Iowa State University
Digital Repository

Retrospective Theses and Dissertations

Iowa State University Capstones, Theses and Dissertations

1982

A method to characterize air exchange in residences for evaluation of indoor air quality

Eduardo Alberto Baptista Maldonado
Iowa State University

Follow this and additional works at: https://lib.dr.iastate.edu/rtd

Part of the Mechanical Engineering Commons

Recommended Citation

Baptista Maldonado, Eduardo Alberto, "A method to characterize air exchange in residences for evaluation of indoor air quality " (1982). *Retrospective Theses and Dissertations*. 7513.
https://lib.dr.iastate.edu/rtd/7513

This Dissertation is brought to you for free and open access by the Iowa State University Capstones, Theses and Dissertations at Iowa State University Digital Repository. It has been accepted for inclusion in Retrospective Theses and Dissertations by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.

المنارة للاستشارات

www.manaraa.com

INFORMATION TO USERS

This reproduction was made from a copy of a document sent to us for microfilming. While the most advanced technology has been used to photograph and reproduce this document, the quality of the reproduction is heavily dependent upon the quality of the material submitted.

The following explanation of techniques is provided to help clarify markings or notations which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting through an image and duplicating adjacent pages to assure complete continuity.

2. When an image on the film is obliterated with a round black mark, it is an indication of either blurred copy because of movement during exposure, duplicate copy, or copyrighted materials that should not have been filmed. For blurred pages, a good image of the page can be found in the adjacent frame. If copyrighted materials were deleted, a target note will appear listing the pages in the adjacent frame.

3. When a map, drawing or chart, etc., is part of the material being photographed, a definite method of "sectioning" the material has been followed. It is customary to begin filming at the upper left hand corner of a large sheet and to continue from left to right in equal sections with small overlaps. If necessary, sectioning is continued again—beginning below the first row and continuing on until complete.

4. For illustrations that cannot be satisfactorily reproduced by xerographic means, photographic prints can be purchased at additional cost and inserted into your xerographic copy. These prints are available upon request from the Dissertations Customer Services Department.

5. Some pages in any document may have indistinct print. In all cases the best available copy has been filmed.

University Microfilms International
300 N. Zeeb Road
Ann Arbor, MI 48106

8224231

Maldonado, Eduardo Alberto Baptista

A METHOD TO CHARACTERIZE AIR EXCHANGE IN RESIDENCES FOR EVALUATION OF INDOOR AIR QUALITY

Iowa State University PH.D. 1982

University
Microfilms
International 300 N. Zeeb Road, Ann Arbor, MI 48106

A method to characterize air exchange

in residences for evaluation of

indoor air quality

by

Eduardo Alberto Baptista Maldonado

A Dissertation Submitted to the

Graduate Faculty in Partial Fulfillment of the

Requirements for the Degree of

DOCTOR OF PHILOSOPHY

Major: Mechanical Engineering

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major Department

Signature was redacted for privacy.

For the Graduate College

Iowa State University
Ames, Iowa

1982

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

NOMENCLATURE

A	Integral of the concentration of tracer-gas over time (ppm•min)
C	Concentration (ppm, %, $\mu g/m^3$)
C_a	Ambient outdoor concentration (ppm, %, $\mu g/m^3$)
C_e	Equilibrium concentration (ppm, %, $\mu g/m^3$)
C_o	Initial concentration (ppm, %, $\mu g/m^3$)
DBT	Dry-bulb temperature (°C)
E	Relative Exposure Index
ET	Effective Temperature (°C)
ET*	New Effective Temperature (°C)
I	Intercept of a straight line in a semilog plot. (I is used in the calculation of E.)
I_{cl}	Intrinsic clothing insulation value (Clo)
M	Metabolic rate (w/m^2)
MRT	Mean radiant temperature (°C)
n	Number of data points in statistical analyses
N	Number of uniformly mixed zones in a building
q	Total amount of tracer gas released (m^3)
$\dot{q}$	Rate of tracer-gas or contaminant release (m^3/s)
$\dot{q}_n$	Effective rate of contaminant release (m^3/s)
r^2	Correlation coefficient
R	Air exchange rate (ACH)
RH	Relative humidity (%)
S	Absolute value of the slope of a straight line in a semilog plot. (S is used in the calculation of E.) (hr^{-1})

SET*	Standard Effective Temperature (°C)
t	Time (s, hr)
T	Transfer index $(m^3/s)^{-1}$
TG	Globe temperature (°C)
V	Volume (m^3)
$\dot{V}$	Air flow rate (m^3/s)
$\dot{V}_{ij}$	Air flow rate from zone i to zone j in a building (m^3/s)
W	Air speed (m/s)
α	Significance level in statistical analyses
ε	Ventilation efficiency
τ	Time constant (s^{-1}, hr^{-1})

Subscripts

i, j	Denote generic zones in a building
r	Denotes reference values

Superscripts

*	Denotes nondimensional quantities
$\hat{}$	Denotes predicted values (statistics)
$\bar{}$	Denotes mean value (statistics)

ACKNOWLEDGEMENTS

I wish to express my deepest appreciation to my Major Professor and friend, Dr. James E. Woods, for his support, guidance and encouragement during this work and during the five very fruitful years I had the privilege of working with him.

