	2.944	- 7.818		0.386	112	III
Chicago Experimental I	3-hr.	0.951	0.305	0.899	3.532	- 5.829	1.3-16	0.769	292	II
	8-hr.	0.873	0.533	0.788	4.059	- 7.320		0.900	233	II
	24-hr.	0.949	0.286	0.845	2.809	- 6.592		0.602	144	II
Pittsburgh Low-Rise Apt. I	3-hr.	0.855	0.117	1.046	0.465	1.295	0.67-58.3	3.573	323	II
	8 hr.	0.853	-0.630	1.29	- 1.99	5.995		3.85	262	II
	24-hr.	0.929	0.376	1.167	-1.795	4.399		2.053	151	II
Baltimore Experimental I	3-hr.	0.809	0.119	0.840	1.333	- 4.469	0.0-16	1.184	290	II
	8-hr.	0.821	0.246	0.621	3.358	-14.007		0.921	256	III
	24-hr.	0.832	0.196	0.603	2.251	-13.909		0.964	201	III
Washington Conventional I	3-hr.	0.879	0.043	0.915	0.818	- 3.045	0.0-12.78	0.642	320	II
	8-hr.	0.863	0.096	0.798	1.778	- 6.830		0.518	252	II
	24-hr.	0.747	0.299	0.602	5.48	- 9.277		0.314	159	III
Baltimore Conventional I	3-hr.	0.727	0.227	0.590	6.571	-12.421	0.0-3.78	0.417	287	III
	8-hr.	0.677	0.198	0.533	4.500	-11.805		0.441	216	III
	24-hr.	0.771	0.121	0.633	2.785	- 8.270		0.376	141	III
Washington Experimental I	3-hr.	0.961	-0.006	0.936	- 1.07	-3.856	0.0-12	0.664	267	II
	8-hr.	0.942	0.006	0.886	- 0.095	-5.062		0.721	201	II
	24-hr.	0.984	-0.051	0.921	- 1.101	-5.008		0.395	110	II

TABLE 37. STATISTICAL DATA SUMMARY FOR METHANE (CH_4 ppm)

Residence	t_{epis}	r	b	m	t_b	t_m	Range of Indoor Observ. Value	SEE	No. of Observ.	Comments
Pittsburgh Mobile Home I	3-hr.	0.914	0.352	0.769	5.246	-12.438	0.0-10.2	0.878	341	II
	8-hr.	0.895	0.251	0.861	3.197	- 5.50		0.917	291	II
	24-hr.	0.880	0.307	0.823	3.315	- 5.656		0.887	203	II
Denver Conventional	3 hr.	0.812	0.579	0.716	7.227	- 8.521	0.11-9.17	0.392	239	II
	8-hr.	0.689	0.930	0.556	9.199	-10.951		0.446	209	III
	24-hr.	0.708	0.813	0.576	6.25	- 7.741		0.359	112	III
Chicago Experimental I	3-hr.	0.921	0.086	0.931	2.629	- 3.884	0.0-3	0.198	301	II
	8-hr.	0.847	0.068	0.917	1.226	- 2.220		0.268	242	I
	24-hr.	0.844	0.120	0.840	1.734	- 3.555		0.251	144	II
Pittsburgh Low-Rise Apt. I	3-hr.	0.832	0.226	0.779	5.628	- 7.630	0.0-6	0.442	324	II
	8 hr.	0.816	0.268	0.753	5.618	- 7.469		0.460	262	II
	24-hr.	0.870	0.215	0.799	4.11	- 5.438		0.362	152	II
Baltimore Experimental I	3-hr.	0.871	0.441	0.763	7.582	- 9.364	0.78-4.9	0.380	290	II
	8-hr.	0.859	0.483	0.731	7.601	- 9.833		0.460	256	II
	24-hr.	0.850	0.474	0.723	6.080	- 8.704		0.444	201	II
Washington Conventional I	3-hr.	0.943	0.127	0.907	4.281	- 5.316	0.67-3.0	0.181	338	II
	8-hr.	0.886	0.210	0.836	4.669	- 6.182		0.253	275	II
	24-hr.	0.918	0.108	0.913	2.335	- 2.949		0.206	183	II
Baltimore Conventional I	3-hr.	0.940	0.212	1.008	0.352	1.164	1.0-18.0	1.744	289	I
	8-hr.	0.940	-0.332	1.141	-1.534	5.039		1.757	224	II
	24-hr.	0.951	-0.554	1.200	-2.222	6.027		1.664	150	II
Washington Experimental I	3-hr.	0.928	0.147	0.995	1.794	-0.0233	0.0-8.1	0.685	297	I
	8-hr.	0.919	0.179	0.986	1.898	-0.490		0.722	238	I
	24-hr.	0.904	0.197	0.994	1.534	-0.164		0.820	157	I

Carbon Dioxide(CO_2)--The last pollutant investigated in this section is CO_2; Table 38 illustrates that the GIOAP model estimates the indoor CO_2 concentrations very well. Nine cases are judged Class II and 15 are judged Class I. Following the procedure used in the other pollutant analysis, the difference between the estimated CO_2 concentrations and the corresponding observed indoor values is at no time greater than 8% of the observed value.

Model Sensitivity--

An integral part of the model validation is a theoretical analysis of the model sensitivity. A study of this nature shows how errors in the estimation of a model parameter affect the model output(s). One of the unique features of the GIOAP model is the transient term. Previous numerical studies simulating the relative balance between the indoor and the outdoor environments have included steady-state conditions only. An assessment of the transient term indicates that this term is most important for stable pollutants but that its contribution is minimal for reactive pollutants. Exclusion of the transient term reduces the correlation between observed and estimated values by about 50% of its value with the transient term included. Exclusion of the transient term has no effect on the estimations of indoor concentrations of the chemically reactive ozone. This behavior is expected from theoretical considerations, since, for ozone, the decay term in the exponent of the transient term is very large; therefore, the transient term approaches zero, which is not the case for stable pollutants. Thus, the GIOAP model becomes a steady-state model for reactive pollutants; the model, however, is very sensitive to the transient term for the stable pollutants. A sensitivity analysis will further indicate which parameters are highly sensitive to errors (i.e., a small error in such a parameter would result in a significant error in the output(s)), and which parameters are relatively insensitive to errors. Knowledge of the sensitivity of the various parameters will assist us in determining priorities in the utility of the model and in estimating parameter values when the model becomes an application

TABLE 38. STATISTICAL DATA SUMMARY FOR CARBON DIOXIDE (CO_2 ppm)

Residence	t_{epis}	r	b	m	t_b	t_m	Range of Indoor Observ. Value	SEE	No. of Observ.	Comments
Pittsburgh Mobile Home I	3-hr.	0.973	42.175	0.948	3.495	-4.199	464-2231	75.482	342	II
	8-hr.	0.929	-10.878	1.033	-0.484	1.4		115.026	296	II
	24-hr.	0.943	12.243	0.999	0.529	-0.027		93.16	204	II
Denver Conventional	3 hr.	0.837	- 5.166	1.061	-0.280	1.567	157-1587	104.417	320	I
	8-hr.	0.730	-35.016	1.174	-1.215	2.711		133.177	297	II
	24-hr.	0.656	-93.259	1.275	-1.840	2.444		132.292	172	I
Chicago Experimental I	3-hr.	0.948	30.654	0.953	2.389	-2.610	394-2094	61.542	322	II
	8-hr.	0.919	21.308	0.948	1.098	-2.025		78.768	247	I
	24-hr.	0.981	15.496	0.964	1.319	-2.314		39.577	148	I
Pittsburgh Low-Rise Apt. I	3-hr.	0.967	43.778	0.941	3.831	-4.231	351-2197	66.333	321	II
	8 hr.	0.953	21.220	0.986	1.334	-0.703		67.825	260	I
	24-hr.	0.929	43.220	0.946	1.696	-1.770		67.398	151	I
Baltimore Experimental I	3-hr.	0.921	35.860	0.943	2.589	-2.368	315-1384	59.053	281	II
	8-hr.	0.900	5.939	0.992	0.328	-0.268		66.851	238	I
	24-hr.	0.910	-23.461	1.051	-1.131	1.415		68.991	176	I
Washington Conventional I	3-hr.	0.979	12.643	0.984	1.154	-1.414	218-1679	48.819	317	I
	8-hr.	0.954	4.027	1.003	0.283	0.014		75.309	259	I
	24-hr.	0.979	18.378	0.960	1.736	-2.669		47.999	175	I
Baltimore Conventional I	3-hr.	0.932	21.506	0.955	2.076	-2.163	326-1463	56.075	318	I
	8-hr.	0.950	20.668	0.949	2.180	-2.595		44.446	257	II
	24-hr.	0.943	7.237	0.986	0.594	-0.549		38.916	177	I
Washington Experimental I	3-hr.	0.893	75.750	0.878	5.611	-4.904	0.0-1100	72.325	318	II
	8-hr.	0.896	41.831	0.948	2.743	-1.796		70.997	265	II
	24-hr.	0.905	53.971	0.908	3.160	-2.790		62.615	169	II

tool. Model validation studies are often undertaken under the best possible conditions; thus, it is necessary to study the model sensitivity in order to define the model's limitations and capabilities.

For a given general model $y = f(\overline{X},\overline{P})$, model sensitivity is defined as:

$$\left.\frac{\partial f(\overline{X},\overline{P})}{\partial p_i}\right| (\overline{X},\overline{P}) = (\overline{X}_0,\overline{P}_0) \tag{14}$$

where

f = the function defining the mathematical model

$\overline{X} = \{x_1, x_2, \ldots, x_n\}$ = the vector of independent variables

$\overline{X}_0 = \{x_{1_0}, x_{2_0}, \ldots, x_{n_0}\}$ = fixed value of $\overline{X}$

$\overline{P} = \{p_1, p_2, \ldots, p_k\}$ = the vector of parameters

$\overline{P}_0 = \{p_{1_0}, p_{2_0}, \ldots, p_{k_0}\}$ = fixed value of $\overline{P}$.

For some insight as to why this formula is used to measure model sensitivity, one must refer to the following equation:

$$df = \sum_{i=1}^{k} \frac{\partial f}{\partial p_i} dp_i \ . \tag{15}$$

Equation (15) indicates that the approximate error (df) of f is a linear combination of the errors in the individual parameters (dp_i, i=1, ..., k) where the coefficient of each dp_i, i=1, ..., k is the corresponding sensitivity coefficient. This approach is used for error or sensitivity analysis when Δf, the actual change in the function, can be approximated by df.

The GIOAP model is a first-order initial value problem given by Equation (3). Thus, for this case, the function f referred to in the definition of model sensitivity is replaced by C_{in}, Equation (4). The GIOAP model sensitivity coefficients are as follows:

$$\frac{\partial C_{in}}{\partial C_{in_0}} = e^{-(D+v)(t-t_0)} \qquad t_0 \le t \le t_f \tag{16}$$

$$\frac{\partial C_{in}}{\partial m_{out}} = \left(\frac{\nu}{D+\nu}\right)\left[\left(\frac{1}{D+\nu} - t_0\right)e^{-(D+\nu)(t-t_0)} - \left(\frac{1}{D+\nu} - t\right)\right] \qquad t_0 \le t \le t_f \qquad (17)$$

$$\frac{\partial C_{in}}{\partial b_{out}} = \left(\frac{\nu}{D+\nu}\right)\left(1 - e^{-(D+\nu)(t-t_0)}\right) \qquad t_0 \le t \le t_f \qquad (18)$$

$$\frac{\partial C_{in}}{\partial S} = \frac{1 - e^{-(D+\nu)(t-t_0)}}{V(D+\nu)} \qquad t_0 \le t \le t_f \qquad (19)$$

$$\frac{\partial C_{in}}{\partial D} = \left(\frac{1}{D+\nu}\right)^2\left(m_{out}\nu t_0 + \nu b_{out} + \frac{S}{V} - \frac{2m_{out}\nu}{D+\nu}\right)e^{-(D+\nu)(t-t_0)}$$

$$-\left[C_{in_0} - \left(\frac{1}{D+\nu}\right)\left(m_{out}\nu t_0 + \nu b_{out} + \frac{S}{V} - \frac{m_{out}\nu}{D+\nu}\right)\right](t-t_0)e^{-(D+\nu)(t-t_0)}$$

$$-\left(\frac{1}{D+\nu}\right)^2\left(\nu b_{out} + \frac{S}{V} - \frac{2m_{out}\nu}{D+\nu} + m_{out}\nu t\right) \qquad t_0 \le t \le t_f \qquad (20)$$

$$\frac{\partial C_{in}}{\partial V} = \left[\frac{S}{V^2(D+\nu)}\right]\left[e^{-(D+\nu)(t-t_0)} - 1\right] \qquad t_0 \le t \le t_f \qquad (21)$$

$$\frac{\partial C_{in}}{\partial \nu} = -\left(\frac{1}{D+\nu}\right)^2\left[m_{out}Dt_0 + b_{out}D - \frac{S}{V} - m_{out}\left(\frac{D-\nu}{D+\nu}\right)\right]e^{-(D+\nu)(t-t_0)}$$

$$-\left[C_{in_0} - \left(\frac{1}{D+\nu}\right)\left(m_{out}\nu t_0 + b_{out}\nu + \frac{S}{V} - \frac{m_{out}\nu}{D+\nu}\right)\right](t-t_0)e^{-(D+\nu)(t-t_0)}$$

$$+\left(\frac{1}{D+\nu}\right)^2\left[b_{out}D - \frac{S}{V} - m_{out}\left(\frac{D-\nu}{D+\nu}\right) + m_{out}Dt\right] \qquad t_0 \le t \le t_f \qquad (22)$$

where

t_0 = initial time

t_f = final time.

In the balance of this document the subscripts referring to indoors and outdoors will be eliminated; thus, we will denote C_{in_0} by C_0, C_{in} by C, m_{out} by m, and b_{out} by b.

The study documented in this report requires several additional, though nonrestrictive, assumptions to be made (see the subsection The GEOMET Indoor-Outdoor Air Pollution Model) in order to implement the model, Equation (4). These assumptions resulted in Equation (5). The sensitivity coefficients for Equation (5) are as follows (see Volume II) for the derivations of the sensitivity coefficients:

$$\frac{\partial C_m}{\partial C_0} = e^{-\sum_{i=1}^{m} (\nu_i+D_i)} \tag{23}$$

$$\frac{\partial C_m}{\partial m_i} = \alpha_i \left\{ \left(\frac{\nu_i}{D_i+\nu_i} \right) \left[\left(\frac{1}{D_i+\nu_i} - t_{i-1} \right) e^{-(\nu_i+D_i)} - \left(\frac{1}{D_i+\nu_i} - t_i \right) \right] \right\} \tag{24}$$

$$\frac{\partial C_m}{\partial b_i} = \alpha_i \left(\frac{\nu_i}{D_i+\nu_i} \right) \left(1 - e^{-(\nu_i+D_i)} \right) \tag{25}$$

$$\frac{\partial C_m}{\partial S_i} = \alpha_i \left[\frac{1 - e^{-(\nu_i+D_i)}}{V(\nu_i+D_i)} \right] \tag{26}$$

$$\frac{\partial C_m}{\partial D_i} = \alpha_i \left\{ \left(\frac{1}{D_i+\nu_i}\right)^2 \left[m_i \nu_i t_{i-1} + \nu_i b_i + \frac{S_i}{V} - \frac{2m_i\nu_i}{D_i+\nu_i} \right] e^{-(\nu_i+D_i)} \right.$$

$$- \left[C_{i-1} - \left(\frac{1}{D_i+\nu_i}\right) \left(m_i \nu_i t_{i-1} + \nu_i b_i + \frac{S_i}{V} - \frac{m_i\nu_i}{D_i+\nu_i} \right) \right] e^{-(\nu_i+D_i)}$$

$$\left. - \left(\frac{1}{D_i+\nu_i}\right)^2 \left(\nu_i b_i + \frac{S_i}{V} - \frac{2m_i\nu_i}{D_i+\nu_i} + m_i \nu_i t_i \right) \right\} \qquad (27)$$

$$\frac{\partial C_m}{\partial V} = \alpha_i \left[\frac{S_i}{V^2(D_i+\nu_i)} \right] \left(e^{-(\nu_i+D_i)} - 1 \right) \qquad (28)$$

$$\frac{\partial C_m}{\partial \nu_i} = \alpha_i \left\{ - \left(\frac{1}{D_i+\nu_i}\right)^2 \left[m_i D_i t_{i-1} + b_i D_i - \frac{S_i}{V} - m_i \left(\frac{D_i-\nu_i}{D_i+\nu_i}\right) \right] e^{-(\nu_i+D_i)} \right.$$

$$- \left[C_{i-1} - \left(\frac{1}{D_i+\nu_i}\right) \left(m_i \nu_i t_{i-1} + b_i \nu_i + \frac{S_i}{V} - \frac{m_i\nu_i}{D_i+\nu_i} \right) \right] e^{-(\nu_i+D_i)}$$

$$\left. + \left(\frac{1}{D_i+\nu_i}\right)^2 \left[b_i D_i - \frac{S_i}{V} - m_i \left(\frac{D_i-\nu_i}{D_i+\nu_i}\right) + m_i D_i t_i \right] \right\} \qquad (29)$$

where

$$\frac{\partial C_m}{\partial ( )} = \frac{\partial C}{\partial ( )} \Bigg|_{(t_m,\ m_m,\ b_m,\ S_m,\ D_m,\ V,\ \nu_m,\ C_{m-1})}$$

( ) = any one of the GIOAP model parameters

$t_0 \le t_i,\ t_m \le t_n = t_f,\ 1 \le i, m \le n$

$$\alpha_i = \begin{cases} 1, & i = m \\ e^{-\sum_{j=i+1}^{m} (\nu_j+D_j)}, & 1 \le i < m \end{cases} .$$

Two major advantages become apparent when the closed form partial derivatives are available. The first is the ease with which the sensitivity coefficients can be computed. The second is that the sensitivity coefficients can be given a thorough analytical treatment, which is difficult, if not impossible, when the partial derivatives are not available in closed form. Each of the seven sensitivity coefficients (Equations (23) through (29)) will be discussed below.

The first sensitivity coefficient to be considered is $\partial C_m/\partial C_0$. Referring back to Equation (23), it is seen that $0 < \partial C_m/\partial C_0 < 1$. Moreover, as time increases, $\partial C_m/\partial C_0$ decreases, which means that the effect of an error in C_0 on C diminishes with time. Finally, since $\partial C_m/\partial C_0$ is positive, an increase in C_0 will cause an increase in C_m, and a decrease in C_0 will result in a decrease in C_m.

Next, the sensitivity coefficients involving m, the slope of the line used to approximate the outdoor pollutant concentrations, will be dealt with. By rearranging and deleting terms from Equation (24), it is seen that

$$0 \leq \left|\frac{\partial C_m}{\partial m_i}\right| < \alpha_i \frac{\nu_i}{D_i+\nu_i} t_i, \qquad 1 \leq i, m \leq n . \tag{30}$$

Equation (30) shows that the effects on C of an error in m at $t = t_i$ will dissipate with time. On the other hand, it should be noted that, if there is a recurrent error in m (e.g., every value of m_i, $i = 1, \ldots, n$ is in error by 20%), the effects will be additive, i.e.,

$$dC_\ell = \sum_{i=1}^{m} \frac{\partial C_\ell}{\partial m_i} dm_i, \quad \ell = 1, \ldots, n \tag{31}$$

with the elements having the lowest indices contributing less and less to the error in C.