Thanks are also due to Professor George H. Junkhan, for his extensive help and counseling during my graduate program; to Professor Arthur E. Bergles, for his continued support; and to Professors Bruce R. Munson and David A. Block, for their advice as members of my advisory committee.

A very special thanks is due to Professor E. Oliveira Fernandes, of the Mechanical Engineering Department of the University of Porto, Portugal, for his most important continued support; and to Professor George K. Serovy, for initiating the efforts that made my stay at Iowa State University possible.

I wish also to thank the Office of the Vice-President for Research of Iowa State University and the Iowa Energy Policy Council (contract #82-4000-03) for providing the funds necessary to conduct the research described in this dissertation, the Luso-American Educational Commission (program G-I-1) and the Portuguese Government, whose financial support made my stay in the United States possible, and to the Iowa State University Engineering Research Institute, Iowa State University Research Foundation, and Iowa State University Mechanical Engineering Department, which, during different parts of my stay in Ames, provided funds necessary for various projects in which I participated.

Special thanks are also due to those who helped conduct this work: to Mr. Roy R. Crawford, for his excellent work coordinating research at the Energy Research House and help with equipment and testing; to Mr. John E. Janssen, Senior Engineering Fellow, Honeywell, who came expressly to Ames to help in the calibration of the tracer gas equipment; to Mr. John B. Knowland, for smoking in the Energy Research House and helping with field testing; and to the families who allowed me to use their houses in the field studies, despite the inconveniences caused.

And, finally, I offer very special words of thanks to Ms. Elaine Johnson, who carefully typed this dissertation and, through her personal sacrifice, made it possible to meet deadlines.

ABSTRACT

Review of literature indicates that methods of assessing indoor air quality are not readily available. From theoretical considerations, a practical procedure for evaluating indoor air quality in buildings is proposed. This procedure is suitable for generalized surveys of buildings where no prior knowledge of indoor air quality problems exists. The procedure is intended to indicate whether or not a more detailed analysis is necessary.

The procedure consists of two main steps: first, a multipoint tracer gas analysis is performed to characterize air exchange rates and ventilation efficiencies in various zones of a building; second, the factors which influence indoor air quality are measured in the zone where they are generated and in the zone with both the lowest air exchange rate and ventilation efficiency.

A model is presented which validates the correctness of the choice of the sampling locations. The Relative Exposure Index, the main concept of this model, is introduced and its relationship to the concepts of air exchange rate and ventilation efficiency is presented. Results of controlled experiments and field studies to validate the model are presented.

It is concluded that there is a need to monitor contaminants at more than just the zone where contaminants are produced if the highest risk for the occupants of the building is to be found; that most rooms in a building can be considered to be uniformly mixed; and that measuring

air exchange rates using artificial mixing via a central air fan or portable fans is not an appropriate means to assess indoor air quality in buildings.

INTRODUCTION

The quality of ambient air has long been a concern throughout the world. Increasing levels of factory and transportation emissions, either particulate or gaseous, have led to stringent regulations. Conversely, the quality of indoor air has received considerably less attention.

More recently, it was realized that indoor pollutant levels were often larger than outdoor levels, in particular after increasing energy costs have led to tightening of building envelopes. Moreover, the vast majority of people spend most of their time in some type of indoor environment, either at home or at work. Concern over the quality of indoor air quality thus began to receive more and more attention. Comprehensive studies have been conducted which attempted to obtain statistical distributions of various factors influencing indoor air quality, to develop models capable of predicting it, and to characterize human response to different factors.

However, surveying buildings for indoor air quality has remained either a research subject or left to the individual survey designs. Due to their site-specific design, both of these methods generally involve high costs and are not accessible to most individuals. Therefore, there have been little means for an individual homeowner to have his house surveyed for indoor air quality.

The work reported herein attempts to develop a standardized method which can be used for such generalized surveys. This procedure requires some initial capital investment for purchasing the necessary equipment, which may restrict the purchaser from performing only a small number of indoor air quality surveys. However, it should be within the financial means of specialized consultants or government agencies. This procedure is designed to be a first step only, i.e., a means of determining if detailed studies should be conducted in a particular building. Therefore, required instruments can be less accurate than those used in research or even industrial use. The smaller survey costs can then be more easily justified in buildings, as most of them are not expected to have serious indoor air quality problems.

This work consists of three main parts: the first two chapters are a discussion on indoor air quality and on the methods that have been used to evaluate it; in the next three chapters, the proposed method for evaluation of indoor air quality will be described and experimentally validated under controlled conditions; and, finally, the results obtained when the procedure was used in field testing of four residences in Iowa are described.

INDOOR AIR QUALITY

Introduction

One of the main purposes of buildings is to provide the occupants with a safe and comfortable environment while protecting them from the climate. As in many other cases, however, the protection offered by buildings does not come without its drawbacks: due to the purpose of protection, the building envelope poses a barrier to the free supply of outdoor air to the building. Thus, any contaminant which may be produced inside the building will also face the same barrier to being exhausted from within, and its concentration may rise to unwanted levels. While some contaminants may only cause unpleasant sensations to the occupants (e.g., odors), others, also known as pollutants, may have deleterious health effects to the occupants if their concentrations reach high enough levels.