The sensitivity coefficients involving b, the intercept of the line used to approximate the outdoor pollutant concentrations, will be examined in this paragraph. From Equation (25), it is clear that

$$0 < \frac{\partial C_m}{\partial b_i} < \alpha_i \left(\frac{\nu_i}{D_i+\nu_i}\right), \qquad 1 \leq i, m \leq n. \tag{32}$$

Thus, the effects of an error in b at t_i on C diminish with time. Also, $\partial C_m/\partial b_i \leq 1$, which means that errors in b are not magnified when they are transmitted to C. In addition, the fact that $\partial C_m/\partial b_i$ is positive means that an increase in b_i causes an increase in C_m, and, similarly, a decrease in b_i results in a decrease in C_m. As in the case of m, recurrent errors in b are additive.

The sensitivity coefficients involving S, the internal pollutant source rate, will be discussed next. It is seen from Equation (26) that

$$0 < \frac{\partial C_m}{\partial S_i} < \frac{\alpha_i}{V(\nu_i+D_i)}, \qquad 1 \leq i, m \leq n. \tag{33}$$

As before, due to the action of α_i, the effects of an error in S at t_i on C will decrease with time. In addition, considering the fact that V is a large number and that the product V times ν+D is large (even though ν is usually in the interval (0.1, 2.0)), it is seen that $\partial C_m/\partial S_i$ will be small. Thus, C is relatively insensitive to errors in S. Moreover, since $\partial C_m/\partial S_i$ is positive, it is seen that an increase (decrease) in S_i will result in an increase (decrease) in C_m. Finally, as in the case of m, recurrent errors in S are additive.

The next sensitivity coefficients to be studied are those that deal with chemical decay rate, D. From Equation (27) it is seen that the expression for $\partial C_m/\partial D_i$ is a very complicated one. As a result, it is hard to make any meaningful analysis or calculate any useful bounds. As before, the effects of an error in ν_i at $t = t_i$ will diminish with time, and the effects of recurrent errors are additive.

The next sensitivity coefficient to be examined is $\partial C_m/\partial V$. Since V does not change from hour to hour, any error associated with V will occur initially and will dissipate with time as in the case of C_0. Also, it is easily seen from Equation (28) that $\partial C_m/\partial V$ is less than zero. Thus, an increase (decrease) in V would cause a decrease (increase) in C_m. Values of V are usually obtainable from plans or blueprints, thus minimizing any error connected with V; thus, V is, for all practical purposes, a known constant, and $\partial C_m/\partial V$ was presented here as a point of interest.

Finally, the sensitivity coefficients associated with the air exchange rate ν will be discussed. As can be seen from Equation (29), $\partial C_m/\partial \nu_i$ is a complex expression, and, due to the interactions of the various elements of the equation, it is difficult to make any meaningful analysis or to compute any useful bounds. As in previous cases, the effects of an error in ν_i at $t = t_i$ on C will diminish with time, and the effects of recurrent errors are additive.

The balance of this section will consist of graphical illustrations representing the effects induced on the indoor pollutant concentrations by errors imposed on different input parameters. Figure 29 represents the nominal conditions, i.e., a CO 8-h episode calculated by the GIOAP model; this episode is extracted from the data set of the Baltimore conventional residence, Visit Number 1. The baseline conditions are also shown in Table 39.

Figure 30 shows how a 50% error on the initial condition affects C_{in} over the 8-h episode. The figure illustrates that for this example the effects of the initial condition error on the indoor concentration are essentially eliminated after 2 h. This case is an example of a nonrecurrent error; i.e., a single parameter is perturbed only once in the episode, and the effects of the introduced perturbation are traced for the duration of the episode. The same type of error behavior in C_{in} seen in this example will occur for any other parameter under similar conditions.

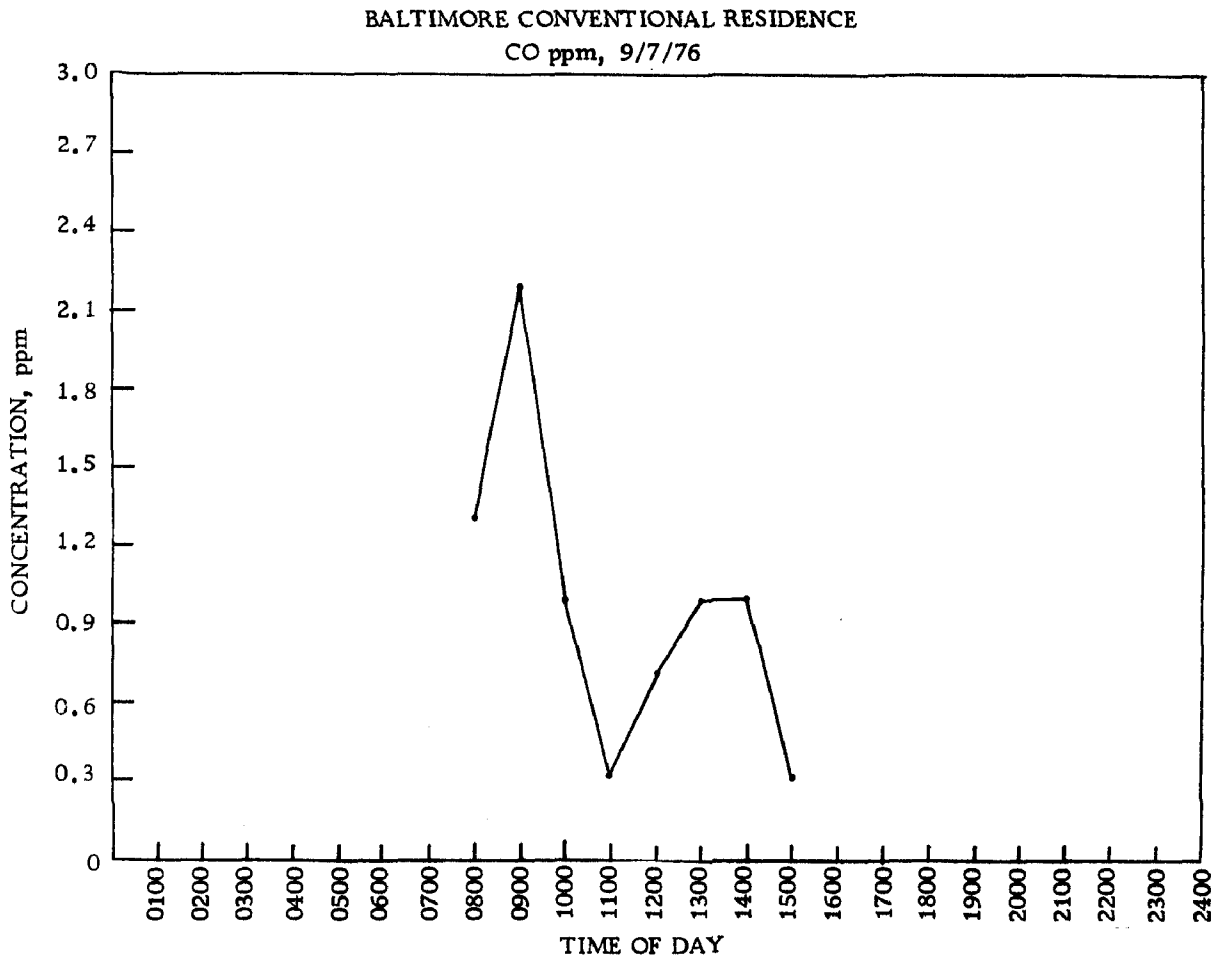

Figure 29. Nominal values.

TABLE 39. NOMINAL CONDITIONS USED IN THE SENSITIVITY STUDY EXAMPLES

House: Baltimore Conventional (Visit #1)
Pollutant: CO
Volume: 13,575 ft^3

Hour	C_{in} (ppm)	C_{out} (ppm)	S (mg/h)	ν (air exchanges/h)
8	1.33	1.33	-	-
9	2.23	1.33	677.77	1.20
10	1.04	0.00	0.00	1.20
11	0.31	0.00	0.00	1.20
12	0.68	0.00	440.14	1.20
13	1.02	0.00	613.13	1.20
14	1.01	0.00	528.17	1.20
15	0.30	0.00	0.00	1.20

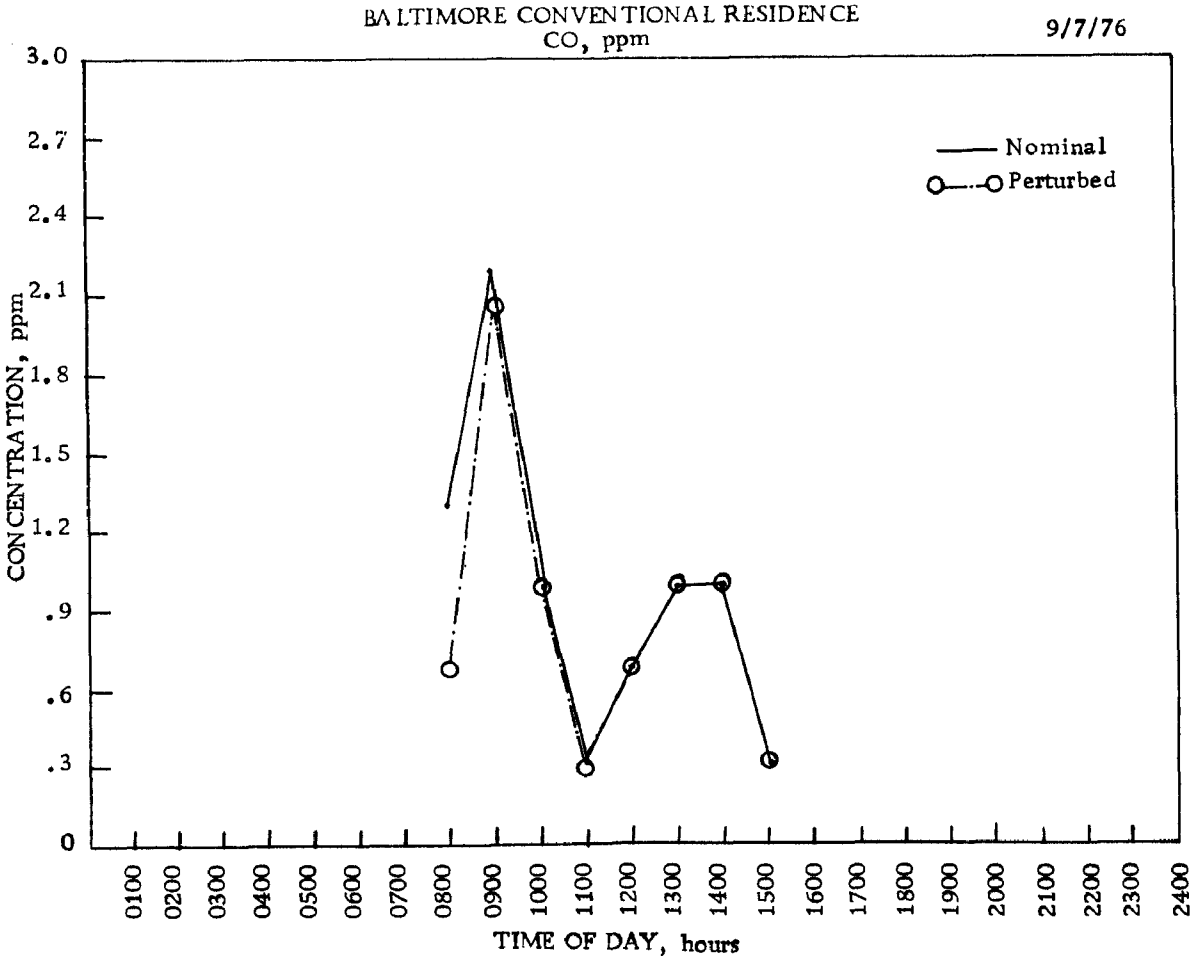

Figure 30. Comparison of nominal values obtained by perturbing C_{in}.

Figure 31 illustrates the errors in the indoor pollutant levels caused by recurrent time-dependent errors in the internal source (S) rate term. The magnitude of the error in S at a given time is 30% of the corresponding internal source rate.

Figure 32 illustrates the errors in the indoor pollutant level caused by a recurrent constant error in the air exchange rate (ν). The nominal input value for ν is 1.2 air exchanges per hour, the error used is 0.2 air exchanges per hour.

Numerical investigations of the above illustrated cases appear in Appendix C (Vol. II) where the sensitivity coefficients, the parameter errors (ΔS, $\Delta\nu$, ΔC_0), the actual output errors (ΔC_{in}), and approximate output errors (dC_{in}) are tabulated.

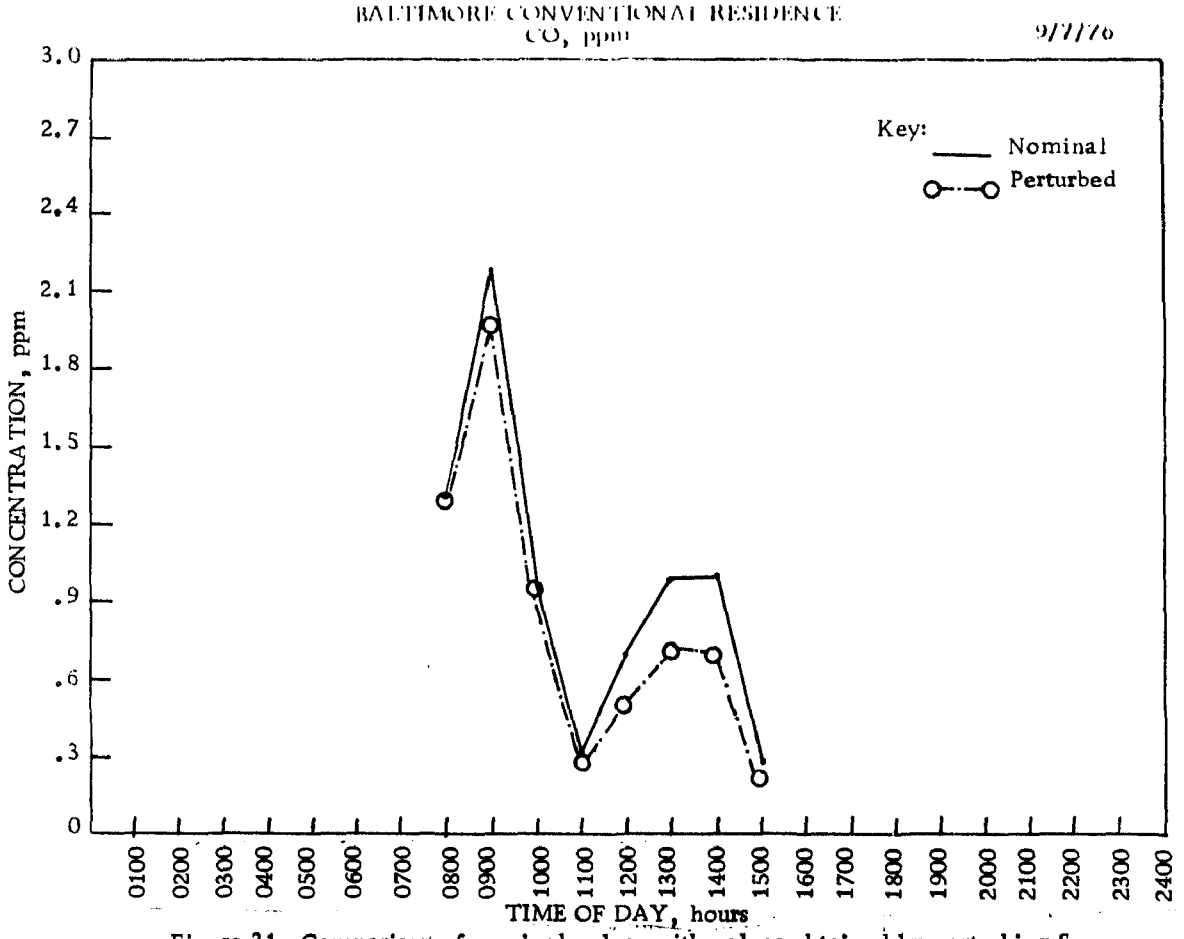

Figure 31. Comparison of nominal values with values obtained by perturbing S.

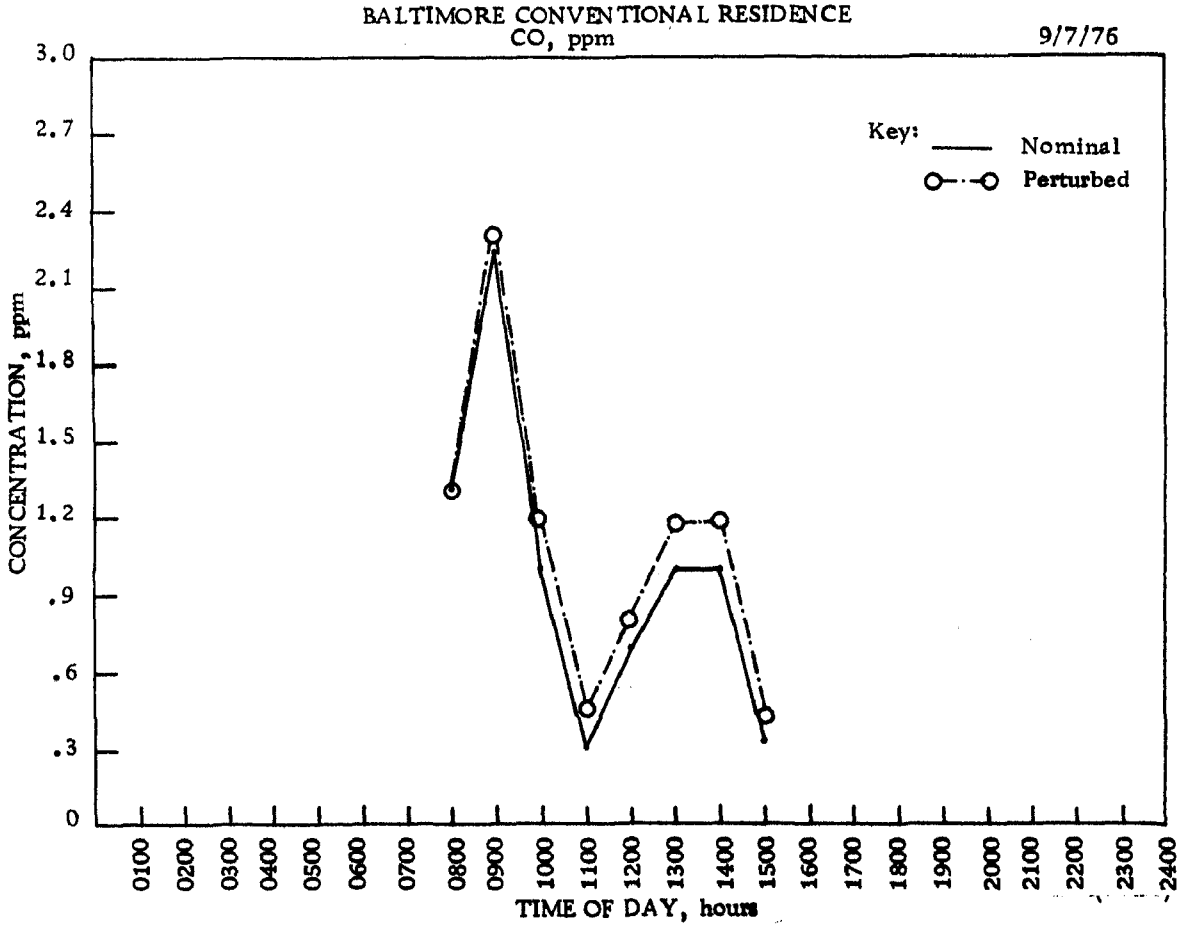

Figure 32. Comparison of nominal values with values obtained by perturbing u.