This contaminant problem has been gradually worsened by the increasingly tighter construction techniques that are being used and by the number (and, to a greater or lesser degree, the toxicity) of chemicals which have become a common part of everyday life. This problem has become known as the problem of "indoor air quality", similarly to the problem of outdoor air quality (or, simply, air quality) which has been known for a longer period of time.

It is, however, incorrect to study this problem by itself. As stated above, buildings are to provide a safe and comfortable environment for the occupants. Thus, the total environmental air quality picture must be simultaneously considered because it is not clearly known how thermal air quality (which is related to thermal comfort) and mass air quality (which is related to health and safety) interact. To account for these considerations, an inclusive definition of indoor air quality will be proposed. An historical perspective on how the various elements of indoor air quality have evolved up to the present time will follow.

Definition

The quality of the air in an enclosed space is defined, herein, as an indicator of how well the air satisfies the following conditions:

1. Thermal factors of the air (i.e., the dry-bulb temperature, relative humidity, and velocity) must be adequate to provide thermal acceptability for the occupants.

2. The concentrations of oxygen and carbon dioxide must be within acceptable ranges to allow normal functioning of the respiratory system.

3. The concentrations of gases, vapors, and aerosols in the air should be below levels that can have deleterious effects, or that can be perceived as objectionable by the occupants.

This definition of indoor air quality includes some qualitative aspects which, depending on how they are interpreted, can influence its application:

Thermal acceptability   It has been shown that different people have different acceptability criteria. In fact, Fanger has shown that even the "best" combination of thermal conditions can only result in thermal acceptability to 95 percent of a large group of people [1].

Thus, as a compromise, thermally acceptable conditions have been defined as those which will satisfy 80 percent or more of the occupants [2].

Thermal interactions with the environment   The thermal acceptablity of an environment does not depend exclusively on the dry-bulb temperature, relative humidity, and velocity of the air. Also important are the temperatures of surrounding surfaces and other radiation sources which may be described by the mean-radiant temperature, the insulation value of the clothing worn by the occupants, and the type of activity performed by the occupants [1]. Thus, the evaluation of the thermal acceptability of the air should be made using typical values for these three interactions which vary with time and from space to space.

Acceptable concentrations   There are no clearly defined boundaries between harmful and safe concentrations for the gases, vapors, and aerosols present in an environment. Thus, the evaluation of the mass quality of the air must be based on judgement after careful evaluation of the scientific information available on the physiological and psychological effects of each product. As new studies are continuously being reported, any list of such levels must be flexible as far as the levels and products themselves are concerned. Appropriate lists can now be found, for example, in OSHA [3] and ASHRAE [4] standards.

If the air meets all conditions listed in this definition, then the air quality is assumed, herein, to be acceptable.

Historical Perspective

The definition of indoor air quality includes two main components: thermal factors and mass factors (i.e., gases, vapors, and aerosols). So far, these two aspects of indoor air quality have been studied independently from each other with few exceptions. Thus, this historical perspective will first deal separately with each of the two types of air quality factors, followed by a discussion of their combined effects.

Thermal factors

Although earlier studies had been done on the subject, the first systematic evaluation of which combinations of the thermal factors led to human comfort was reported by Houghten and Yaglou in 1923 [5, 6]. In their purely experimental studies, Houghten and Yaglou determined the locus of dry-bulb temperature and humidity content of the air which produced the same thermal sensation to a person, as well as the limits within which people felt comfortable at different levels of clothing. They also introduced the concept of Effective Temperature (ET), defined as the dry-bulb temperature of still air saturated with moisture which induced a sensation of warmth or coolness like that induced by the given set of conditions. This work became the basis of comfort standards and environmental design for most of the fifty years that followed.

As further data concerning human comfort continued to be obtained by different researchers, it became apparent that the Effective Temperature scale overestimated the effect of humidity at low temperatures and underestimated its effect at higher temperatures [7]. However, it was not until 1971 that a "New Effective Temperature" (ET*) was proposed by Gagge and his co-workers [8]. Unlike the Effective Temperature, ET* was based on a thermal model of the human body in interchange with an environment and then verified with experimental data. Furthermore, while ET pooled air velocity, radiant effects, activity level, and clothing insulation values into discrete ranges for data analysis, ET* allowed for continuous variation of these factors in a manner similar to the dry-bulb temperature and moisture content of the air. In this way, errors due to the pooled treatment of those four factors were reduced. This work, together with similar comfort envelopes which were nearly simultaneously developed at Kansas State University [9] and by Fanger [1], became the basis of new comfort standards [10].

These comfort models are still the basis of present-day comfort evaluations. Refinements of details in the models have, however, been made.