CONCLUSIONS

This study indicates that the GIOAP model performs well. The fundamental principles and assumptions used in the formulation of the model are similar to the concepts used for other indoor numerical models; however, the model is different from previous numerical efforts not only because it is applicable to, and has been applied to, a large variety of pollutants, but also because it simulates short periods of time since the transient term is included. Most importantly, the model stands alone because it is the only indoor-outdoor numerical model that has been validated against a large set of observed data.

The GIOAP model has been tested under a wide variety of meteorological and behavioral conditions. Weather conditions encountered ranged from late autumn in Denver, to summer in Baltimore, to winter in Pittsburgh. Behavioral patterns varied widely; e.g., families with children versus families without children, and families with smoking members versus nonsmoking families. In addition the model has simulated conditions in residences of different structural characteristics; e.g., detached dwellings, row houses, apartments, and mobile homes. Thus, the model not only provides good estimates of indoor air pollutant concentration levels for different pollutants, but also does so for various types of residential structures under diverse meteorological and behavioral conditions.

The transient term included in the GIOAP model does not appear in other numerical models that estimate indoor air pollution levels. Examination of the GIOAP model and simulations with and without the transient term have led to the following conclusions: 1) the transient term contributes substantially when the variation of indoor concentrations for stable pollutants is simulated, 2) the transient term becomes less significant for moderately reactive pollutants, and 3) the transient term is unimportant for ozone which is a highly reactive pollutant.

The model validation phase was undertaken under "best" conditions; i.e., the parameter values used for simulation were the best estimates available.

For C_0, m, b, and V the actual values were obtained from the monitoring data. The large data base available for this study was utilized to compute constrained best least-squares estimates for S and ν, the two parameters most difficult to obtain. The estimates for these two parameters were computed with the Parameter Estimation Procedure. Finally, values for D for various pollutants were obtained from the available literature.

The motivation for obtaining the "best" estimates for all the parameters underscores our desire to validate the GIOAP model under ideal conditions, to characterize its performance without considering the problems of obtaining realistic values for the input parameters, and, subsequently, to determine its sensitivity resulting from errors in the values of the input parameters.

The GIOAP model was statistically tested using two sets of rules: 1) strict statistical tests, and 2) predetermined empirical criteria. Under "best" conditions, the model performance is divided into three categories:

1. Not Validated--Due to low outdoor levels and a negative interference of CO_2 on the SO_2 monitor, a large number of hourly SO_2 concentrations are measured close to the threshold value of the monitor. In the indoor environment, SO_2 and NO_2 have an approximately equal half-life; it is thus judged that the GIOAP model validate satisfactorily against higher indoor SO_2 concentrations.

2. Adequate--Eighty-five percent of the observed indoor ozone values are in the low range of 0-6 ppb. The model estimated values are mostly within 2 ppb (less than the instrument precision) of the observed values. The numerical output does not satisfy the predetermined model validation criteria, but it provides realistic estimations of the indoor ozone concentrations.

3. Satisfactory--Model estimated values are within 25% of the observed indoor values for the following pollutants: CO, NO, NMHC, CH_4, CO_2, and NO_2.

Under "best" conditions the GIOAP model provides realistic estimates of the observed indoor pollutant concentrations. However, due to the nature of model usage, it is necessary to investigate the performance of the model under less than ideal conditions. As a result, a sensitivity study of the model is necessary. The set of parameters associated with the model has been divided into two groups: 1) those parameters that remain constant throughout an episode (C_0, V), and 2) those that must be estimated for every hour of the episode (m, b, S, ν, D).

The model is comparatively insensitive with respect to parameters in the first group; i.e., errors in C_0 and V have relatively little effect on the model output. In addition, the effects of errors in C_0 and V dissipate with time. Errors in the second group have more impact on the model output. This is due to two factors: 1) estimates of parameter values in this group are more susceptible to error than the parameters in the first group, and 2) errors can be introduced at each hour of the episode because these parameters must be estimated every hour. In an effort to stratify the parameters of this group on a relative basis, they are ranked as follows from the least to the most sensitive: 1) S, 2) b, and 3) D, m, and ν. S is the least sensitive because the magnitude of the numerator is less than one, and the denominator, which contains a factor of V, is relatively large. b is considered to be somewhat more sensitive than S because $\partial C/\partial S = (1/\nu V)(\partial C/\partial b)$ and because, within the range of values being used, $1/\nu V$ is less than 1. Finally, D, m, and ν are considered to be the most sensitive, even though the complexity of their respective sensitivity coefficients does not allow any general conclusions to be drawn. Intuition and the examples studied suggest that these are the three most sensitive parameters.

THE STEADY-STATE TSP MODEL

Introduction

A recent EPA indoor-outdoor study of Total Suspended Particulate (TSP) matter has led to the general conclusion that indoor TSP levels are approximately equal to outdoor concentrations (Henderson et al. 1973). Examination of the data base available to the GEOMET Indoor-Outdoor Pollution project clearly shows that the ratio of TSP indoor concentrations to outdoor concentrations varies from 0.3 to 3.6. An effort has been undertaken to identify the factors that influence this ratio and to formulate a model that would predict the indoor TSP matter levels.

The need for a separate procedure to relate the indoor TSP levels with corresponding outdoor TSP concentrations became evident early in the project. The nature of the pollutant and the type of TSP data collected are not suitable for simulations with the GIOAP model, because the model requires fine time resolution for the pollutant concentrations and other input parameters. The experimental design for TSP matter requires that from each of the four sites, one 24-h average be obtained for each day of the monitoring period.

The TSP empirical model formulated for this study is a steady-state model built on the available data. A portion of the TSP matter found indoors is of outdoor origin, while the remaining portion is attributed to indoor activities. Studies on particulate matter have concentrated on quantifying source strengths of individual indoor TSP generating mechanisms, such as vacuum cleaning, operation of a fan, smoking, frying, housecleaning, use of sprays, moving in and out of the house, ventilation devices, and others. The steady-state TSP model does not require knowledge of individual TSP source strengths; rather it quantifies indoor TSP levels as a function of the family activity index. This approach takes advantage of the data available to the project and utilizes the questionnaire which was answered on a daily basis by a responsible member of the household. The procedure followed employs a portion of the available data to define the indoor TSP strength as a function of the activity scale, and the remaining data to verify the numerical predictions.

TSP matter is generated indoors by either thermal or mechanical sources. Thermal sources are smoking and cooking. The term mechanical sources refers to the processes of resuspension and dispersion of existing indoor particulate matter. In this section we will describe a phenomenological model which is a combination of theoretical principles and empirical parameters. The model quantifies indoor sources, both mechanical and thermal, as a function of the indoor activity index and predicts the total indoor TSP levels as a function of outdoor levels and indoor source strengths.

TECHNICAL APPROACH

Theoretical Considerations

The fundamental principle involved in relating the indoor and outdoor TSP levels is expressed by a mass balance equation which requires that the rate of change of the indoor levels equals the sum of four processes: 1) the rate by which TSP enters the house; 2) the rate by which TSP is generated indoors; 3) the rate by which TSP escapes from the house; and 4) the rate by which TSP matter is "removed" from indoor air. Each term will be discussed in detail in the following paragraphs.

The rate of change of the indoor concentration is assumed to be zero, this steady-state assumption is due to the nature of the data available to this and most other TSP monitoring projects. Thus, the first, most basic assumption of the steady-state TSP model is that the indoor particulate levels are constant over each 24-h period.

A fundamental difference between gas contaminants and particulate matter is that only a portion of the TSP matter passes through the cracks of each structure; the remaining portion settles on the outside surface of each structure which acts as a barrier. A cleansing factor, f, determines the portion of TSP that passes through this barrier.

In the indoor environment TSP is generated by two broad mechanisms: TSP is generated either by a thermal source or by the resuspension and dispersion of existing particulates. The nature of the data available to this project

is not suitable for estimating the rates of individual sources; however, indoor source strengths and resuspension rates have been found to be proportional to the daily family activity. The indoor generation term is given by S(k), where k is the activity index discussed earlier in Section 2 of this document.

The indoor TSP matter concentrations decrease by exfiltration and by removal mechanisms. Several removal mechanisms have been identified indoors: residential filtering devices, adsorption, and gravitational settling. The total decrease rate of indoor particulate matter by the removal mechanisms is denoted by R.

The steady-state equation that expresses the above procedures is given by

$$\nu f C_{out} - \nu C_{in} - R C_{in} + S(k) = 0 \qquad (34)$$

where

C_{in} = TSP concentration indoors, $\mu g/m^3$
ν = air exchange rate, air changes/time
f = cleansing factor, pure number
C_{out} = TSP concentration outdoors, $\mu g/m^3$
R = removal rate, number/time
$S(k)$ = indoor source strength rate, $(\mu g/m^3)$/time
k = activity index, pure number.

The first term of Equation (34) is the infiltration term. The next two terms denote the rate of reduction in the TSP indoor concentrations by exfiltration and removal mechanisms. The fourth term is the indoor source strength term.

Source Estimation--

Simple manipulation of Equation (34) leads to the following equation

$$S = (\nu + R)\, C_{in} - \nu f C_{out}. \tag{35}$$

Daily values for C_{in} and C_{out} are obtained from the data sets of eight residences; a portion of the data is used to establish a physical relationship between indoor and outdoor TSP levels. The air exchange rate is calculated daily using the following equation:

$$\nu = 0.28 + 0.012\ \Delta T \tag{36}$$

where ΔT (°F) is the daily temperature difference between indoor average and outdoor average temperature. The general expression for the air exchange rate given by Equation (36) has been derived from the analysis of experimental SF_6 data obtained by the study. It is a comprehensive equation which includes detached homes, apartments, mobile homes, and row houses. This ν equation is very similar to an equation obtained by Hunt and Burch (1975) for air exchange rates under experimental conditions.

The cleansing factor or the fraction of the TSP matter that "passes" indoors must be distinguished from the infiltration rate. Of the total amount of particulate that could infiltrate indoors, only a fraction f does because the remainder is stopped by the structural barrier. J. Alzona (Univ. of Pittsburgh, private communication, 1976) has elaborated on the physical meaning of this factor and suggests that its value is smaller than 0.5. Using the data from this project, different values have been estimated for this factor; the calculated f values vary between 0.23 and 0.38. It must be realized that a zero indoor TSP source is required for an experimental estimation of this factor. The f value used in the steady-state particulate model is 0.3, which is an assumed value supported by other studies and calculations on the indoor-outdoor data base.

The "removal" term of the steady-state TSP model is estimated by RC_{in}, where R stands for the removal rate of the indoor TSP concentrations. Adsorption and gravitational settling are the two indoor TSP removal mechanisms.

Hunt (1972) estimates that the total fraction of TSP deposited per unit time is given by $R = k/(Q + k)$, where k is a first-order rate constant most nearly approximating the actual deposition rate, and $Q = V_r E/V$, with V_r the rate of recirculation, V the volume of the structure, and E the filter efficiency. For the general conditions found in the indoor residential environment, k values are between 2.5 and 4.0, and E is approximately equal to one. The removal rate value assumed for this study is R = 0.8.

Utilizing data from eight residences and Equation (35), the calculated range of indoor source strengths varied between 10 and 200 $(\mu g/m^3)$/24-h. The calculated source strengths show association with two quantities: the outdoor TSP levels and the activity index. The source strength is proportional to the outdoor levels because resuspension is a major mechanism of indoor particulate matter generation. The data set of this project conclusively shows that the resuspended TSP is proportional to the portion that infiltrates on the same day and not any previous days. The activity index (k) quantifies the means by which the particulate matter becomes resuspended. Analyses of the calculated source strengths show that the indoor TSP concentrations attributed to resuspended particulates are equal to $0.24\ k\nu C_{out}$. The second category of indoor particulate sources, the indoor generation of TSP matter, is also found to be proportional to the activity index and inversely proportional to the daily air exchange rate. The proportionality constant takes the value of 1.5 $(\mu g/m^3)/(TIME)^2$. Thus, the total source term takes the following final form.

$$S(k) = 0.24\ k\nu C_{out} + \frac{1.5\ k}{\nu}. \qquad (37)$$

It is apparent that in the formulation of the steady-state TSP model a series of complex physical effects, such as the sheltering effect, the removal of particulate matter by adsorption and gravitational settling, and the indoor TSP generation processes, have been expressed in terms of admittedly oversimplified parameters. Realistic representation of these complex dynamic systems requires more data, additional basic research, and change of emphasis of the present study; thus, the parameterization approach followed in the formulation of the TSP model is preferred.

Indoor TSP Generation Rates--

The approach followed is an empirical procedure which requires continuous manipulation of the data. Examination of the source strength values from the first eight residences leads to the following:

- The resuspension source strength rate is proportional to the air exchange rate ν, the removal factor R, the cleansing factor f (in this study R = 0.8 and f = 0.3), and the outdoor TSP level.
- The resuspension source strength rate is proportional to the activity index value for typical and active families.
- The activity index value for inactive houses takes the value of 4. This is because the measures for low activity days do not seem to be as realistic as for other days.
- The indoor generation rate of TSP matter is inversely proportional to the air exchange rate and proportional to the activity index. The constant of proportionality has been estimated to be 1.5 units for every activity unit.
- For residences with air exchange rates equal to or less than 0.2 air changes per hour, the value of the activity index k in the generation term of Equation 37 is increased to 1.5, its value obtained from the questionnaire. Thus, the source term for these very tight houses takes the following form:

$$S(k) = 0.24\ k\nu C_{out} + 1.5\ \frac{(1.5)k}{\nu}\ .$$

Table 40 is a summary of the relationship between the classes of families and the two types of indoor TSP generation.

TABLE 40. INDOOR TSP SOURCE STRENGTH SUMMARY
$S = S_R + S_G$

	Resuspension rate ($S_R = 0.24\ k\nu C_{out}$)	Generation rate ($S_G = k(1.5)/\upsilon$)
Inactive	k = 4	k floats
Typical	k floats	k floats
Active	k floats	k floats for $\upsilon \geq 0.2$ k = (1.5) (Value of daily k index) for $\upsilon < 0.2$*

* Owing to the few examples available, this has not been verified separately.

DISCUSSION AND CONCLUSIONS

The steady-state TSP model developed in this section employs an empirical approach to estimate indoor levels of TSP matter. Using a portion of the data base, a two-part indoor TSP source strength term is formulated. The indoor TSP source strength consists of the resuspension term, which refers to the reentrainment and dispersion of TSP matter that preexists indoors and becomes airborne by mechanical procedures, and the generation term, which refers to sources that produce particulate matter in the indoor environment. Table 41 illustrates pairs of observed vs. estimated values for three different houses corresponding to families with three different activity levels.

Figure 33 illustrates that the estimated value is almost always within the range of the observed daily values. Thus, while it may not agree with the observed indoor average, it falls within the observed daily range. An effort was undertaken to verify the estimated values against the observed indoor TSP averages using a portion of the data base that was not utilized in the formulation of the model. On a pair comparison, over 60% of the pairs (observed indoor averages and predicted values) are within 30% of each other, an additional 35% of the pairs are within 50%, and the remaining 5% show larger differences.

TABLE 41. COMPARISON OF INDOOR OBSERVED TSP LEVEL, AGAINST TSP LEVELS ESTIMATED WITH STEADY STATE MODEL

Inactive		Typical		Active	
Indoor Observed	Indoor Estimated	Indoor Observed	Indoor Estimated	Indoor Observed	Indoor Estimated
11.3	22.4	148.0	107.0	68.3	63.5
25.3	27.7	115.0	111.0	101.3	108.6
x	x	105.0	102.0	108.7	128.5
x	x	84.0	69.0	89.0	105.2
26.7	20.5	58.0	45.0	77.7	47.2
39.7	34.3	114.7	61.3	72.0	79.9
x	x	136.7	44.0	81.7	98.0
31.7	29.6	63.7	49.5	43.7	32.7
28.8	37.7	103.3	38.0	45.7	74.6
26.7	20.0	x	x	88.7	55.6
21.7	19.2	102.0	60.0	83.5	73.2
35.7	62.4	94.3	142.0	91.0	65.7
75.3	93.8	137.0	87.7	86.0	78.8
x	x	88.7	48.0	93.0	45.2
36.0	42.6				
56.7	61.9				

x = not available

In the past the TSP indoor-outdoor association has been given as a ratio relationship. The present indoor-outdoor study has conclusively demonstrated that this does not realistically describe the situation and that ratios of indoor values to outdoor levels vary from 0.3 up to 3.6 depending on a series of inputs. Among the most crucial factors that determine the indoor-outdoor TSP relationship is the family activity. The steady-state TSP model takes this factor under consideration, and it estimates the observed indoor-outdoor ratio relationships.

Further work needs to be undertaken. More reliable family index values are necessary. The questionnaire used and the approach suggested have provided valuable information; however, the integrity of some of the answers is questionable. In addition, further work needs to be done in order to estimate the removal factor and the cleansing factor which have been parameterized in this present study.

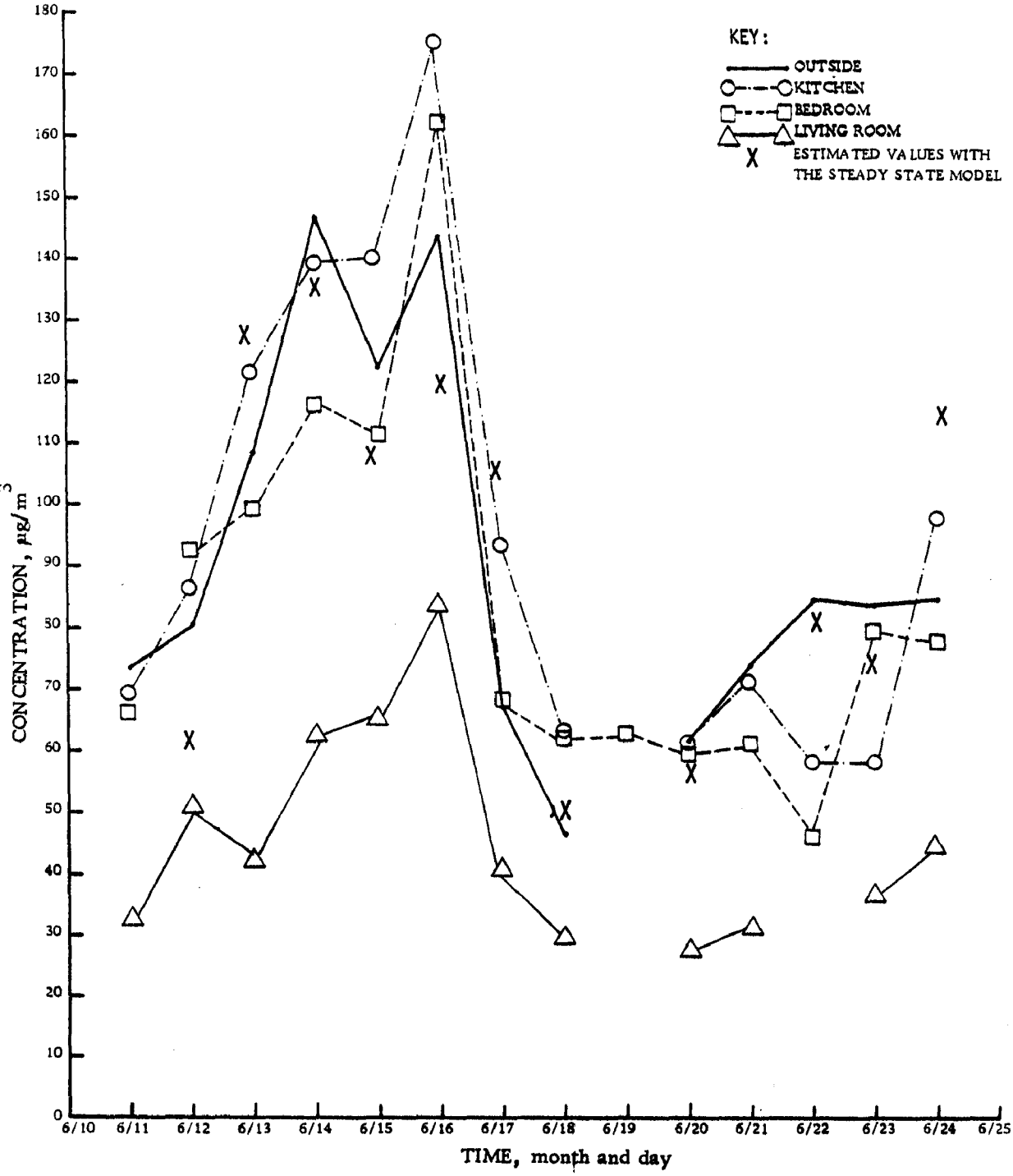

Figure 33. Estimated values of indoor TSP using the steady-state model for the Pittsburgh high-rise apartment 3.