1. The Pierce model (Gagge, et al.) was first updated in 1972 when the "Standard Effective Temperature" (SET*) was proposed [11]. While ET* referred to the same comfort sensation in an environment with the same radiation, air velocity, metabolic rate, and clothing insulation as the given set of factors, SET* related to a standard environment where all these factors were specified (relative humidity of 50 percent, mean radiant temperature equal to dry-bulb temperature, air velocity such that the effective convective heat transfer coefficient is 2.91 W/m^2 °C, clothing insulation value of 0.6, and sedentary activity).

In this way, completely different environments could be directly compared in the same scale. More recently, the model was adapted to cover a wider range of environments, namely under hypo- and hyperbaric conditions including helium-oxygen atmospheres [12].

2. At Kansas State University, a model based on Pierce's model was developed which fit the experimental data more closely [13, 14]. These two models, as well as Fanger's model [1], were shown to have only small differences and compare favorably with experimental data [15].

3. Research was done to better characterize the insulation value of clothing ensembles consisting of combinations of a set of standard garments [16, 17].

4. Studies showed that the response to localized air velocities (jets) resulted in a strong interaction between the air temperature and jet speed, with the tendency towards less comfortable sensations at high jet speeds even when thermal equilibrium exists [18, 19]. Recent studies also showed that the uncomfortable sensations increased as the jet fluctuated with higher frequency [20, 21].

5. Radiative fields were characterized in greater detail and the amount of radiation assymetry tolerated by people were studied [21, 22].

6. Thermal sensations under nonsteady environmental conditions were evaluated for several types of variations (e.g., temperature drifts, changes in activity) and it was shown that the faster the rate of change, the higher the percentage of dissatisfied people was [23, 24].

Any of these models (with subsequent improvements) or the recently published ASHRAE comfort standard [2], which is based on these models,

Table 1. Summary of comfort envelope and effect of the thermal factors [25]

Factor	Acceptable Range	Required Adjustment	Limits of Adjustment	Reference
Dry-bulb temperature[a] DBT (°C)	$22.2 \leq DBT \leq 29.5$	--	--	9
Relative humidity RH (%)	$20 \leq RH \leq 80$	$-27 \frac{\%}{°C}$	$21.1 \leq DBT \leq 30.7$	9
Air velocity[b] W (m/s)	$0.2 \leq W \leq 0.8$	$0.47 \frac{m/s}{°C}$	$22.2 \leq DBT \leq 31.2$	18
Mean radiant temperature[c] MRT (°C)	$DBT \pm 11.1$	$-0.7 \frac{MRT}{DBT}$	$14.3 \leq DBT \leq 37.5$	26
Clothing insulation value[d] I_{cl} (Clo)	$0 \leq I_{cl} \leq 1.5$	$-0.14 \frac{Clo}{°C}$	$15.6 \leq DBT \leq 33.7$	27
Activity level[e] M (Met)	$0.7 \leq M \leq 3.0$	$-0.5 \frac{Met}{°C}$	$16.3 \leq DBT \leq 30.9$	28

[a]DBT for thermal sensations from slightly cool to slightly warm at standard conditions (RH = 50%, Clo = 0.6, MRT = DBT, sedentary activity, still air).

[b]$W \leq 0.2$ m/s considered still air.

[c]Symmetrical field assumed.

[d]1 Clo = 0.155 m^2 °C/W.

[e]1 Met = 58.2 W/m^2.

can be used to evaluate the suitability of the thermal factors to provide acceptable air quality. The comfort envelope, i.e., the combination of factors which produce thermal comfort, and the relative importance of each factor are listed in Table 1 [25].

Mass factors

The importance of controlling the concentrations of the mass factors in indoor environments has been recognized for centuries. This is proven by the presence of vent-holes and other openings to enhance air exchange with the outdoor environment in early structures used to house people. However, the need for the air exchange was not understood beyond its necessity to sustain the health of the occupants.

As scientific knowledge gradually increased, and the basic composition of the air became known, ventilation was first believed to be necessary to avoid the depletion of oxygen in occupied spaces. But, in the eighteenth century, experiments showed that the increase in carbon dioxide concentration rather than the depletion of oxygen was the reason for unhealthy indoor environments [29]. Thus, O_2 and CO_2 were the two first mass factors of indoor air quality to be identified.

In 1824, Tredgold [30] proposed the first quantitative attempt to control indoor air quality: while admitting the presence of other "noxious gases" in the air, Tredgold rationalized the need to supply 4 cfm per person of outside air to purge carbon dioxide and water vapor produced by the occupants as well as supplying oxygen for other combustion purposes in the spaces. The 4 cfm value was subsequently criticized by others who argued for higher values.

Later, in the second half of the nineteenth century, the idea that other organics produced by the occupants were the main cause of unhealthy indoor environments was introduced [29]. The recognition that human bioeffluents were important mass factors of indoor air quality, together with an attempt to reduce the risk of infection, led to an increase in the recommended outdoor ventilation rate to a minimum of 30 cfm [31]. This value was adopted as the minimum allowable ventilation rate by ASHRAE in 1896 [32].