On the other hand, the steady-state TSP model illustrates how basic physical principles can be expanded to apply to a variety of conditions and to estimate indoor TSP concentrations. The model has been successfully used to predict indoor concentrations when the outdoor TSP concentration and the family activity index are known. In addition, the model can be used to predict the indoor TSP levels when only the outdoor levels are known and a family activity classification is assumed. For such cases the activity index is given the values of 4, 7, and 10 for inactive, typical, and active families, respectively.

In conclusion, several features of this phenomenological approach separate the steady-state TSP model from previous efforts to estimate indoor TSP levels: 1) individual indoor source strengths are not estimated; rather, an overall family activity index is used to relate outdoor TSP levels to indoor concentrations; 2) the model, in agreement with the observed data, shows that as a factor indoor resuspension of infiltrated TSP matter is at least as important as the indoor generation of total suspended particulate matter; 3) previous studies have used a constant ratio value to relate outdoor TSP levels to corresponding indoor concentrations; the steady-state TSP model estimates indoor TSP levels and ratio values which vary as a function of the activity index. The calculated ratio values show good agreement with the observed ratios. The steady-state TSP model is easy to use, inexpensive, and does not require complex computer procedures to estimate the indoor TSP levels.

SECTION 4

ENERGY CONSIDERATIONS*

The evaluation of the relationships between total energy use for a residence, its space conditioning energy use, and the conditioning energy use due to infiltration are important when examining the energy use profiles within selected residences. In order to evaluate the total energy use within a residence, certain data are required.

ENERGY DATA COLLECTION

It is essential that the total power consumption be measured on an hourly basis. For each residence, measurements are made by employing two recording ammeters. Each meter is connected such that the positive legs of the power lines to a residence are monitored. The instrument range normally employed for the measurement is 0-50 A; however, during the winter heating season, often a 0-250 A range is employed. The recording ammeter chart has five 12-min divisions per hour. The average percent chart deflection for each 12-min period is estimated for each strip chart, and five 12-min periods are added together for each hour. This average percent of the chart deflection is then multiplied by the instrument range, which results in the estimation of the electric current. The amperage per hour is then multiplied by the voltage of the positive line, giving a net result in watthours. One hundred-twenty volts is used as the average line voltage for residential use. Final reporting is represented in kilowatthours.

In addition to the above measurement, daily readings of watthour meter are usually made. This information is reported in kilowatthours per day.

The above procedure identifies the power usage due to electrical equipment, but it does not identify the energy used by equipment operating with different fuel sources. Oil and gas furnaces are examples of such types, and measurements are discussed below.

Oil Furnaces

To determine the hourly consumption of heating oil, a recording ammeter is attached to one leg of the 120 V power line going to the furnace oil pump. Each time the pump is activated, the duration of its operation is recorded on the recording ammeter. The oil pumping time per hour is determined from this recording. This time is then multiplied by the pump rate and burner nozzle specification which is supplied by the furnace manufacturer to obtain the volume of oil consumed per hour. A daily measurement of the oil consumption is made by measuring the volume of the oil tank and the daily replacement employing a dip stick. This measurement is used as a quality control check for the hourly measurements.

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* Prepared by Hittman Associates, Incorporated.

Gas Furnaces

Gas consumption rates from gas furnaces are monitored indirectly by attaching a recording ammeter on the furnace blower. The furnace thermostat is set at a fixed temperature point during the data collection, and the furnace operates on the following cycle:

1. Gas ignites to heat furnace bonnet to set temperature (time for this activity is measured and is constant for each cycle).

2. When the bonnet reaches its proper temperature, the furnace blower is switched on, and the activated recording ammeter measurement begins.

3. Gas combustion continues until the thermostat reaches desired temperature, then the gas valve is closed electrically.

4. The blower continues to operate until the furnace bonnet cools to a predetermined temperature and the blower is deactivated. This portion of the time cycle is measured and is constant. The gas consumption per minute, while the furnace is in operation, is read from the gas meter.

From the above data the gas usage per hour is calculated.

After conversion to Btu's, the energy required by a gas or oil furnace is added to the energy due to electrical equipment, and the total power consumption is obtained. Power consumption can then be plotted against time, so that an hourly profile can be produced. The profile reflects the energy requirements for space conditioning and inhabitant use.

It is important that the space conditioning energy be compared with the total power requirements of a residence. This is determined by measuring the hourly conditioning electricity used by air conditioners, heat pumps, and electric furnaces. This is in addition to the measured values for gas and oil furnaces. Measurements for electric furnaces, heat pumps, and air conditioners are discussed below.

Electric Furnace

For an electric furnace, the amperage is monitored with the recording ammeter. This ammeter is connected to the power line of the resistance heating coil. Should more than one resistance heating coil be employed within the furance, and they are wired separately, the amperage of each line is monitored. Since all electric home heating units are 240 V, only one of the two positive 240-V lines is monitored. The average percent chart from the recording ammeters is determined for each hour, added together, multiplied by 2 to account for the 240 V supply, then multiplied by the ammeter range to obtain watts per hour. Kilowatthours are reported.

Heat Pumps and Air Conditioners

The methods for monitoring power consumption for heat pumps and air conditioners are the same except that heat pumps normally have auxiliary resistance coils. The power consumption for these coils is monitored as described for the electric furnace. A heat pump or central air conditioner is monitored by employing a recording ammeter on one leg of the 240 V supply line. The calculations to obtain kilowatthours are the same as described above for the electric resistance furnace.

Utilizing the previous methodology, it is possible to plot the hourly profiles of total power consumption and space conditioning energy usage for all the residences being studied. An important question remains unanswered, How much of the conditioning energy use is due to infiltration of outside air?

Calculation of Air Infiltration

Based on the physical and climatological data collected at each of the residences, the energy required in changing the temperature and humidity of infiltrated air to meet inside requirements can be shown relative to the total house power and space conditioning energy on an hourly basis. These relationships are the next topic of discussion.

It has been previously mentioned that indoor air quality is a function of air exchange rates within residences. Infiltration of outside air is considered to be one of the major components of heating and cooling loads. During the heating season, depending on how well a structure is insulated, 14 to 53% of the total residential structure heat loss is due to infiltration, while in the cooling season, 11 to 27% of the total structure heat gain is due to infiltration (Hittman Associates, 1977). Thus, the significance of reduced infiltration relates directly to the annual energy use of a residence.

Infiltration is commonly known as air leakage into a residence through cracks and interstices around windows, doors, floors, and walls. Its magnitude depends on the type of construction, workmanship, condition of the structure, and climatological environment.

The air flow rate into or out of a residence due to infiltration or exfiltration depends greatly on the resistance to air flow through openings in the residence as well as the indoor-outdoor pressure difference, the indoor-outdoor temperature difference, and the life style of the inhabitants.

The size of the openings has a great effect on the amount of air flow in or out of a residence. Openings usually occur around windows, window frames, doors, door frames, exterior walls, and the ceiling areas. It is often easier to consider all these crack areas as if they were one opening through which all the in-out air flow is occurring. The opening is

commonly called the "equivalent orifice area" (EOA). It is a very effective measure by which the relative air-tightness of a residence can be compared with other residences.

Currently, two recommended calculation procedures (crack methods) give reasonable estimates for the equivalent orifice area (ASHRAE, 1977). It must be understood that the accuracy of these methods is limited by the data available on the air leakage characteristics for the variety of components used in a residence and by the differences that develop between the components as tested and as installed or constructed.

The first method, though more complex, will result in a better estimate for the equivalent orifice area. It is based on the openings in the building envelope and is a constant for a particular residence. The major openings are the cracks in windows, doors, window and door frames, walls, and ceilings. Therefore, the EOA can be expressed as:

$$EOA = \left(L_x \cdot t_w\right) + \left[\left(\frac{L_w' \cdot t_w'}{L_{sw} \cdot t_{sw}}\right)^{1/n} + 1\right]^{-n} \cdot \left(L_w' \cdot t_w'\right) + \left(L_{wf} \cdot t_{sf}\right)$$
$$+ \left(L_d \cdot t_d\right) + \left(L_{gd} \cdot t_{gd}\right) + \left[\left(\frac{L_d' \cdot t_d'}{L_{sd} \cdot t_{sd}}\right)^{1/n} + 1\right]^{-n} \cdot \left(L_d' \cdot t_d'\right)$$
$$+ \left(L_{df} \cdot t_{df}\right) + \left(L_{ew} \cdot t_{ew}\right) + \left(L_c \cdot t_c\right) \qquad (38)$$

where:

EOA = Equivalent orifice area for the residence

L_w = Crack length for prime windows without storm windows

t_w = Crack width for prime windows without storm windows

L_w' = Crack length for prime windows with storm windows

t_w' = Crack width for prime windows with storm windows.

n = Flow exponent, ranges from 0.5 and 1.0 (assume 0.6)

L_{sw} = Crack length for storm windows

t_{sw} = Crack width for storm windows

L_{wf} = Crack length for storm windows

t_{wf} = Crack width for window frames

L_d = Crack length for doors without storm windows, except sliding glass doors

t_d = Crack width for doors without storm windows, except sliding glass doors

L_{gd} = Crack length for sliding glass doors

t_{gd} = Crack width for sliding glass doors

L'_d = Crack length for storm doors

t'_d = Crack width for storm doors

L_{df} = Crack length for door frames

t_{df} = Crack width for door frames

L_{ew} = Crack length for exterior walls

t_{ew} = Crack width for exterior walls

L_c = Crack length for ceiling

t_c = Crack width for ceiling.

A still useful, but less sophisticated method for estimating the equivalent orifice area can be represented by the following equation:

$$EOA = (N_W \cdot A_W \cdot C_W) + (N_D \cdot C_D) + (A_{wr} \cdot C_{wr}) \quad (39)$$

where:

N_W = Number of windows

A_W = Area of average window

N_D = Number of doors

A_{wr} = Total wall and roof area.

The coefficients C_w, C_D, and C_{wr} are obtained from Table 42, depending on the type of windows, doors, wall, and roof construction found in a residence.

TABLE 42. ESTIMATED VALUES FOR C_w, C_D and C_{wr}

Windows	C_w
Poorly Fitted	12.0×10^{-3}
Average Fitted	8.0×10^{-3}
Weatherstripped	6.5×10^{-3}
With Storm Windows	5.5×10^{-3}
Doors	**C_D**
Poorly Fitted	0.3
Average Fitted	0.25
Weatherstripped	0.20
With Storm Doors	0.17
Walls and Roof	**C_{wr}**
Poor Workmanship	5.6×10^{-4}
Good Workmanship	2.8×10^{-4}

It is now possible to estimate an effective opening, equivalent to all the crack area in a residence. This effective opening or equivalent orifice area is ranked in Table 43 for each residence included in this study according to its relative "airtightness."

The EOA by itself is not sufficient in characterizing the structural parameters necessary for proper estimation of the energy use due to infiltration. A second parameter, namely "building size or volume," is incorporated with the EOA to reveal a new parameter known as the "orifice coefficient." As shown below, this parameter is the normalization of the equivalent orifice area by the building volume, and this results in a factor that represents not only building tightness but also building size.

$$\text{Orifice Coefficient (OC)} = \frac{\text{Equivalent area of all the openings in the building envelope (EOA)}}{\text{Volume of the residence (V)}}$$

As a result of this normalization, the residences in Table 43 are presented in Table 44 in order of their relative tightness and size.

TABLE 43. EQUIVALENT ORIFICE AREAS

Residence	Building Type*	Equivalent Orifice Area (ft^2)†	Air Tightness
Pittsburgh Apartment	MFLR	0.53	Tight Residence
Pittsburgh Apartment	MFHR	1.29	
Pittsburgh Mobile Home 2	MH	1.42	
Baltimore Experimental	SFA	1.81	
Chicago Experimental	SFD	2.16	
Baltimore Conventional	SFA	2.65	
Pittsburgh Mobile Home 1	MH	2.81	
Washington Experimental	SFD	3.65	
Denver Conventional	SFD	3.89	
Washington Conventional	SFD	4.27	Loose Residence
Chicago Conventional	SFD	4.29	

* MFLR = Multi-Family Low-Rise; MFHR = Multi-Family High-Rise; MH = Mobile Home; SFA = Single-Family Attached; SFD = Single-Family Detached.

† It is assumed that doors and windows are not in the open position.

TABLE 44. ORIFICE COEFFICIENTS

Residence	Building Type	Orifice Coefficient ($ft^{-1} \times 10^{-4}$)
Chicago Experimental	SFD	0.7
Pittsburgh Apartment*	MFLR	0.8
Pittsburgh Apartment*	MFHR	1.8
Pittsburgh Mobile Home 2	MH	2.0
Baltimore Experimental	SFA	2.3
Washington Conventional	SFD	2.3
Washington Experimental	SFD	2.5
Chicago Conventional	SFD	2.8
Baltimore Conventional	SFA	2.9
Pittsburgh Mobile Home 1	MH	3.3
Denver Conventional	SFD	4.6

* It is assumed that doors and windows are not in the open position.

Although the Washington conventional residence has an EOA of 4.27 ft^2, it had a lower measured infiltration rate than the Baltimore conventional residence which had an EOA of 2.65 ft^2. This is in complete agreement with the orifice coefficients which are 2.3 x 10^{-4}/ft and 2.9 x 10^{-4}/ft for the Washington and Baltimore residences, respectively.

The orifice coefficient is a good representation of building parameters, but it is recommended that physical inspection of the residences be made during future research in this area. This study did not allow for the cutting of holes, or dismantling of any of the residences in order to verify potential crack areas. In most instances, engineering judgment is used in the evaluation of these cracks. For example, a tight residence may have a window and frame crack width of 1/16" and 1/64" respectively, while a loose residence may have 5/64" and 3/128" for its window and frame crack widths.

Once the air exchange rates (air changes/h) are found experimentally for various residential types, a methodology can be developed to estimate the amount of infiltration. In this study, tracer gas in the form of SF_6 is utilized in determining hourly air exchange rates. SF_6 is used mainly because it is nontoxic and decomposes at a relatively high temperature.

By measuring the dilution of the SF_6 gas with time it is possible to obtain the air exchange rate in a residence. It is released in the return air duct of a furnace and monitored in the bedroom, living room, and kitchen. Then the concentration of SF_6 is measured with time, and the air exchange rates (air changes/h) computed using the following formula:

$$\dot{Q} = V \cdot \left[\left(\frac{\ln C_o - \ln C}{\Delta t} \right) \cdot 60 \frac{\text{min}}{\text{h}} \right] \tag{41}$$

where:

$\dot{Q}$ = Air change rate (air change/h)

V = Volume of the residence (ft^3)

C_o = SF_6 concentration at time t = 0

C = SF_6 concentration at time = 't'

Δt = Elapsed time between t = 0 and t = 't' in minutes

In order to properly characterize infiltration into residences, data on climatic conditions is collected. Measurements are taken on an hourly basis to provide readings on wind speed, wind direction, inside-outside temperature, and relative humidity. Equipment and techniques used to obtain climatic data are discussed in Volume II, Chapter 1.

In order to calculate the infiltration energy use, the SF_6 measurements, indoor/outdoor dry bulb temperatures, and indoor/outdoor relative humidity are utilized. First the SF_6 measurements are used directly to identify the infiltration rates (air change/h). Then, using the indoor/outdoor dry bulb temperatures, the sensible heating and cooling loads are calculated. Depending on season (heating or cooling) and presence of humidifiers, relative humidity is used along with the dry bulb temperature to calculate both sensible and latent heat loads due to infiltration. Based on the performance of heating/cooling equipment, the energy use associated with the infiltration loads can be determined.

CALCULATION OF ENERGY USE

The energy use due to the infiltration is estimated by the following equations:

For Heating

$$Q_H = \frac{0.0187(\dot{Q})\ (V)\ (T_r - T_o)}{E} \tag{42}$$

where

Q_H = Heating energy use due to infiltration energy

E = Heating system efficiency

For cooling

$$Q_c = \frac{0.075(H_r - H_o)\ (Q)\ (V)}{E_c} \tag{43}$$

where

Q_c = Cooling energy use due to infiltration (Btu)

H_r = Indoor enthalpy (Btu/lbm)

H_o = Outdoor enthalpy (Btu/lbm)

E_c = C.O.P. of cooling system.

As previously mentioned, one of the objectives of this study is to develop an infiltration model that will relate to residential air quality. The development of such a model includes a summary of steps already taken. First, the building's physical parameters that can affect infiltration rates are identified. Based on the building's physical parameters, EOA is computed as defined. The "orifice coefficient" is then computed by normalizing the calculated EOA. The measured infiltration rates (air exchange rates) can then be normalized with respect to the calculated "orifice coefficient." Finally, the overall model has to be specified.

The infiltration rate is calculated by use of the following model:

$$\dot{Q} = OC\left(A+B\left[T_r-T_o\right] + CV^2\right)^{0.66} \tag{44}$$

where

$\dot{Q}$ = Air change rate (air changes/h)

OC = Orifice coefficient

T_r = Indoor temperature

T_o = Outdoor temperature

V = Wind velocity (mph)

The parameters A, B, and C have been evaluated empirically for a few residences. These values can be used as a first estimate for other residences as well.

The parameters have been evaluated for single-family detached (SFD), single-family attached (SFA), and mobile home (MH) type structures based on data available from SF_6 measurements. The model was then used to calculate the infiltration rates for the hours for which SF_6 measurements were not available.

Data from three SFD structures is used in the evaluation of the following model. This correlation should be utilized only in the evaluation of single family detached homes.

$$\dot{Q} = OC\left(950 + 6135\left[T_r-T_o\right] + 592V^2\right)^{0.66} \tag{45}$$

where

$\dot{Q}$ = Air change rate (air changes/h)

OC = Orifice coefficient

T_t = Indoor temperature

T_o = Outdoor temperature

V = Wind velocity (mph)

Correlation coefficient = 0.95.

Once the air change rate is known from Equation (44), it is a simple matter of using Equations (42) or (43) in order to evaluate the energy due to infiltration.

The hourly total energy use, conditioning energy use, and infiltration energy use are plotted in Figure 34 for the Baltimore conventional residence. As can be seen in this graph, the conditioning energy use represents a high percentage of the total energy use during the entire day, while the infiltration energy use accounts for 50 to 87% of the total energy use. The high percentage occurs during the hours at which the internal load (mainly cooking) and solar radiation heat gain are highest for the day.

Similar energy use patterns are given in Figure 35 for the Washington conventional residence. It is noticed here that the conditioning energy use in the summer also represents a high percentage of the total energy use during the day, except for those hours in the morning when the outside temperature drops to its lowest value. The infiltration energy use accounts for a smaller percentage of the total energy use than that given for the winter in the previous graph. This is due to two factors: first, the infiltration rates were low for this residence compared to those of the Baltimore conventional residence; second, the negative effect of internal loads in the summer reduces the percentage of infiltration load from the total load.

Similarly, a preliminary model has been developed for single family attached structures more commonly known as townhouses. The correlation developed resembles the following:

$$\dot{Q} = OC \left(3592 + 28539 \left[T_r - T_o\right] + 1659V^2\right)^{0.66} \qquad (46)$$

where

Q = Air change rate (air changes/h)

OC = Orifice coefficient

T_r = Indoor temperature

T_o = Outdoor temperature

V = Wind velocity (mph)

Correlation coefficient = 0.9.

Again, energy use data is presented in Figure 36 for the Pittsburgh low-rise apartment. This graph indicates that the filtration energy use between the hours of 1500 and 1800 is larger than the total conditioning energy use. This simply says that the internal load and solar gain during those hours is higher than that due to conduction and infiltration. Therefore it could be stated that the infiltration energy use could reach 100% of conditioning energy use in some residences.

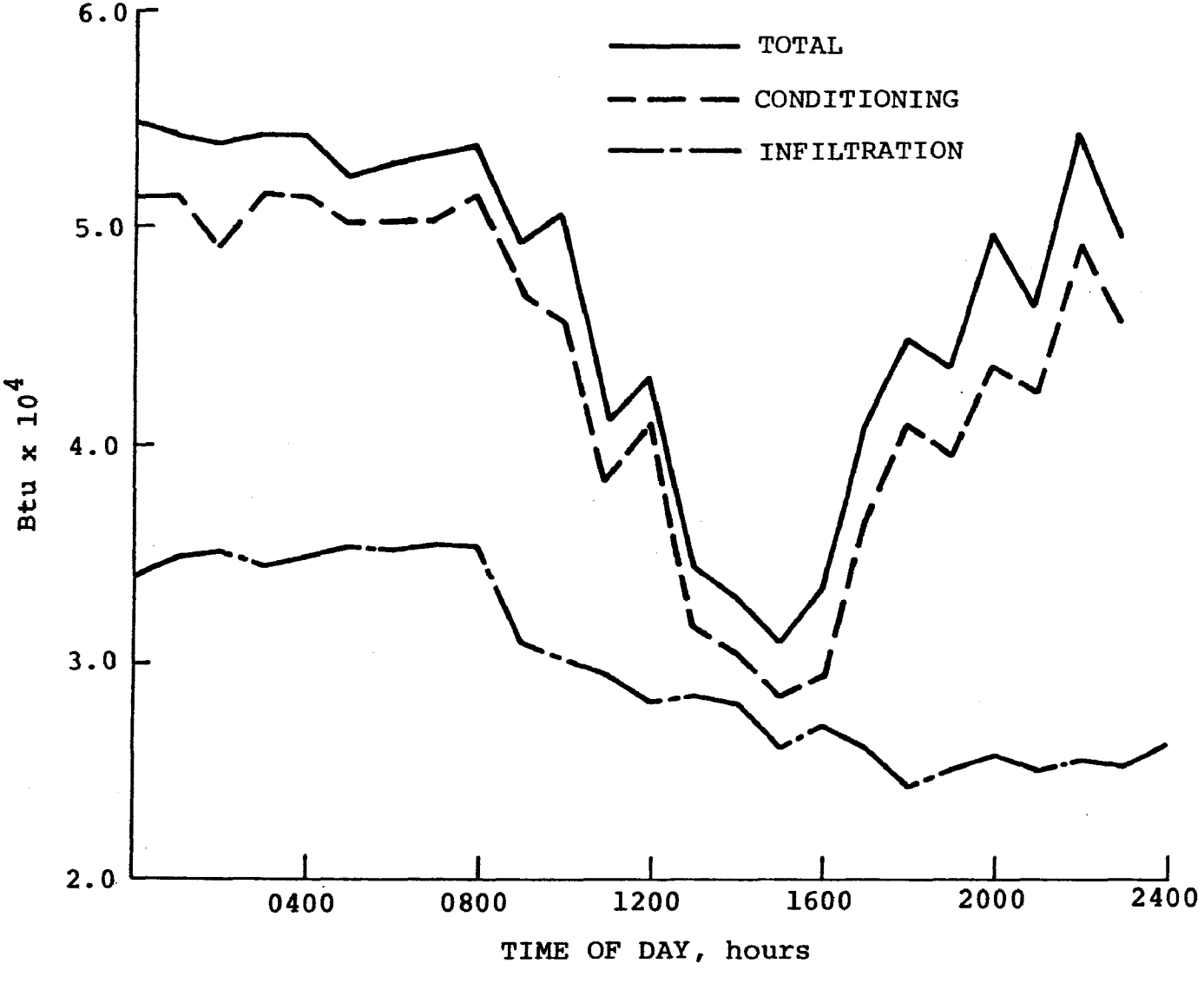

Figure 34. Energy use profile for Baltimore conventional residence on January 31, 1977.

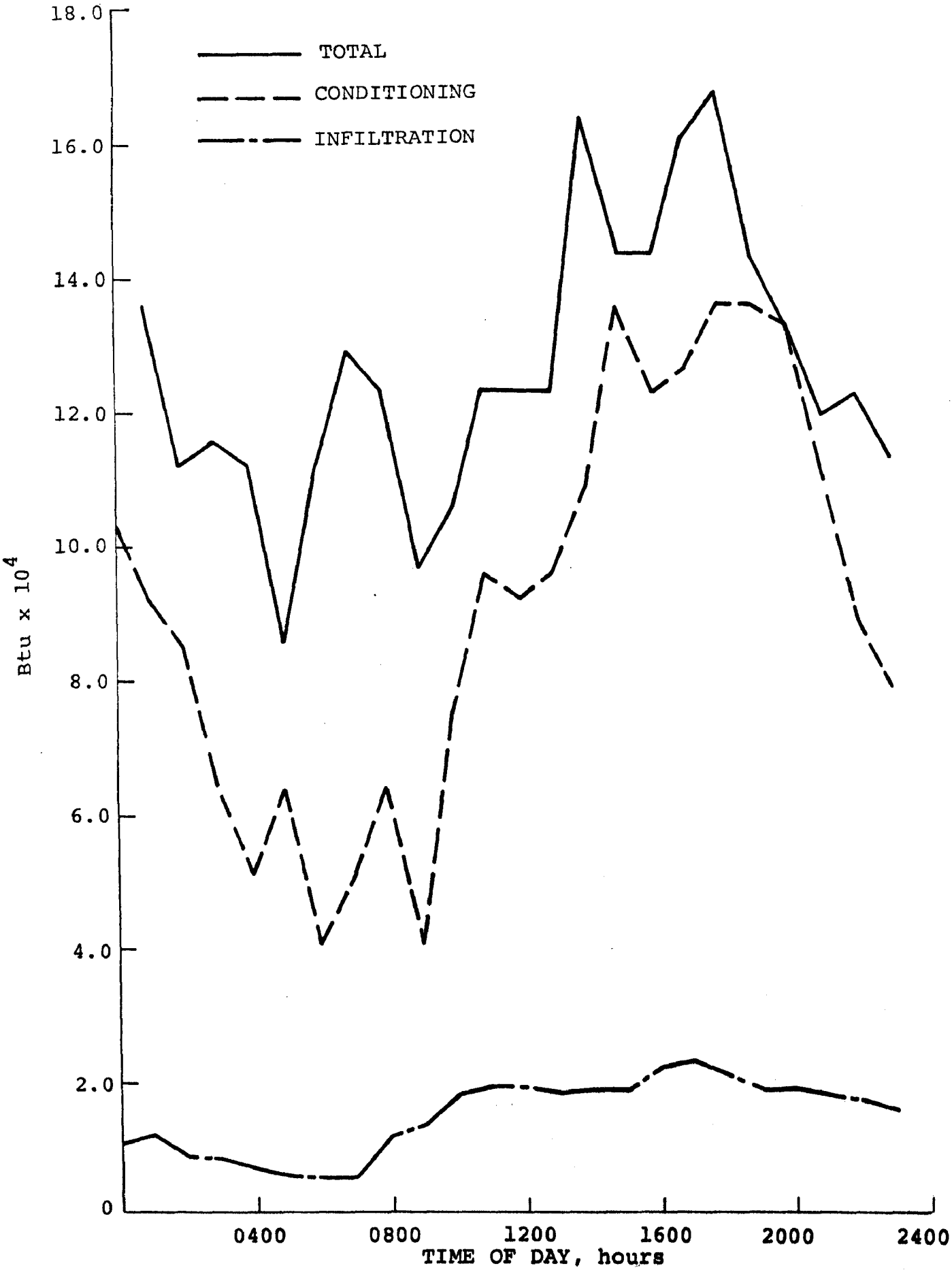

Figure 35. Energy use profile for Washington conventional residence on July 10, 1977.

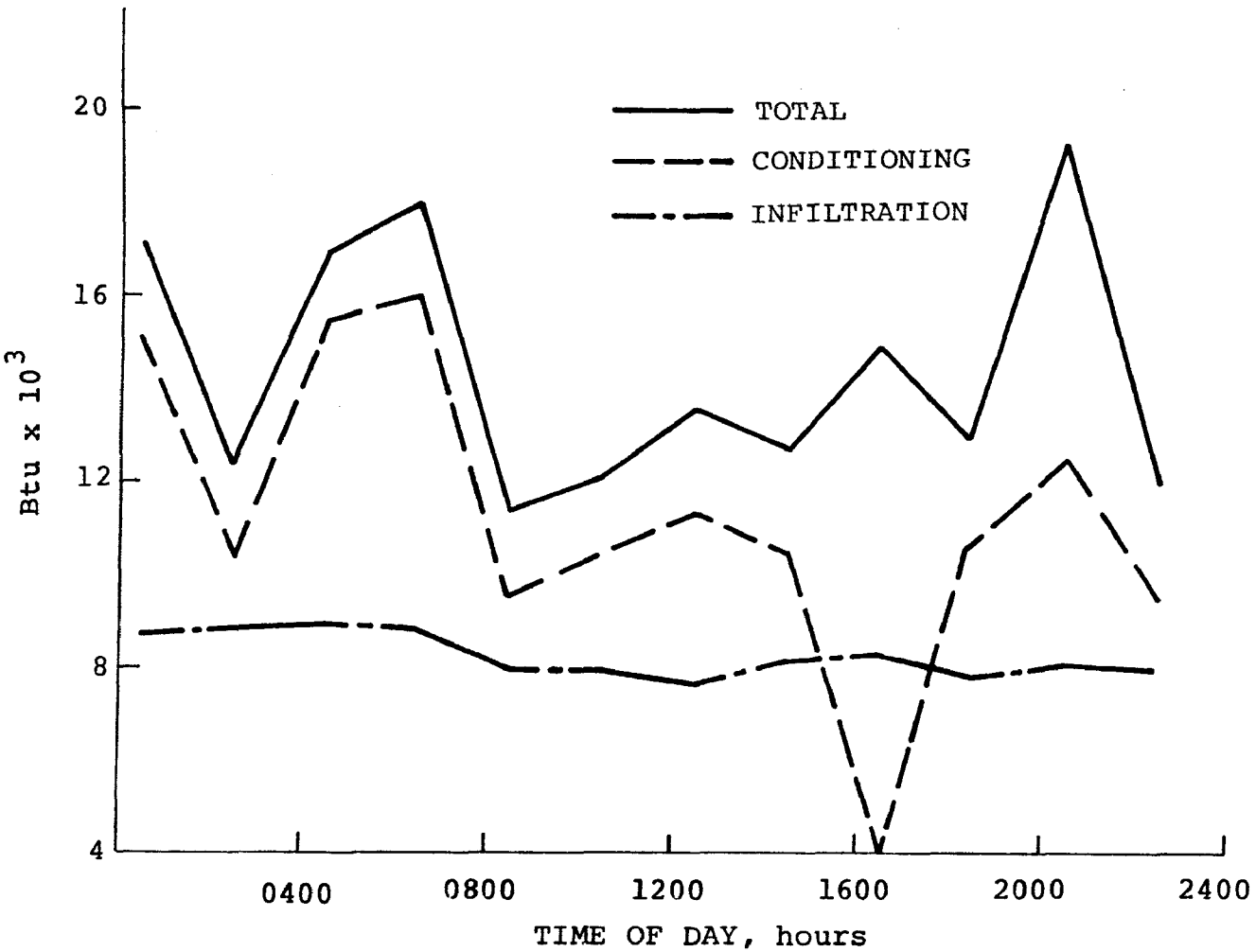

Figure 36. Energy use profile for Pittsburgh low-rise apartment on April 7, 1977.

A model has been also developed for mobile homes, using one of the homes monitored in this study. A preliminary finding indicates the existence of the following relationship:

$$\dot{Q} = OC \left(-5672 + 1299 \left[T_r - T_o\right] + 496V^2\right)^{0.66} \quad (47)$$

where

$\dot{Q}$ = Air exchange rate (air changes/h)

OC = Orifice coefficient

T_r = Indoor temperature

T_o = Outdoor temperature

V = Wind velocity (mph)

Correlation coefficient = 0.9.

It may seem strange that the "A" term is negative, but H. Ross (U.S. Department of Energy, private communication, 1977) has indicated that Princeton University has come up with a similar finding.

The energy use patterns for mobile home No. 1 in Pittsburgh on Feburary 17, 1977, are given in Figure 37. This figure indicates that the percentage of infiltration energy use in this mobile home is far less than the other residences studied. One of the major elements contributing to this fact is the relatively high skin load in this mobile home.

To summarize, many important relationships have been developed and presented in regards to energy use and infiltration in residential structures. For the three types of residences monitored in this study, the following items have been culminated.

- Total energy use as computed by summing the Btu input of all fuel types utilized
- Space conditioning energy use as measured directly
- Infiltration rate (air changes/h) as measured by SF_6 data
- Identification of physical building paramaters
- Computation of the Equivalent Orifice Area (EOA)
- Normalization of the infiltration rates (evaluated from SF_6 data) with respect to the orifice coefficient
- Evaluation of the parameters for the specific infiltration models.

Figure 37. Energy use profile for Pittsburgh Mobile I on February 17, 1977.

It is suggested that more research be done to empirically verify the infiltration models presented in this report. Furthermore, additional experimental data is needed to expand the data base necessary for proper correlation of the model. Once this has been accomplished, it will be easier to estimate the infiltration rate of various residential structures.

Section 5

RESIDENTIAL AIR QUALITY AND ENERGY CONSERVATION MEASURES

Two important ideas about energy conservation and indoor air quality in residences are shaping national decisions on conservation measures. The first is that a residence shelters its occupants from high ambient pollutant concentrations. The second is that measures to conserve energy in a residence do not affect the indoor air quality. The facts are that, while a residence under certain conditions may shelter its inhabitants from high concentrations of some pollutants, under different conditions its occupants may be exposed to concentrations higher than outdoor levels for other pollutants. Also, energy conservation measures will change the air quality characteristics of a residence; these changes may affect air quality either adversely or beneficially.

ENERGY AND COST SAVINGS THROUGH AIR EXCHANGE RATE REDUCTION

Three mechanisms of heat exchange between indoors and outdoors determine the energy conserved in the residential environment: 1) heat conduction; 2) heat transmission through the windows; and 3) heat transmission through door and window openings or structural cracks. The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE, 1972) defines air infiltration, the third heat exchange mechanism, as the rate of air flow into and out of a building without the interference of the building's occupants. Air infiltration must be distinguished from natural ventilation which refers to air changes induced by the inhabitants through specified openings, such as windows, doors, and by ventilators. The majority of residences do not have mechanical systems that control the air exchange rate. The air exchange rate measured by the tracer dilution technique used in this project is a comprehensive term: it estimates the air flow rate into and out of a residence caused by air infiltration and by intentional air movement (natural ventilation) through windows and doors. Energy conservation measures carried out to reduce heat conduction and heat transmission through the windows do not substantially affect the indoor air quality. These measures are essential elements in the effort to conserve energy in residences and will be discussed later in this section.

The physical quantity that associates energy conservation measures with indoor residential air quality is the air exchange rate. Air infiltration is the important link in developing a scheme for monitoring both minimal energy waste and acceptable air quality in residences. The air exchange rate ν is the signature parameter which may simultaneously represent energy and air quality measures.

Infiltration heat losses and heat gains in residential structures are affected by the summation of the following forms of air flow mechanisms: 1) infiltration-exfiltration; 2) infiltration due to door and window

openings; and 3) infiltration due to operation of the HVAC systems. As noted earlier, a fourth mechanism, mechanical control of air exchange rates, is not applicable to residential buildings. Infiltration is the largest factor affecting cooling and heating loads in residences. During the heating season, depending on how well a structure is insulated, 14 to 53% of the total heat losses are due to infiltration. In the cooling season, 11 to 27% of the total structure heat gains are due to infiltration (Hittman Associates, 1977).

The structural components having the greatest effect on the infiltration rate are windows and doors because they have the largest potential for air leakage. Consequently, typical approaches to effectively reduce infiltration rates are weatherstripping around doors and windows, caulking around window and door frames, and the addition of storm doors and windows. Infiltration losses and gains can be reduced by as much as 30% through the implementation of these measures. Table 45 illustrates an example of a 1500 ft^2 house analyzed in three climatic regions. The air exchange rate reference level for this residence is 0.8 air changes per hour; this is considered to be the most frequently occurring rate for existing residential structures.

An air exchange rate of 1.2 air changes per hour is incorporated in Table 45 for comparative reasons. In order to conserve energy, the infiltration rate is first reduced by one-third, then by one-half, and finally it is reduced to one-quarter of its original reference level of 0.8 air changes per hour. Reduction of the air exchange rate, an energy conservation measure, drastically affects the infiltration heat losses during the heating season, and the infiltration heat gains during the cooling season. The heat losses or gains are decreased to about 60% of their original values in all three climatic locations. Table 45 shows the estimated savings that may be obtained by reducing air infiltration. The first five columns in Table 45 are self-explanatory. The sixth column, Infiltration Energy Savings, presents the energy savings in number of therms associated with the various reductions in the air exchange rate. The next column, Dollar Savings, denotes the estimated dollars that could be saved if the designated reduction occurred during the current year. Maximum Implementation Investment, the next column, estimates the maximum investment the homeowner would undertake to save the corresponding number of therms per year over an assumed period of time. Incorporated in this estimate is an 11% home improvement loan over 5 y and a fuel escalation cost of 5% per year. The last column, Projected Implementation Cost, indicates the current material and construction costs required to retrofit the simulated residences and reduce the current air exchange rate of 0.8 to the desired levels.