In 1905, Flugge showed that dry-bulb temperature and humidity were the cause of discomfort and unhealthy conditions rather than other compounds in the air [33]. While this caused required ventilation rates to drop [29], the importance of the human bioeffluents continued to be recognized. In fact, the first quantitative experimental analysis of ventilation requirements, conducted by Yaglou, Riley, and Coggins [34] and reported in 1936, established ventilation requirements to provide "odor-free" environments as functions of available air space per person. Also, despite the very low outdoor air requirements for dry-bulb temperature and humidity control, standards continued to require at least 5 cfm of outdoor air per occupant [35, 36].

With the scientific and technological progress which took place in the latter part of the twentieth century, there were many advancements in the study of the mass factors of indoor air quality:

1. There was a better characterization of the contaminants which were already known to exist. Among the most important, Wang measured the generation rates of twelve different organic bioeffluents [37]; the

emission rates from gas stoves [38, 39], from unvented gas-fired space heaters [38], and from wood-stoves [40] were characterized; and the contaminants released by mainstream and sidestream smoking were the subject of numerous studies as shown by a summary published in a U.S. National Academy of Sciences report [41].

2. New contaminants were identified. Some had always been present in the environment but only recently detected in significant levels in buildings. In this category, the most important contaminant is radon, which is radioactive and is released by the soil, construction materials (e.g., concrete), and water [42]. Others were introduced into the environment in the recent past by new building materials and consumer products which are now being manufactured. Examples of this last type of contaminant include formaldehyde released by particle-board and urea-formaldehyde insulation [43], aerosols released by insecticides and cleaners [44], and organic substances released by paints and building material treatments [45].

3. The health effects of indoor air pollutants were extensively studied and safe levels were defined for the most common contaminants. To address only the most common or most dangerous contaminants, it has been shown that even small concentrations of carbon monoxide can have adverse effects upon the heart, the brain, and the muscles [46]; that nitrogen dioxide, another combustion by-product, can cause respiratory disturbances [47]; that radon causes an increased risk of lung cancer [48]; that formaldehyde, even at concentrations as low as 0.01 ppm, can

cause eye irritation and neurophysiologic disturbances [49]; and, finally, that levels of carbon dioxide as low as 0.5 percent (i.e., approximately ten times the outdoor levels) can cause headaches to people exposed to it for long periods of time [50]. Acknowledging these threats to the health of the occupants, standards, either mandatory [3, 51] or voluntary [4], have been published limiting the maximum allowable or recommended concentrations for various contaminants. In residential buildings, however, mandatory standards do not usually apply, and only recommended values can be used. A summary of these recommended values is given in Table 2 for some of the best known contaminants.

This progress took place continuously, but it was particularly rapid in the last decade as an indirect consequence of the continuous escalation of fuel prices which started in the early 1970s. As energy costs increased, energy conservation measures were taken in new and existing buildings which frequently included the tightening of the building boundary without consideration of ventilation requirements [52]. Lower air exchange rates thus resulted which led to higher contaminant concentrations indoors. In many cases, the levels that were reached caused serious physical problems to the occupants and brought the spotlight upon the problem of indoor air pollution [53, 54] which led to increased research on the subject.

It is clear from the previous discussion that the study of the mass factors is more subtle and less well-defined than the study of the thermal factors. While there are models capable of predicting the

Table 2. Summary of recommended maximum allowable concentrations of contaminants

Contaminant	Exposure Time	Recommended Maximum Concentration[a]
Carbon dioxide	continuous	0.25%
Carbon monoxide	1 hour	35 ppm
	8 hours	9 ppm
Formaldehyde	continuous	0.1 ppm
Nitrogen dioxide	1 year	0.05 ppm
Ozone	1 hour	0.12 ppm
Particulates	24 hours	260 $\mu g/m^3$
	1 year	75 $\mu g/m^3$
Radon	1 year	0.01 WL[b]
Sulfur dioxide	24 hours	0.19 ppm
	1 year	0.04 ppm

[a]From ASHRAE Standard 62-1981 [4]. Values are time-weighted averages over the specified time of exposure.

[b]WL = Working Level

combined effect of all thermal factors, there is no such model for the mass factors. Rather, the study of the mass factors has been made contaminant by contaminant, which is not the way they commonly influence the building occupants. Thus, the mass air quality of the indoor air must presently be evaluated by comparison of the prevalent concentrations of individual contaminants with the levels accepted as safe by the most current standards.

Interactive effects of thermal and mass factors

Occupants of an indoor space are simultaneously affected by both thermal and mass factors, but the studies discussed in the previous sections deal exclusively with one type or another. It was shown that each factor creates some amount of strain (i.e., the magnitude of health risk to the exposed individual [55]) upon people as it deviates from its normal most desirable value. However, when more than one factor creates strain on a person, it is not clear that the resultant effect is purely additive. There are possible interactions that my reduce or increase their total combined effect. With very few exceptions, these interactions have not yet been studied, and, thus, the total effect of an indoor environment still cannot be fully characterized.

One of the few interactions that has been studied is the effect of dry-bulb temperature and relative humidity upon the perception of odors. Although there were several previous attempts to characterize the odor-humidity interaction [56], the first comprehensive study to consider both temperature and humidity effects was done by Kerka and Humphreys [57]. In this study, several types of odors were considered and the types of interactions found varied slightly among them. The greatest tendency, however, was to a decrease in odor intensity as dry-bulb temperature and humidity increased. A better characterization of their data for tobacco smoke was later given by Woods [58], who showed a strong correlation between odor intensity and the enthalpy of the air.