It can be seen that the maximum amount of permissible energy conservation investment ranges from $500 to a high of $3900. Depending on the type of HVAC system, local fuel costs, and amount of desired infiltration reduction, the most that can be spent must fall within this range for the example 1500 ft^2 single-family residence. The material and construction costs range from $500 to $1600, again depending on the desired amount of reduced infiltration. Present construction and material costs will allow only a one-third

TABLE 45. ENERGY SAVINGS THROUGH REDUCED INFILTRATION FOR A SINGLE-FAMILY DETACHED RESIDENCE

Air Change Rates	Air Change Rate Reduction	Infiltration[A] Loads (10^5 BTU) HT	CL	HVAC Energy Forms	Infiltration Energy[B] Savings (Losses) (10^5 BTU) HT	CL	Dollar[C] Savings (Losses) ($)	Maximum[D] Implementation Investment ($)	Projected Implementation Cost ($)
Baltimore									
1.20		428	131	Gas/Elec	(316)	(30)	$ (11)	N/A	N/A
				Oil/Elec	(302)	(30)	(27)	N/A	N/A
				Electric	(217)	(30)	(302)	N/A	N/A
0.80		235	74						
0.50	Approximately One-Third	159	51	Gas/Elec	125	12	$ 44	$ 588	$ 505
				Oil/Elec	119	12	57	760	505
				Electric	85	12	114	1523	505
0.40	One-Half	126	41	Gas/Elec	179	17	$ 63	$ 840	$ 830
				Oil/Elec	170	17	81	1083	830
				Electric	122	17	164	2182	830
0.20	One Quarter	95	31	Gas/Elec	234	23	$ 83	$1108	$1610
				Oil/Elec	219	23	106	1410	1610
				Electric	157	23	212	2825	1610
Chicago									
1.20		572	98	Gas/Elec	(412)	(22)	$(115)	N/A	N/A
				Oil/Elec	(392)	(22)	(173)	N/A	N/A
				Electric	(281)	(22)	(385)	N/A	N/A
0.80		325	56						
0.50	Approximately One Third	225	39	Gas/Elec	167	9	$ 47	$ 662	$ 505
				Oil/Elec	159	9	90	939	505
				Electric	114	9	157	2103	505
0.40	One-Half	173	30	Gas/Elec	253	14	$ 71	$ 948	$ 830
				Oil/Elec	241	14	107	1430	830
				Electric	172	14	238	3181	830
0.20	One Quarter	139	22	Gas/Elec	310	18	$ 88	$1172	$1610
				Oil/Elec	295	18	132	1758	1610
				Electric	211	18	293	3893	1610
Houston*									
1.20		154	282	Gas/Elec	(150)	(61)	$ (99)	N/A	N/A
				Oil/Elec	Note E	(61)	Note E	N/A	N/A
				Electric	(90)	(61)	(118)	N/A	N/A
0.80		73	173						
0.50	Approximately One Third	45	126	Gas/Elec	51	26	$ 38	$ 501	$ 505
				Oil/Elec	Note E	26	Note E	Note E	Note E
				Electric	31	26	44	593	505
0.40	One-Half	36	109	Gas/Elec	68	36	$ 51	$ 682	$ 830
				Oil/Elec	Note E	36	Note E	Note E	Note E
				Electric	41	36	60	801	830
0.20	One Quarter	25	86	Gas/Elec	89	49	$ 68	$ 911	$1610
				Oil/Elec	Note E	49	Note E	Note E	Note E
				Electric	53	49	80	1058	1610

* Example of a Southern City.

NOTE A: Weather Base

Yearly Heating Degree Days	Baltimore	4425	Yearly Cooling Degree Days	Baltimore	1112
	Chicago	6013		Chicago	983
	Houston	1387		Houston	2570

NOTE B: Includes the following HVAC Seasonal Efficiencies

	Baltimore	Chicago	Houston
Gas	0.61	0.60	0.54
Oil	0.64	0.63	Note E
Electric (Resistance Heat)	0.89	0.88	0.90
Electric (Air Conditioning)	1.90	1.89	1.79

NOTE C: Energy Costs ($ Dollars/Therm)

	Gas	Oil	Electricity
Baltimore	0.24	0.36	1.18
Chicago	0.21	0.37	1.28
Houston	0.34		0.78

NOTE D: Assumes 9% load for 30 y.

NOTE E: Oil is not a source of heat in the Houston area.

reduction in air change rate from the assumed base value of 0.8 air changes per hour in warm regions. Furthermore, it is only in the colder climatic regions that an additional reduction in infiltration can be cost-effective for HVAC systems utilizing the three fuel types. A reduction in the air exchange rate is seen to be cost-effective if the maximum implementation investment is greater than or equal to the projected implementation cost. All values included in this table have been generated by numerical models; the output is subject to the constraints of the model used for simulations.

The techniques used in arriving at the above estimations are explained in the literature (Hittman Associates, 1977). The estimates included in Table 45 may be thought of as indicative of the effects that reduction of the air exchange rate would have in the Baltimore experimental and the Chicago conventional residences. The Houston residence is included as an example of a southern city with different climatic and financial inputs. The magnitude of the quantities illustrated is not as important as the relative change estimated. From this perspective the application of presently known insulation, weatherstripping, and caulking techniques reduce the infiltration rate and conserve energy. These energy conservation measures are cost-effective if the air exchange rate of a residence is reduced from an average value of 0.8 air changes per hour to about 0.5 air changes per hour. Additional energy will be conserved if further reduction of the infiltration rate is carried out, but it may not be cost-effective.

AIR QUALITY IMPACTS OF ENERGY CONSERVATION

The data base collected by the field monitoring program of this project and the numerical simulations with the GIOAP model demonstrate that the impact of reducing the air exchange rate on residential air quality depends on two additional elements: 1) the strength of an indoor pollutant emission source, and 2) the chemical nature of the pollutant. The relative importance of these factors on the indoor air quality levels will be estimated with numerical simulations.

Gas cooking appliances are not the only sources of indoor-generated gaseous pollutants; however, they are major contributors to the observed indoor concentrations of such pollutants. CO will be utilized as the inert pollutant that indicates the effect of reducing air exchange rates on the residential air quality. Several input parameters of the GIOAP model are assumed:

1. A typical 24-h variation of the ambient CO concentrations is illustrated in Figures 38 and 39. This is the average variation for downtown Los Angeles and may not be typical for a residential area. However, it is chosen to specifically illustrate the points made in the following few pages.

2. One burner is emitting CO between the time periods of 0700 and 0800 hours, and 1200 to 1300 hours; one burner and the oven are emitting CO for the 2-h period between 1600 and 1800 hours;

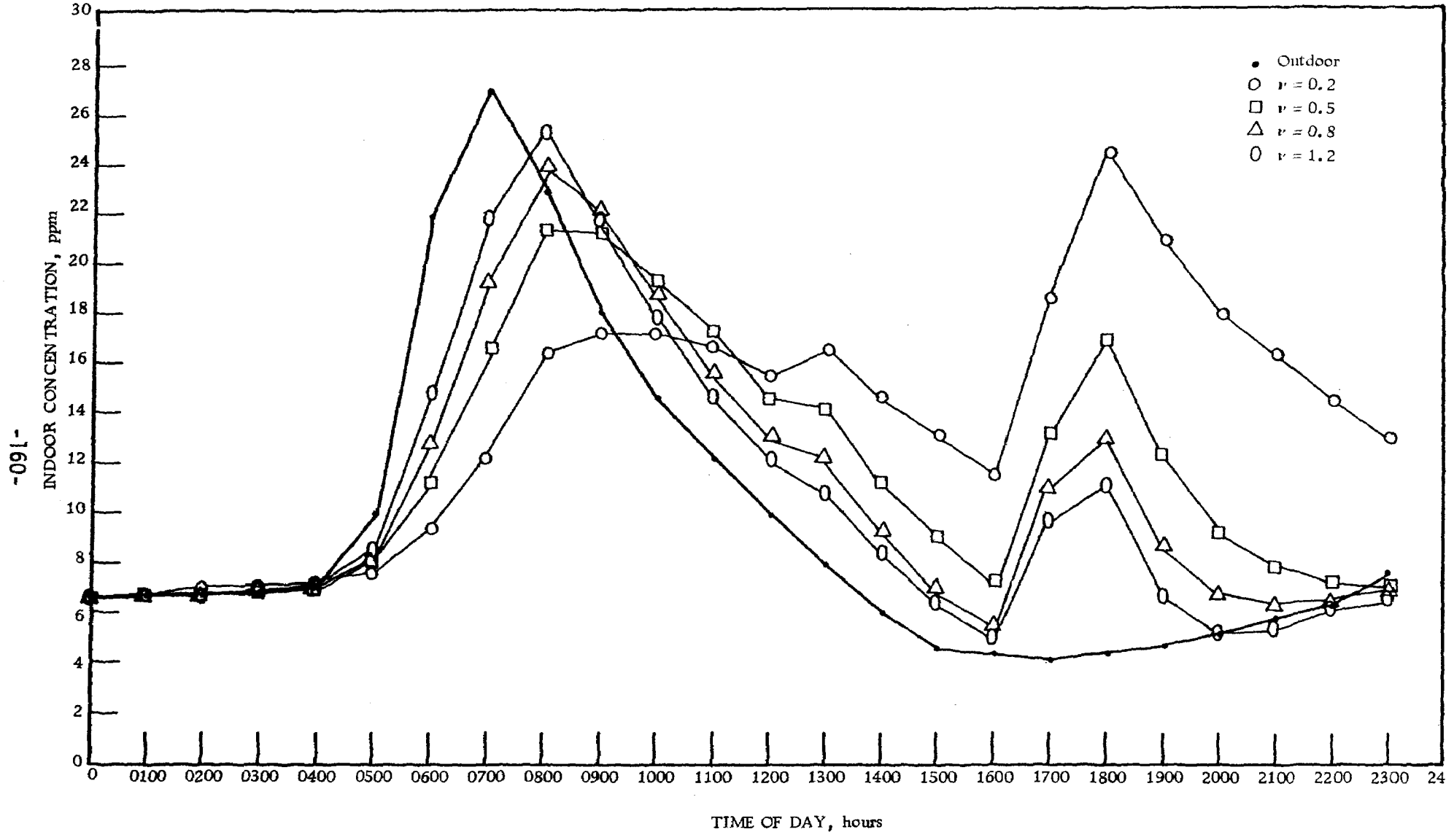

Figure 38. Effect of reducing the air exchange rate in a residence with indoor CO sources.

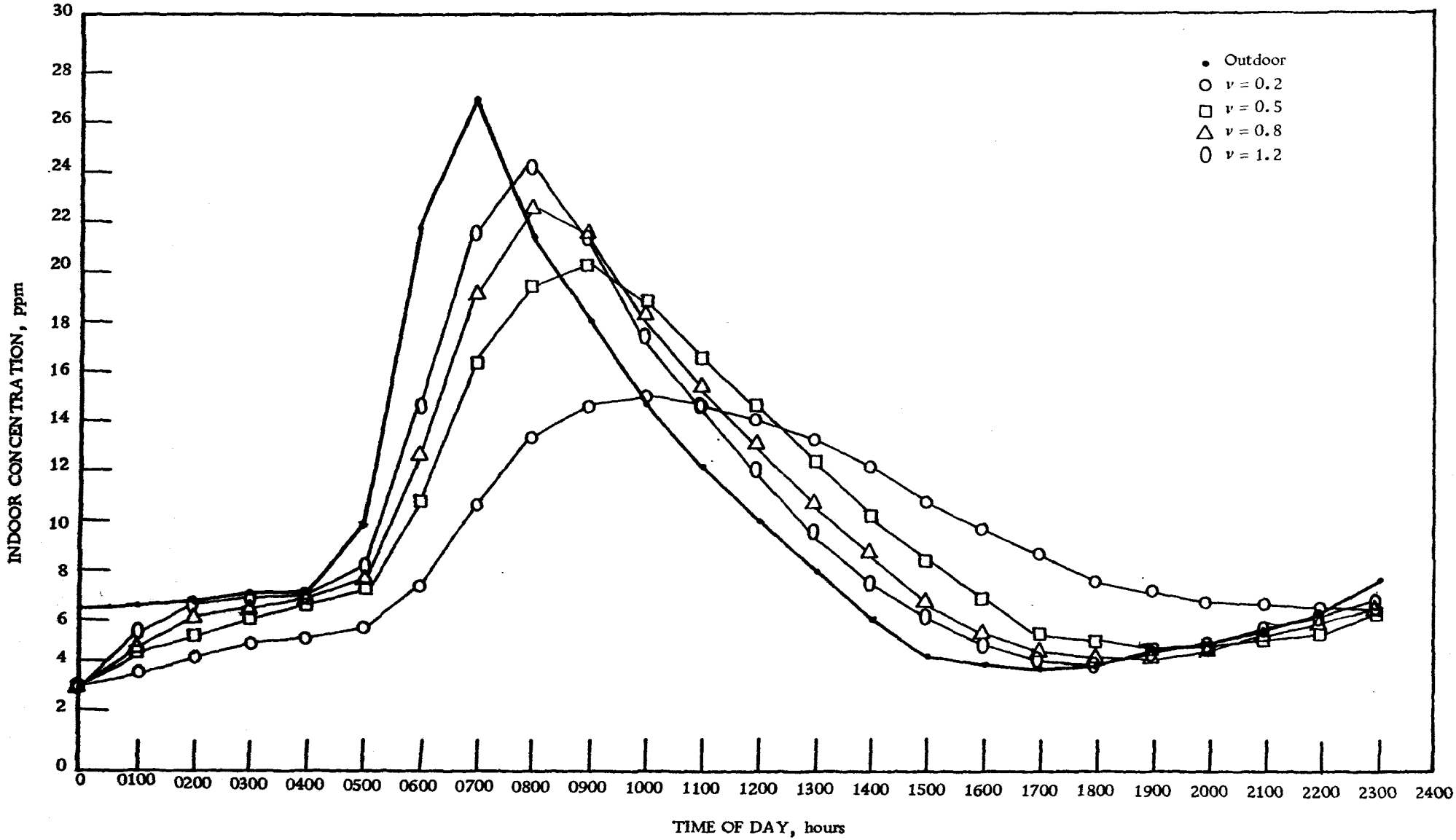

Figure 39. Effect of reducing the air exchange rate in a residence without indoor CO sources.

during the remaining hours CO emissions are from the pilot light. The emission rates corresponding to these indoor CO sources are obtained from the literature. Emissions from the gas furnace are assumed to be negligible. Residences with electric cooking appliances are assumed to have zero or very low CO indoor sources.

3. The volume of the residential structure simulated is 15,000 ft^3.

4. One representative air exchange rate is used throughout a 24-h period.

The effect of reducing the air exchange rate in a residence with indoor CO sources versus one without indoor sources is illustrated in Figures 38 and 39, respectively. Simulations of a residence with an indoor pollutant source, Figure 39, shows that, in the early morning hours when the simulated outdoor levels are high and the indoor sources are weak, reduction of the air exchange rate, denoted by ν, decreases the indoor CO concentrations. However, later during the time period between 1600 and 1800 hours, when the ambient CO concentrations are low and the indoor emission sources are strong, the effect is the opposite, and reduction of the air exchange rates leads to higher indoor CO levels. This morning and late afternoon-early evening behavior has been noticed in the monitoring study and can be explained by physical principles. The high outdoor levels remain outside because reduced air exchange rates imply that less air infiltrates indoors. The afternoon deterioration of the indoor air quality is due to the "trapping," lack of dispersion, of the indoor-generated CO. The "trapping" of the pollutant in the indoor environment of an electric residence is also illustrated in Figure 39 which shows that the reduction of the air exchange rate has a less pronounced effect on the overall indoor air qualtiy. The cumulative 24-h exposure is a parameter of interest because it illustrates the total effect of reducing infiltration rates. The cumulative exposure is measured in units of concentration-hours and is equivalent to the area under the curve of concentration vs. time. Table 46 shows the ambient exposure and the exposures for the four air exchange rates considered.

TABLE 46. ESTIMATED 24-HOUR INDOOR CARBON MONOXIDE EXPOSURE*

Air Change Rate	Residences with Gas Cooking Appliances Typical Operation of Indoor CO Sources	Residences with Electric Cooking Appliances No Indoor Sources
Ambient	226	226
1.2	247	223
0.8	258	222
0.5	275	221
0.2	320	210

* Units: ppm-hours.

CO is an inert pollutant; the effect of reducing the air exchange rate on the concentrations of a relatively reactive pollutant is quite different. Owing to the reactive nature of NO_2, indoor concentrations of the pollutant are generally lower than corresponding outdoor levels. If the indoor NO_2 emission source is strong, it is likely that for a short period of time, during the operation of the source, the indoor NO_2 concentrations will be higher than the outdoors. Simulations, similar to the ones described in detail for CO, demonstrate that for a typical daily variation of ambient NO_2 concentrations, the outdoor 24-h exposure is 4188 $\mu g/m^3$-hours, the range of indoor exposure with gas cooking appliances varies from 2067 to 2873 $\mu g/m^3$-hours, corresponding to residences with air exchange rates of 0.2 and 1.2 air changes per hour, respectively. For the same ambient conditions, the indoor 24-h exposures of an electric house with no NO_2 emission rates vary from 479 to 1972 $\mu g/m^3$-hours. The low cumulative exposure is manifested in the residence with 0.2 air changes per hour, while the other end of the range refers to simulations of a residence with 1.2 air changes per hour.

The data base collected for this project, combined with the results of numerical simulations carried out with the GIOAP model, demonstrate that from the perspective of air quality, reduction of the air exchange rate, an energy conserving measure, may lead to deterioration of the residential air quality. If the pollutant under consideration is inert and is not generated indoors, the effect of decreasing the air exchange rate is not substantial. If the pollutant is inert and, in addition to infiltrating from outdoors, is generated indoors, reduction of the air exchange rate increases the indoor contaminant levels. On the other hand, if the pollutant is reactive and is not generated indoors, reduction of the air exchange rate will decrease the indoor pollutant concentrations. Finally, if the pollutant is reactive and is generated indoors, reduction of the air exchange rate will decrease the indoor pollutant concentrations. The major source of indoor-generated pollutants, cooking with gas appliances, emits both inert and relatively reactive pollutants. Thus, a decrease of the air exchange rate in a residence with gas appliances results in an overall increase of the CO and NO indoor concentrations and a decrease of the NO_2 concentrations.

It is apparent that reduction of the infiltration rate leads to energy conservation and often to deterioration of the residential air quality. However, further examination gives rise to a "desirable" air exchange rate which takes under consideration the following factors involved in the complex residential energy-air quality system:

- The relative changes of the indoor air quality induced by the reduction of the air exchange rate,
- The cost estimates involved in carrying out energy conservation methods balanced against the financial gains to be realized by the measure, and
- The national requirements to conserve energy and protect the welfare of individuals.

An air exchange rate of 0.5 air changes per hour is suggested as a practicable level for existing houses with gas cooking appliances. This air exchange rate is derived on the basis of presently available retrofitting techniques, cost estimates, and pollutant emission rates. A residential air exchange rate of the proposed magnitude represents a reduction of the current average residential rate of 0.8 air changes per hour; it is cost-effective (recall discussion of Table 43) and does not induce drastic changes in the indoor air quality. In houses with electric cooking appliances, a major source of indoor pollutant emissions is eliminated; therefore, energy conservation and cost-effectiveness become more important in the deterioration of a practicable air exchange rate. Regardless of this change of emphasis, the practicable air exchange rate remains 0.5 air changes per hour because of pollutants that are not emitted by gas appliances.

Several points must be made with respect to the practicable air exchange rate:

1. The practicable air exchange has been determined by considering changes in the magnitude of the pollutant concentrations but not in the resulting health effects. This approach is preferred because the health effects due to increasing indoor pollutant concentrations have not been studied extensively and are not well understood.

2. The numerical value of the practicable air exchange rate should be thought of as a small range varying between 0.4 and 0.6 air changes per hour.

3. The practicable rate does not imply that current construction techniques capable of building dwellings with very low air exchange rates (0.1 air changes per hour) should not be used; rather it states that in such super tight-energy conserving residences special care must be taken to keep indoor pollutant concentrations from reaching levels that exceed the EPA promulgated NAAQS.

AIR QUALITY CONTROL MEASURES

The practicable air exchange rate is one of many means suggested for controlling residential indoor air quality. However, techniques can be applied that may reduce the levels of indoor air pollutants. If in fact these measures are implemented, a further decrease in a structure's air exchange rate could be possible, which would result in additional energy conservation. The following discussion investigates several measures to control residential indoor air quality.

Indoor-generated pollutants are dispersed by infiltrated air. If the emission rates of gas appliances remained at current levels while sharp decreases in air exchange rates occur, indoor air pollutants could accumulate to potentially dangerous levels. Gas appliances emit NO, NO_2, and CO internally, and elevate residential concentrations of these pollutants. There is an agreement among relevant studies on the emission rates of indoor

pollutant sources; Table 47 (Cote et al. 1974) is an example of pollutant emission rates from gas appliances. Research must be directed towards reducing the emission rates of indoor pollutant sources. Substantial decrease of these emission rates may lead to further reduction of the practicable residential air exchange rate and conserve additional energy.

One approach towards reducing pollutant levels may be found by venting pollutant-generating appliances. At first review, this is an attractive idea, but history has proven otherwise. Approximately 40 y ago, vented gas ovens/stoves were being produced in this country. There were even isolated cases of vented gas ovens/stoves being produced circa 1946 because standards set up by the American National Standards Institute (ANSI) and the American Gas Association (AGA) called for manufacturers to make them available if they were so requested by consumers. About 1950 this standard was dropped, and the vented oven has not been manufactured since. Economics and consumer demand led to the demise of this device. The draft diverter, which is necessary for proper stack flow, had to be installed approximately 6 in. from the stove, with the chimney or stack being installed an additional 6 in. from the wall. This resulted in the stove being at least a foot away from the wall. This was necessary to eliminate any possible fire hazards, but, as a result, it increased costs because of the additional material and installation procedures required. It also became an undesirable consumer product because the stove had to be considered a separate element and therefore could not be built into the kitchen cabinetry (McGee, 1977). Furthermore, the makeup air required for the venting had to come from the kitchen area, thus introducing an energy conservation problem.

It has been mentioned that as air exchange rates decrease the concentrations of indoor-generated air pollutants increase, thus leading to a potentially harmful environment. A gas stove/oven combination is a major source of CO. The installation of a CO detector will alert the inhabitants of high indoor CO concentrations. This device would sense the levels of CO in the kitchen and activate an alarm if the levels became dangerous. Venting of kitchen appliances, opening the windows and curtailing cooking activity would be some of the necessary steps towards reducing indoor CO levels. Currently, such devices cost between $950 and $1100. The desire to conserve energy and protect the public health appears to be a sufficient cause for using the CO alarms in institutional buildings. In addition, the increasing public awareness of possible health hazards from deteriorating indoor air quality combined with possible mass production of the devices will lower present cost and increase the accessibility and use of such alarms.

Baumeister (1967) suggests the following techniques for removing gaseous pollutants from the air:

- Combustion of pollutant gases sometimes coupled with a catalytic converter
- Absorption of the gas by a solution

TABLE 47. SUMMARY OF POLLUTANT EMISSION OF GAS APPLIANCES FOR SEVERAL TYPICAL OPERATING CONDITIONS IN HARTFORD DWELLINGS

Appliance	Operation	Heat Input Rate (Kcal/h)	Pollutant Emission Rates mg/Hr		
			NO	NO_2	CO
Older Gas Stove with Cast Iron Burners	Pilot Lights:	150	6.8	8.2	62.9
	1 Burner - High Flame	2700	250.0	140.0	1031.0
	3 Burners - High Flame	6780	793.0	494.0	3220.0
	Oven:				
	Transient	2300	361.0	366.0	4117.0
	Steady-State	2200	201.0	161.0	1166.0
	Broiler:				
	Transient	3000	411.0	369.0	4050.0
	Steady-State	3800	337.0	184.0	3108.0
Newer Gas Stove with Pressed Steel Burners	Pilot Lights:	100	0.5	1.9	84.2
	1 Burner - High Flame	3500	450.0	277.0	1785.0
	3 Burners - High Flame	10200	1408.0	669.0	3213.0
	Oven:				
	Transient	4000	1324.0	316.0	4040.0
	Steady-State	2200	171.0	111.0	3564.0
	Broiler:				
	Transient	4900	617.0	395.0	4145.0
	Steady-State	3700	503.0	211.0	2800.0
Unvented Space Heater	Low Flame-Steady-State	2800	214.0	130.0	1770.0
	High Flame-Steady-State	6200	837.0	272.0	1978.0
Domestic Gas Furnace*	-----	Approx. 3000		2700.0	1080.0

* From Compilation of Air Pollution Emission Factors (Revised), U.S. EPA, February 1972.

- Absorption of the gas molecules to a surface of a solid
- Condensation of a vapor by regulating temperature and pressure.

These methods of cleaning gas from an airstream are often used to remove pollutants from a waste airstream; however, due to their energy requirements, high operating temperatures, high initial and maintenance costs, and large-scale requirements, they are not suited for application as residential gas cleaners. Research must be directed toward improving and applying control techniques to remove gaseous pollutants from the residential environment.

Control of indoor-generated pollutants may be accomplished by a range hood that filters the pollutants as they are generated. Currently, the Minimum Property Standards published by the U.S. Department of Housing and Urban Development (1973) recommends that a range hood must be equipped with a minimum capacity of 40 ft^3/min per linear foot of hood length in kitchens. However, questions have arisen about the efficiency of these devices to effectively filter out the gaseous pollutants generated. Additionally, these units generate considerable noise during operation, and thus tending toward infrequent use. Research is warranted towards improving the efficiency of the hoods and reducing the noise resulting from their operation.

Additional pollution is created by certain lifestyle activities and hobbies. Smoking, cooking, and general indoor activities that may result in reentrainment of settled dusts are major sources of indoor suspended particulate matter. Generally, TSP may be classified as solid particulates or liquid particulates.

Solid particulate pollutants consist of dusts, fumes, and smoke. Dusts are solid particles, typically smaller than 100 μm, that are carried airborne by natural or mechanical processes. Fumes are solid particles formed by the condensation from the gaseous state. Generally, the particle size of fumes is less than 1 μm. Smoke is small solid or liquid particles, from 0.1 to 0.3 μm, generated by the incomplete combustion of organic materials.

Liquid particulate pollutants are made up of mists and fogs. Mists are small airborne droplets of material, less than 10 μm, that normally are liquids. They can be formed by spraying, mixing, atomizing, or by chemical reaction. Fogs are airborne droplets, ranging from 2.0 to 80.0 μm, that are formed by condensation of vapors.

A separate classification of airborne pollutants is usually created for biological organisms, which range in size from submicroscopic viruses to the largest pollen grains. Bacteria range from 3.0 to 30 μm, spores from 1.0 to 10 μm, and pollen from 10 to 100 μm (Honeywell, 1976).

The size of particulate pollutants commonly found in residences ranges from 0.001 to 100 μm in diameter. Visible particles, which make up less than 10% of the total airborne particles, tend to settle on horizontal surfaces. The remaining 90% of airborne particles are invisible and tend to deposit by contact with both horizontal and vertical surfaces. Both groups contribute to the dirt that causes most of household cleaning activity.

Four major methods are used to clean air of particulate matter:

- Impingement systems that use a coarse filtering medium coated with a viscous substance on which the pollutant particles adhere,
- Unit or panel filters that use a densely packed medium that traps particles out of the air stream,
- Diffusion systems that drive particles from the main stream by random air movements and forces them against fiber filters, and
- Electrostatic precipitators that remove particles by charging them, then collecting them on an oppositely charged plate.

Each of the systems has been used in industrial and commercial buildings for removing particulate matter of various types and sizes, but only two systems have been used in residential buildings; the panel filter and the electrostatic precipitator. The other two systems have not been used, primarily due to their relatively high operating costs as well as their large space requirements.

Typically, these air-cleaning devices are not located directly within the space being conditioned. Therefore, it is necessary to circulate air from the conditioned space through the air cleaner and back to the space. In order to provide adequate cleaning, the distribution system should draw air from and return air to all areas within the residence.

Three operating characteristics distinguish the types of air cleaners: efficiency, air flow resistance, and dust-holding capacity. Efficiency measures the ability of the air cleaner to remove particulate matter from the air stream, averaged over the life of the cleaner. Air flow resistance is the measure of the static pressure drop across the air cleaner at a given air flow rate. Dust-holding capacity is the measure of the ability of an air cleaner to hold a particular type of dust. A complete rating of an air cleaner would then require data on the efficiency, air resistance, and dust-holding capacity, as well as the effect that dust loading of the air cleaner has on both efficiency and air resistance.

Panel filters are flat, narrow units typified by the commonly used fiberglass home furnace filter. The media used in panel filters are random fiber mats or blankets of varying fiber sizes and densities packed 1 or 2 in. thick and held by a rigid frame. In some designs the filter medium is permanent, requiring periodic cleaning. In some designs the entire panel is discarded after it has accumulated a dirt load.

Panel filters operate primarily on the straining principle; the filter fibers are so dense that the air passages are smaller than the diameter of the particles. Therefore, the particle becomes trapped and is strained out of the airstream. In addition, some particles are removed by adsorption to the fiber surfaces.

Operating characteristics of residential panel filters are given in Table 48. The straining operation of the filters results in a high filtering efficiency as long as the particle size is large (greater than 10 μm). Smaller particles tend to pass through the filter without becoming trapped.

The dense media used in panel filters result in good dust-holding capacity while monitoring a relatively low resistance to air flow. As the filter becomes dirt-loaded, its resistance increases from about 0.05 in. H_2O to a replacement value of 0.5 in. H_2O. While the filter itself requires no energy to operate, as its resistance to air flow increases, the load on the fan is increased, resulting in an increase in fan energy requirements.

In addition, the ineffectivenss of the filter to remove particles smaller than 10 μm would result in a gradual buildup of a layer of particles on the heat exchanger surfaces of the furnace, reducing its operating efficiency.

TABLE 48. PERFORMANCE OF PANEL FILTERS

Characteristic	Panel Filters
Arrestance Efficiency	85-90%
Dust Spot Efficiency	5-10%
Dust Holding Capacity	90-180 gm/1000 ft^3/min
Resistance to Air Flow	0.05-0.5 in. H_2O
Initial Cost	$ 5-20
Maintenance	Low (periodic replacement)
Smallest Particle Removed	10.0 μm
Power Consumption	0 W

The initial cost of a panel filter system is low. Maintenance costs are also low since the only maintenance required is the periodic replacement or cleaning of the filter element. However, since the panel filter is effective only on particles greater than 10 μm, the units can remove only a portion of the pollutants that are found in residences.

Electronic air cleaners are units that remove particles from the air by using the principle of electrostatic precipitation. In residences using forced air systems, the unit is mounted in the return air duct. In other residences that do not use a central air system, individual room-sized units are available.

Residential electronic air cleaners are two stage units. Return air enters the first stage and passes through a strong electric field that electrically charges (ionizes) any particles in the airstream. The air and charged particles then enter the second stage which has an alternating series of negatively and positively charged plates. The grounded plates attract and hold the positively charged particles, removing them from the airstream. In some units, a thin prefilter section made of cleanable, fibrous material is installed in front of the electronic air cleaner to remove large particles.

As the unit operates, a layer of dirt is gradually built up on the collector plates. This dirt includes particles from tobacco tar, cooking fats, and other viscous contaminants that act as an adhesive. To remove this material it is necessary to periodically clean the unit using water and detergent. Most units are equipped with indicator lights to signal when the unit needs cleaning.

Operating characteristics of residential electronic air cleaners are given in Table 49. The units are efficient devices for removing smoke and fumes as well as atmospheric dust. An important feature of the electronic air cleaner is its ability to achieve a high degree of air cleaning efficiency without introducing excessive resistance to air flow. Actual resistance is about the same for electronic air cleaners and panel filters. But unlike the panel filter, resistance does not increase significantly between the periodic cleanings. Therefore, the energy required to operate the fan system remains nearly constant. In addition, since the system is effective in removing a large range of particle sizes, the furnace heat exchanger surfaces would remain cleaner and would therefore operate more efficiently.

The initial cost of an electronic air cleaner is high when compared to panel filters, but this initial cost will be offset by the benefits resulting from a cleaner environment in the residence. Since the electronic air cleaner efficiently removes dirt that can soil walls and furnishings, savings may be realized from a reduction in housekeeping expenses.

TABLE 49. PERFORMANCE OF ELECTRONIC AIR CLEANERS
(ASHRAE 1975)

Characteristic	Electronic Air Cleaner
Arrestance Efficiency	70-98%
Dust Spot Efficiency	70-95%
Dust Holding Capacity	High
Resistance to Air Flow	0.10-0.30 in. H_2O
Initial Cost	$150-300
Maintenance	Low (periodic cleaning)
Smallest Particle Removed	0.01 μm
Power Consumption	20-60 W

Electronic air cleaners do require power to operate. This electric use, which averages 20 to 60 W, would result in an increase in the annual electric bill by less than $8.50, subject to market pricing.

The two cleaning devices previously discussed offer varying costs and efficiency of operating. While neither is best suited for all applications, a weighing can be made of the following characteristics of each:

Advantages	Disadvantages
Panel Filters	
• Low initial cost	• Low efficiency on small particles
• Low maintenance	• Resistance to air flow increases with dust loading
• No power requirements	
Electronic Filters	
• High efficiency on large and small particles	• High initial cost
• High efficiency on smoke	• Requires power to operate
• Constant resistance to air flow	

Advantages	Disadvantages

Electronic Filters (Continued)

- Low maintenance
- Automatic indication when unit needs cleaning.

Figure 40 shows some of the most common particulates found in the residential environment and the effective range of panel and electronic air filters for removing particulate matter.

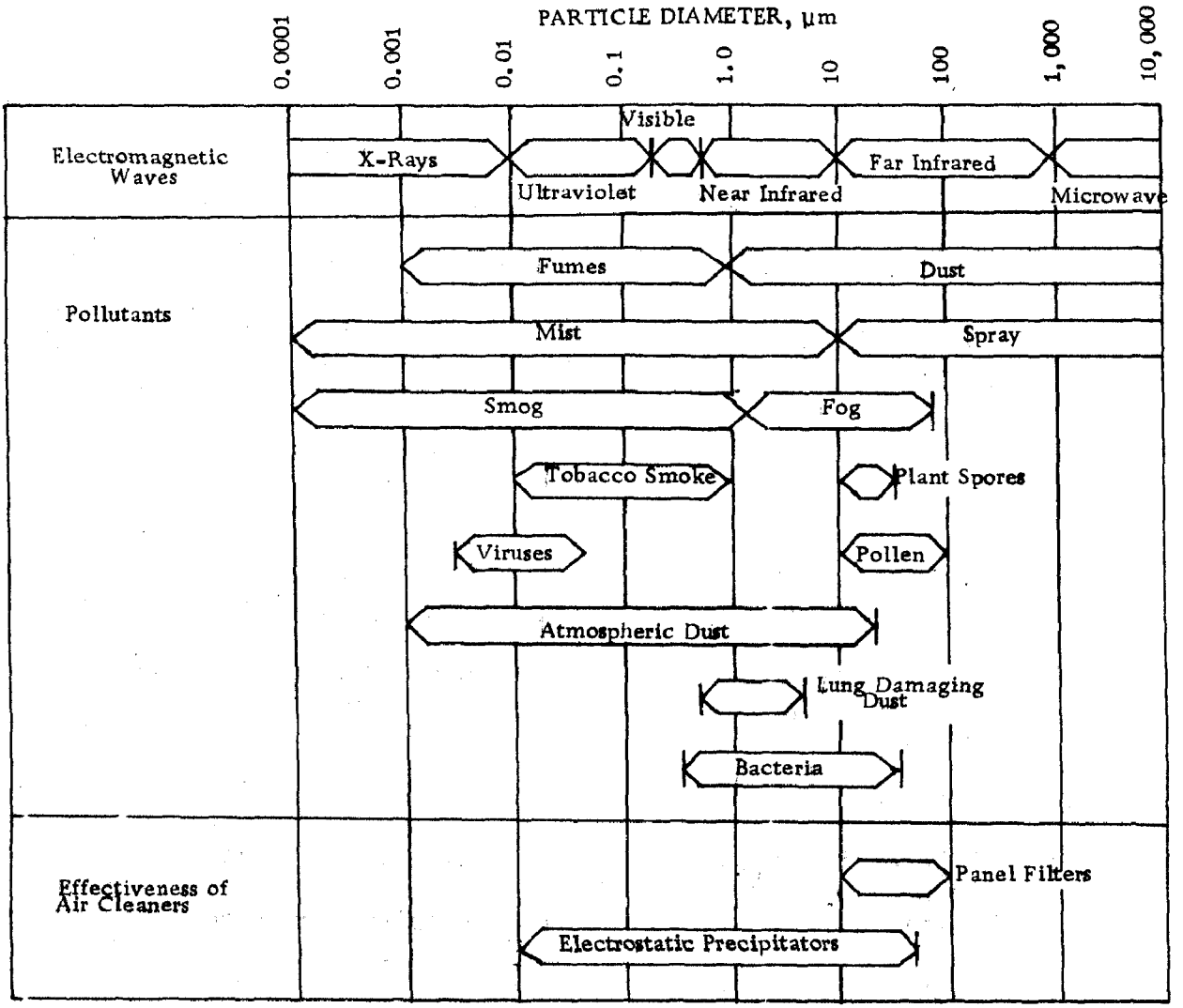

Figure 40. Characteristics of particulate pollutants.

Energy Conservation Measures

As more energy conservation techniques are applied to residential structures in the form of insulation, storm doors, storm windows, weather-stripping, and caulking, the greater is the decrease in infiltration. Today residential structures are being built or modified to resist infiltration heat losses during the winter and lower infiltration heat gains during the summer. This is very beneficial in cutting energy usage of residential structures, but it creates the potential problem of increased indoor air pollution. However, several energy conservation measures can be implemented with minimal effects on indoor air quality levels.

Energy management techniques in residential structures will result in substantial reductions of energy consumption. In addition, structural modifications that reduce conduction/radiation heat losses can be applied to obtain considerable energy savings while exerting almost no effect on the air exchange rate of the residence.

One such structural modification that can effectively reduce energy consumption, while leaving air infiltration rates virtually unchanged, is the reduction in thermal conduction through the roof/ceiling surfaces. The heat loss through the roof/ceiling accounts for 8 to 14% of the total structure heat loss in both cold and warm regions during the heating season. The magnitude (not percentage) of these losses is larger in colder climates and, therefore, will have a greater impact on total energy cost. In a program performed for ERDA (Energy Research and Development Administration), Hittman Associates (1977) found that heat gains through the ceiling represent 2 to 5% of the total structure heat gains during the cooling season. There are two items which can be implemented to improve the thermal performance of roof/ceiling.

First, the thermal conduction through the roof/ceiling can be reduced, and secondly, ventilation of the attic can be improved. Reducing the conduction is easily accomplished by the addition of more insulation. The insulation may be in the form of batts, blankets, loose-fill, or foamed-in-place. The addition of insulation increases the thermal resistance of the roof/ceiling interchange. This thermal resistance, measured as the R-value, is the reciprocal of the heat transfer coefficient or the inverse of thermal conductance. Oil or gas heating systems in colder climatic regions should have an insulation value of R-30, while electric heating system losses in similar climatic regions should have R-38 in the ceiling. Under the present fuel price schedules, new homes with R-19 in the ceiling cannot justify the dollar savings resulting from any additional amounts of insulation, except in the coldest climatic regions of in electrically heated homes.