Another type of interaction that has been studied concerns the perception of factors in an indirect way. It consists of determining the influence of temperature and humidity upon the generation rate of several contaminants which, in turn, causes changes in indoor concentrations that may be perceived by the occupants. Examples include the outgassing of formaldehyde [59], radon exhalation from building materials [60], and the influence upon the populations of dust mites and other allergens capable of causing respiratory disturbances [61].

Finally, another interaction recently reported concerns thermal comfort and the concentration of carbon dioxide [62]. A study showed that children felt warmer when the CO_2 concentration was higher despite equal environmental values of SET*. This also seems to be confirmed by medical studies that show lower body temperature with increased CO_2 concentration in the inspired air [63].

These interactions are proof of the importance that interactive effects may have upon people and of the need to develop a comprehensive understanding of these effects upon the occupants for a better characterization of indoor environments.

THE MEASUREMENT OF AIR EXCHANGE RATES IN BUILDINGS

Introduction

In the previous chapter, the importance of limiting the indoor concentrations of contaminants while maintaining thermal comfort was established. The main methods of controlling the mass air quality of indoor air are source control, dilution control, and removal control [64].

Source control consists of minimizing the net generation rate of contaminants indoors. Examples include the use of local exhausts (such as in kitchens, bathrooms, and biological cabinets in laboratories), the reduction of the generation rates through the use of barriers (such as paints), and the total elimination of the source by product substitution or prohibition of the activities which lead to contaminant generation (e.g., smoking).

Dilution control consists of exchanging enough indoor air with outdoor air containing smaller amounts of contaminants, therefore keeping indoor concentrations below their allowable levels. This air exchange can be accomplished by infiltration through cracks in the building boundary, by natural ventilation through openings designed for this purpose, by mechanical ventilation, or by a combination of these methods.

Removal control consists of separating the contaminants from the indoor air, thus removing only the unwanted contaminants from the environment. Examples include the use of mechanical filters and electronic air cleaners for particle removal and chemical filters such as activated charcoal filters to remove gases and vapors.

While source and removal control have mostly been used in nonresidential buildings (although they are presently becoming more and more common in residential buildings), dilution control is the most common method of control in residential buildings. Therefore, it is important to know how much indoor air is being exchanged by outdoor air to properly assess indoor air quality.

When mechanical ventilation is used, its contribution to the building air exchange rate can usually be made by measuring the flow rates which are delivered at each supply outlet and/or at the supply and exhaust ducts. But infiltration, which is always present in a building, and natural ventilation are not susceptible to such an accurate measurement: while mechanical ventilation is a steady-state phenomenon, natural ventilation and infiltration are driven by inherently nonsteady forces such as wind and temperature difference between indoors and outdoors. In addition, even if the air flows could be measured, they would have to be located first, which is virtually impossible to do for any building, no matter how small the building is. Thus, indirect methods have been used to evaluate the air exchange rate in buildings.

Among the various methods to evaluate the natural air exchange rate of a building, the two most important are pressurization tests and tracer-gas studies. A pressurization test consists of replacing an opening in the building boundary (e.g., a door) by a fan which is capable of creating a positive or negative pressure differential of a specified magnitude between the interior of the building and outdoors. The required fan speed to achieve the specified pressure differential is a measure of the amount of air which escapes through the building boundary. An estimate of the tightness of the building can then be made which is an indication of how much infiltration (or natural ventilation) can be expected under different driving conditions (i.e., wind and temperature differentials) [65].

The pressurization test, however, does not acccunt for the directionality of the wind, which creates a positive pressure differential on one side of the building while it creates a negative differential on the leaward side. Thus, the amount of air which crosses the building boundary cannot be directly inferred from a pressurization test. However, when a pressurization test is performed in conjunction with some kind of visualization technique such as infrared thermography or smoke tracing tests, the locations and relative magnitudes of the cracks through which infiltration takes place can be determined [66, 67].

Also, there have been attempts to correlate air leakage measured in pressurization tests with infiltration rates under normal conditions [68, 69]. These models usually carry large uncertainties, especially for short-term predictions, and, thus, are more useful to compute typical values of average seasonal air exchange rates.

To obtain a quantitative estimate of infiltration and natural ventilation, the tracer-gas method is required. Given its importance and possible variations, this method will be presented and discussed in detail in the next sections.

The Tracer Gas Method

In 1824, Tredgold established the relationship between the concentration of indoor carbon dioxide and the rate of ventilation to the space [30]. This relationship was first used to experimentally estimate the rate of ventilation in 1858 by Max von Pettenkofer, who measured CO_2 produced by human respiration or by burning candles [70]. In the late nineteenth century, to improve the accuracy of the method, the concentrations of carbon dioxide were increased by releasing compressed gas into the space to be studied [70]. But experimental errors associated with the measurements were large and, thus, the method never was routinely used to evaluate ventilation rates in buildings [71]. Attempts to use water vapor as the tracer gas, as proposed by Houghton and Blackshaw in 1933 [71], also proved inaccurate due to absorption of water vapor by walls and furnishings [70].