Attic temperatures can build up to 30 °F or more above the outdoor temperature. This can increase the heat gain through the ceiling during the summer if proper ventilation is not provided. If mechanical ventilation through the use of an exhaust fan is installed in the attic, an adequate amount of outside air must be supplied or the exhaust fan will draw cool conditioned air from the space below, thereby increasing infiltration (Professional Builder, 1974).

Energy conservation can also be obtained by the reduction of thermal conduction through the structure's walls. The heat loss through the walls accounts for 12 to 19% of the total structure winter heat loss in both cold and warm regions. The magnitude (not percentage) of those losses will have a greater impact on total energy costs for residences in the colder climates. During the cooling season, 3 to 5% of the total structure heat gain is due to heat flow through the walls (Hittman, 1977). Insulating exterior walls is cost-effective only if there are high local fuel costs, severe climatic conditions, no existing wall insulation, or the structure is electrically heated. As a retrofit measure, the cost and benefits are difficult to determine because exterior walls usually cannot be insulated without puncturing the sheathing or the interior wall surface. Usually, walls are only insulated if there is an air space of at least 3 or more inches. Even with foamed insulation, problems arise because of possible moisture accumulation, settling, shrinkage, and inability to fill voids which minimize the effectiveness of insulation. As a retrofit item, additional wall insulation is one of the least cost effective of all those available.

A third structural modification which can be applied to residential structures is the insulation of floors. The heat loss through the floors represents 6 to 22% of the total structure heat losses. During the cooling season, the floors are sources of 1 to 11% of the structure heat losses (Hittman, 1977). The contribution of a floor over a nonheated basement or enclosed crawl space to the heating load is quite different from any other structural component because it is proportional to ground temperature, which is warmer than outdoor air in the winter, and usually cooler in the summer. A heat loss through the floor in the summer is a result of the cooler ground temperature, and this helps to lower the cooling loads. However, leaving the floor uninsulated to take advantage of the floor's cooling effect in summer causes large heat losses during the winter. Since the detrimental effect of heat losses in the winter is larger than the beneficial effect of the heat losses in the summer, insulating the floor has a net beneficial effect in cooler or more severe climatic regions, especially when electric heat is utilized.

During the heating season, the windows affect the overall heat balance in residential structures by losing heat to the outside through conduction (which varies from 23 to 37% of the total structural heat losses) and gaining heat by allowing solar radiation (which varies from 9 to 27%

of the total structural heat gains) to penetrate into residences (Hittman, 1977). The combined effects are a net heat loss during the heating season. Increasing the window R-value (i.e., adding double or triple glazing and/or storm windows) will effectively decrease conduction heat losses, and also lower radiation heat gains. A proportionally greater amount of the heat losses will be decreased than the heat gains, thus reducing the total heating load that must be met by the heating system. During the cooling season, window conduction heat gains reinforce the radiation heat gains, and as a result, make windows one of the largest structural components affecting cooling loads.

As a further illustration, Figures 41 and 42 graphically show how heat gains and losses are reduced for a 1200 ft^2 single-family detached residence in the Baltimore area utilizing increased insulation and the infiltration parameters are described in Table 50. Techniques used to arrive at these comparative diagrams are found in the relevant literature (Hittman, 1977). These graphical illustrations show the relative change in the magnitude of heating and cooling loads that can be realized through various energy conservation measures.

ENERGY MANAGEMENT IN RESIDENCES

HVAC Controls

Application of energy management techniques in residential structures can result in substantial reductions of energy consumption. Management techniques which can be applied to residential structures are modifications to the heating, ventilating, and air conditioning (HVAC) systems and their mode of operation. The following discussion will investigate the potential for applying these modifications.

A simple adjustment of the thermostat control is the first, easy, and rather effective energy management step. Nighttime temperature setback on a thermostat control is a very easy and effective method to reduce energy usage. Utility companies and manufacturers have indicated that for each 1 °F that the thermostat is turned down, a savings of 1% of the annual fuel bill will result. Lowering the thermostat by 10 °F during the night may reduce annual fuel bills by 10% in northern climates and 30% in southern climates. Nighttime setback can be a manual or automatic operation. Automatic thermostats include either a clock or a clock-triggered resistor. The latter is used to retrofit manual thermostats to automatic operation, while the former is best used for new installations.

An existing HVAC system can be retrofitted with an automatic flue control to reduce energy consumption. Flue control in the form of an automatically controlled flue damper conserves energy by retaining heat in the heat exchanger of a residential furnace during nonoperational periods so as to minimize the off-cycle heat loss through the stack. If it is assumed that the flue damper can cut as much as 80% of the off-cycle heat losses

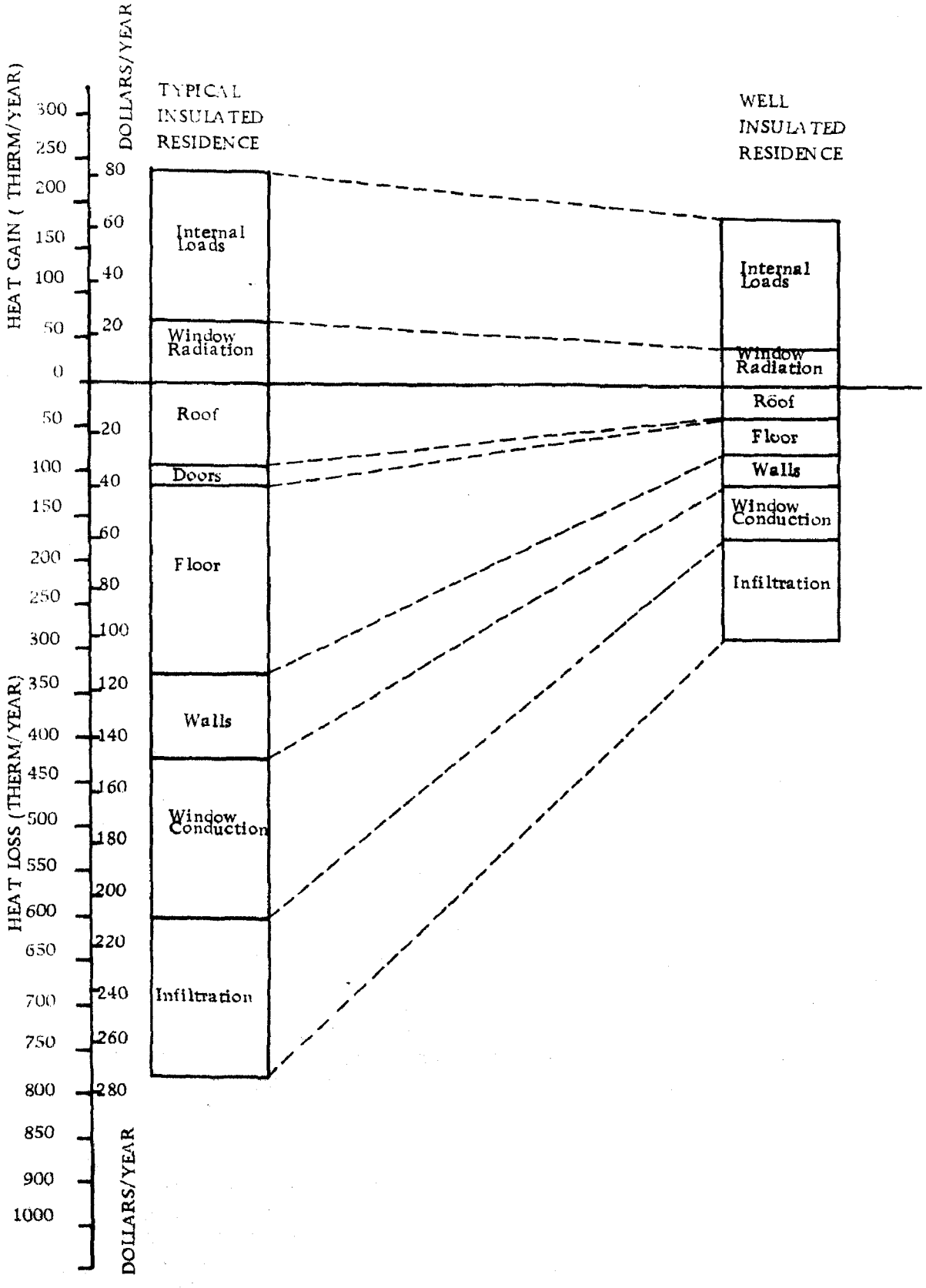

Figure 41. Single-family detached--Baltimore, heating (Hittman Associates, 1977).

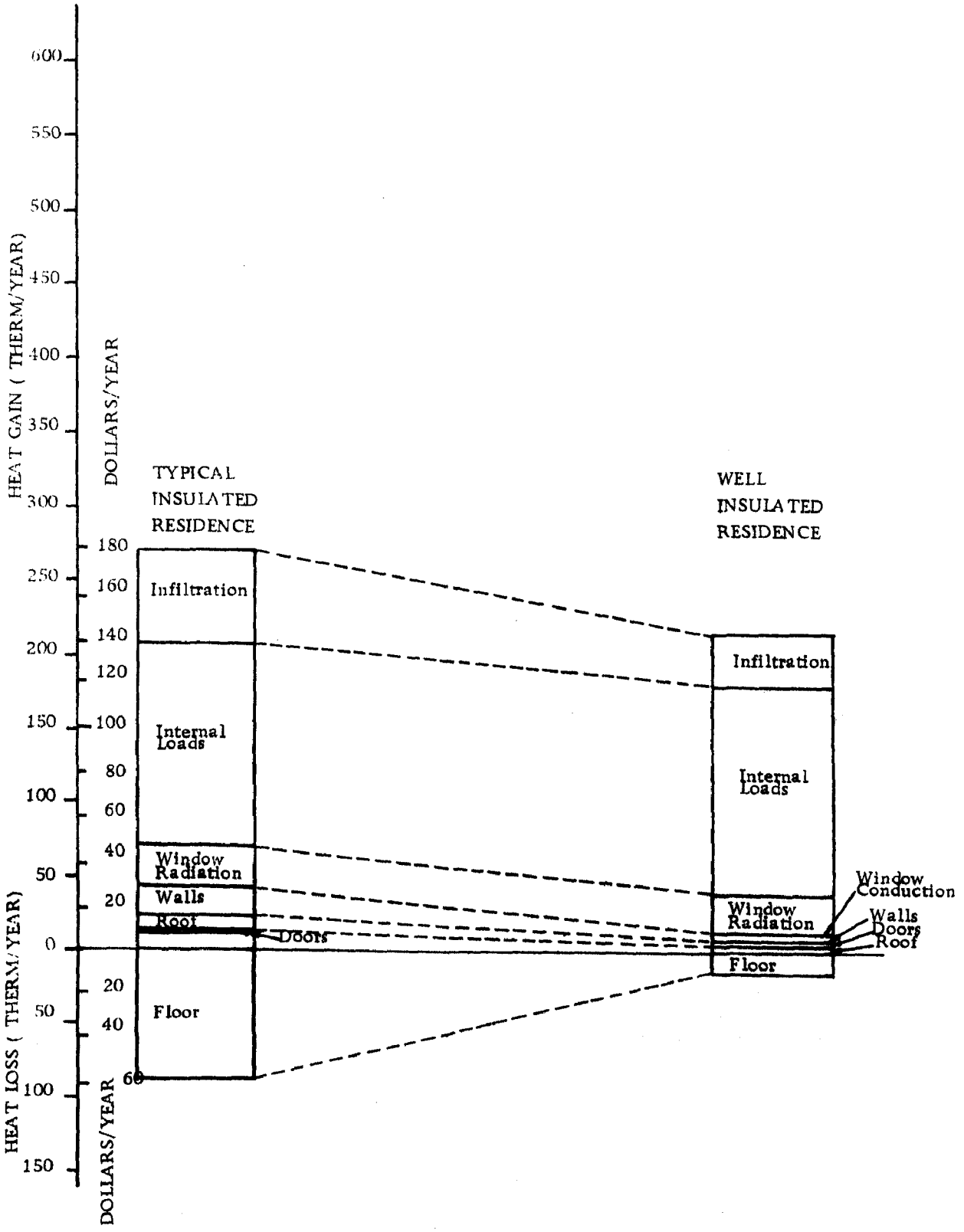

Figure 42. Single-family detached--Baltimore, cooling (Hittman Associates, 1977).

TABLE 50. SPECIFICATIONS FOR A TYPICAL AND WELL INSULATED RESIDENCE (HITTMAN ASSOCIATES, 1977)

Typical Insulated Residence

Specifications

Component	Conductance	Comments
Roof	0.065	6" Loose Fill Insulation (R-13)
Doors	0.413	Wood Doors
Floor	0.200	Uninsulated
Walls	0.084	3-1/2" Glass Fiber Batts (R-11)
Windows	1.01	Single Glazing

Infiltration Parameters	Yes	No
Weatherstripping		X
Storm Windows		X
Storm Doors		X
Caulking		X

Well Insulated Residence

Specifications

Component	Conductance	Comments
Roof	0.031	12" Glass Fiber Insulation (R-38)
Doors	0.102	Metal/Foam Sandwich and Storm Doors
Floor	0.033	10" Glass Fiber Insulation (R-30)
Walls	0.038	6" Glass Fiber Insulation and 2" Rigid Foam (R-31)
Windows	0.420	Double Glazing and Storm Windows

Infiltration	Yes	No
Weatherstripping	X	
Storm Windows	X	
Storm Doors	X	
Caulking	X	

through the stack, a 4 to 7% reduction in the annual fuel consumption will result in either northern or southern climates, though certainly the magnitude of these savings will be noticed only in the colder regions regions (Hittman Associates, 1977).

A technique that can be applied to the HVAC combustion unit is that of the intermittent ignition. Currently, many gas residential heating systems are equipped with pilot lights. The substitution of these with electronic ignition can result in a 3 to 6% savings in the annual fuel bill in northern climates and a 15 to 22% savings in the southern climatic regions.

Another technique that can be implemented with existing HVAC systems is to lower the furnace fan shutoff temperature. By allowing the fan to run longer after the furnace has shut off, the heat that would otherwise escape up the chimney is available for space heating. The cost of running the fan is in many instances offset by the 2-3% annual fuel savings.

A technique that has successfully been employed in large office and commercial buildings and that should be investigated for residential structures is that of a variable zonal ventilation system. This system yields increased air exchange rates in individual rooms on a need basis. In the residential environment, high levels of pollutants are generated in the kitchen and other activity rooms. Use of the variable zonal ventilation system in these rooms can reduce elevated pollutant concentrations by mechanical ventilation near the point of production before emissions can contribute significantly to the general household pollutant levels. This approach may decrease total residential energy consumption. The major disadvantage of such a system is its expense, which is too high to make it feasible for single family residential use.

Other modifications can be applied to the heating, ventilating, and air conditioning systems in addition to those previously mentioned. The majority cannot be considered as retrofit items but should be considered whenever complete replacement of an existing system or the installation of a new one is necessary. A list of some of these items follows:

- Size heat installation for peak winter load (most installations are now sized for twice the peak load)
- Place all new ductwork within the conditioned space (up to 10% annual fuel savings)
- Use outside preheated combustion and dilution air (requires ductwork to furnace or placing the furnace outside)
- Increase the Coefficient of Performance (C.O.P.) of air conditioning and heat pump systems (requires increased coil effectiveness, higher compressor efficiencies, and higher motor and fan efficiencies).

Indoor air pollution is a complex function of internal volumetric air change. A high air exchange rate often cleanses the indoor air of pollutant buildup; however, increased air exchange rates result in additional energy consumption. A balance must be obtained between energy consumption and residential indoor air quality.

Problems associated with energy conservation measures and air quality in residences have been outlined in this section. In addition, the number of scenarios suggested demonstrates that substantial reductions of the energy consumed by a typical household are possible with minimal impact on the indoor residential air quality.

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16. ABSTRACT

A 24-month study was undertaken to characterize the indoor residential air quality. Seventeen residential dwellings were monitored, each for a 14-day period. Air samples were collected from four locations: one outdoor site adjacent to the building; and three indoor sites, the kitchen, bedroom, and living room. "Continuous" sampling was carried out for CO, SO_2, NO, NO_2, CO_2, O_3, CH_4, and THC. TSP, RSP, $SO_4^=$, NO_3^-, Pb, ammonia, and aldehydes were monitored intermittently. Aerosol samples were collected for elemental analysis by the Proton Induced X-ray Emission (PIXE) technique. In addition, data on energy parameters, infiltration rates, and family activities were obtained by observations, field experiments, and daily questionnaires, respectively. Each residence was monitored with minimal interference in the daily activities of the occupants; thus, the residential pollutant concentrations were determined under real-life conditions.

The air quality of the residential environment was determined to be markedly different from the outdoor ambient air quality. Three classes of air pollutants have been identified with respect to indoor-outdoor pollutant relationships: 1) concentrations of CO, NO, CO_2, NMHC, and aldehydes in the residential environment are often higher than outdoors; 2) TSP and RSP are sometimes lower and sometimes higher indoors than outdoors; and 3) indoor concentrations of SO_2, O_3, $SO_4^=$, and NO_3^- are almost always lower than the corresponding outdoor pollutant concentrations. Indoor concentrations of TSP, O_3, NMHC, and CO have been observed to equal or exceed the National Ambient Air Quality Standards for these pollutants. The observed elevated levels of indoor pollutant concentrations are attributed to indoor pollutant sources.

(continued)

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16. ABSTRACT (Continued)

Two numerical models formulated in the course of this study are discussed in this document. The GEOMET Indoor-Outdoor Air Pollution (GIOAP) model simulates indoor conditions and estimates indoor gaseous pollutant concentrations as a function of outdoor levels, air exchange rates, indoor source strengths, and pollutant decay rates. Unique characteristics of the GIOAP model include the transient term, a first-order chemical decay term and fine time resolution. Estimated concentrations of CO, NO, NO_2, and NMHC were within 25% of the observed values. Ozone predictions did not meet the predetermined GIOAP model validation criteria but were realistic and often within 2 ppb of the observed O_3 concentrations. The second model formulated during this study, the Steady State TSP model, is an empirical model which estimates indoor TSP levels as a function of outdoor levels, air exchange rates, removal mechanisms, and indoor TSP source terms. The indoor TSP source terms include a reentrainment term and a pollutant generation term, both of which are functions of the family activity index generated from information obtained by the questionnaires. Estimations made using the Steady State TSP model compare favorably, always within 50% and most often within 30%, with the observed levels.

Finally, the relationship between energy conservation measures and air quality in the indoor environment is examined. The parameter that associates energy conservation measures and air quality in residences is the air exchange rate of the structure. Reduction in the air exchange rate will conserve energy, but it may lead to deterioration of the residential air quality. A practicable air exchange rate of 0.5 air changes per hour was determined by numerical simulations. This level is a cost-efficient reduction from the current average residential air exchange rate of 0.8 air changes per hour. Thus it will conserve energy. In addition, it will not substantially deteriorate the indoor air quality. A number of scenarios that conserve energy in residences and do not affect indoor air quality are also discussed in this study.

The observed indoor air pollutant concentrations were, on the average, not very high; however, persistent moderate and, at times, elevated pollutant levels were observed. The lack of studies concerning the health implications of such levels is briefly discussed.