In 1935, however, Marley introduced hydrogen into the space and measured its concentration with a katharometer [72]. As hydrogen is not present in significant amounts in outdoor air, is not produced inside the space to be studied, and does not react with and is not absorbed by the surroundings, the sources of error were significantly reduced. In addition, the use of the katharometer, which detected changes in the thermal conductivity of air caused by the presence of hydrogen in varying concentrations, also greatly reduced measurement errors.

After Marley demonstrated the practical applicability of the tracer gas method, much research was done to further improve on the accuracy of the concentration measurements by looking for more adequate tracers and detection methods. The main properties that tracer gases should have were found to be similar density and diffusion coefficient to those of air, chemical inertness (i.e., they should be nonexplosive and should not react with anything present in the test area), stability (i.e., no phase change or absorption possible at the conditions in the space), and nontoxicity, at least at the concentrations used in the tests. In addition, they should not be produced within the test area and should be easily and accurately detected at low concentrations. As a result, the katharometer was also used with helium, carbon dioxide, and water vapor [73]. In addition, infrared absorption was used with carbon dioxide, nitrous oxide, sulfurhexafluoride, methane, and carbon monoxide, among others [73, 74]. Other methods include ultraviolet absorption, chemical analysis, gas chromatography, and radioactive tracers detected by Geiger-type counters [73].

No matter which tracer gas and detection method combination is used, the mathematical treatment of the problem is based on a mass balance of the tracer in the space, which is assumed to be fully mixed. The mass balance equation can be expressed as:

$$-V \frac{dC}{dt} = \dot{V} C \qquad (1)^1$$

[1] Herein, the outdoor concentration of the tracer gas will be assumed to be either zero or constant. In the latter case, all equations are still valid with a change of variables: $C = (C - C_a)$.

and the steady-state decay solution as:

$$C = C_o e^{-Rt} \tag{2}$$

where R is the number of air changes per unit time, normally one hour:

$$R = \frac{\dot{V}}{V} \tag{3}$$

The "fully mixed" assumption, because of its importance, deserves a detailed analysis. The concern about making sure that the tracer was uniformly mixed with the air prior to the onset of the decay procedure and that the decay occurred at the same rate at all the monitored points was expressed early on. For example, Marley and those who continued his work at the British Building Research Board took measurements with several katharometers throughout the studied space to check for uniform mixing [75]. The same concern was recognized by Coblentz and Achenbach, who designed a portable infiltration meter for the U.S. Bureau of Standards in the 1950s [76]. The instrument they designed was a helium katharometer connected to ten sensing probes which were to be distributed throughout the studied building.

Tests conducted with multiprobe instruments as those described in the previous paragraph showed that the "fully mixed" assumption was valid in some cases but, in others, different rates of decay were observed in different parts of the building [77, 78]. When the non-uniformity occurred, whole-house infiltration rates were calculated as an average of room rates weighted on a room-volume basis [79].

However, it was realized that, if uniform mixing could always be ensured, single-point sampling was possible and the tracer gas procedure would be easier to use on a routine basis. To accomplish whole-house homogeneity, the most common method used has been the continuous use of the central air fan during the tracer-gas test or, if there was not one, portable fans placed throughout the house caused enough air movement to ensure mixing [80, 81]. In addition, the single sample was sometimes obtained simultaneously from several points within the building [81]. These techniques became a common method of measuring air exchange rates by the tracer-gas method [82]. Although this method will indeed result in accurate measurements in many cases, several cases can be foreseen which could result in errors:

1. Air jets from supply registers could be directed towards a leakage area, thus creating extra driving force for exfiltration (and, consequently, infiltration).

2. In residences with mechanical ventilation, forced circulation may cause additional leakage through the outdoor dampers. This is the case of the Iowa State University Energy Research House (ISU ERH), as will be shown later.

3. There is no guarantee that a forced air system will result in perfect mixing throughout the whole space. There is evidence that nonuniform mixing can occur even in small rooms depending on the relative location of the supply and exhaust registers [83, 84]. Similar nonuniform mixing situations have been measured in larger multizone-controlled buildings with continuous forced air supply [85, 86]. In all

probability, it should be expected that the more complicated the air handling system in a building is, the greater the potential for non-uniform mixing in the space.

Thus, simply conducting a tracer gas decay test in a building with forced air movement inside does not appear to be a sufficient condition to ensure complete mixing. Testing for uniform mixing should always be conducted to ensure that it indeed exists throughout the building.

A different approach has thus been followed by other researchers who accepted the fact that nonuniform mixing exists and that the tracer gas studies should take it into account rather than eliminating it. One method, designated as the equilibrium concentration method, consists of emitting the tracer gas continuously at a uniform rate. Under steady-state conditions, the concentration of tracer at any point in the studied space will approach an equilibrium value. When uniform mixing exists, the equilibrium concentration is the same at all points and the air exchange rate can readily be determined from the solution of the tracer gas balance equation:

$$-V\frac{dC}{dt} = \dot{V}C - \dot{q} \tag{4}$$

As the tracer gas is released at a constant rate, this equation is linear and the solution is:

$$C = \left(C_o - \frac{\dot{q}}{RV}\right)e^{-Rt} + \frac{\dot{q}}{RV} \tag{5}$$

At equilibrium (i.e., no time dependence as e^{-Rt} goes to zero):

$$C_e = \frac{\dot{q}}{RV} \tag{6}$$

When there is nonuniform mixing, Eq. (4) no longer applies and the equilibrium concentration changes from point to point. In 1960, Lidwell introduced the concept of "Transfer Index" to account for the nonuniform air exchange rates [87]. The Transfer Index T, defined as

$$T = \frac{1}{q} \int_{0}^{\infty} C \, dt \tag{7}$$

has the dimensions of the reciprocal of a ventilation rate, which Lidwell called the "effective ventilation rate". Indeed, when there is complete mixing, the Transfer Index becomes

$$T = \frac{C_e}{\dot{q}} \tag{8}$$

or, from Eqs. (6) and (3):

$$T = \frac{1}{RV} = \frac{1}{\dot{V}} \tag{9}$$

In this way, different points within a space can be characterized by a Transfer Index and, the larger its value, the lower the air exchange rate at that point.

A related concept is usually designated by ventilation efficiency [88]. Rather than emphasizing the absolute magnitude of the Transfer

Index or the value of the "area under the curve" as Sandberg called it, ventilation efficiency is defined as the ratio of the integrals of the concentrations at two points:

$$\varepsilon = \frac{\int_0^\infty C_r \, dt}{\int_0^\infty C_i \, dt} \tag{10}$$

A value of $\varepsilon = 1$ denotes that the ventilation rates (or air exchange rates) at both points are similar, while $\varepsilon < 1$ denotes that the air exchange rate at point i is lower than at the reference point r (i.e., higher concentrations remain for longer periods of time at point i). The concept of ventilation efficiency has also been used to characterize multipoint decays of tracer gas which was introduced over a short period of time as in the rate of decay technique rather than continuously as Lidwell proposed.

The Transfer Index method was not the only one proposed to deal with the problem of nonuniform mixing. Noting that the rates of decay at several points in a building tended to be different and, although not exponential, the error of considering them as such was small, several authors have proposed the use of the decay rates to characterize the relative ventilation efficiency of different points of a building [86, 88].

Finally, other less used methods include using the simple ratio of tracer-gas concentrations as an index of local ventilation [88], and the so-called "steady concentration method", which differs from the equilibrium concentration method by regulating the rate of injection of tracer gas so that the concentration at the measurement point remains steady [73].

In the latter method, sophisticated control equipment is required, but results can be obtained in a shorter period of time than with the equilibrium method. Its complexity has, however, prevented it from being used often.

Consequences of the Use of Different Tracer-Gas Methods to Measure Air Exchange Rates upon Indoor Air Quality Evaluation

As described earlier in this chapter, the need to measure air exchange rates resulted from the wish to verify that the ventilation rate supplied to a building was in accordance with the minimum established for appropriate indoor air quality. Currently, this concern is also present, but another purpose has also evolved: the need to predict the energy consumption of a building. A major portion of the design heat loss or gain in a building results from the need to condition outdoor air to the wanted indoor characteristics. Coupled to high energy costs, the ventilation supplied to a building can thus represent a major portion of the total operating budget required for its operation [89]. This has resulted in numerous efforts to model building energy consumption and to determine ways of reducing energy costs.

To model and predict natural ventilation rates, correlations have been developed which relate the amount of infiltration to weather conditions (i.e., wind speed and direction, and ambient air dry-bulb temperature), building characteristics (i.e., dimensions, geometry, and construction details), and site parameters (i.e., landscape profile, and size and distribution of any obstructions surrounding the building) [68, 69]. These correlations have been developed from data collected from both pressurization and tracer gas tests over long periods of time. But, although it is possible to obtain reasonable accuracy for the particular building where the measurements were taken, extending the results to other buildings has always resulted in large uncertainties, certainly larger than the uncertainties normally associated with the infiltration measurements [74]. Therefore, performing tracer-gas testing with the fan continuously running or even by circulating the air with portable fans should result in sufficient information for energy quantification purposes.

The study of indoor air quality, however, poses a completely different set of questions to be answered by an air exchange rate study. Except for commercial buildings where forced air supply occurs continuously[1], most buildings, residences in particular, only have forced air supply during short periods of time. In reality, those buildings which have central air systems are usually controlled in such a way that the central air fan is on only when heating or cooling is thermostatically called for. Even during design days, this results in cyclic on and off periods of the central air fan. Thus, during most of the time throughout the year, the only causes of air movement in the building result from natural causes (i.e., bouyancy and infiltration). Furthermore, many buildings have perimeter hot water or steam systems and some are based on the principles of passive solar energy design. In these cases, air movement results from natural causes year round.

---

[1]Forced air occurs sometimes at constant flow rates, and sometimes at variable flow rates such as in variable air volume systems.

As discussed in the previous section, nonuniform mixing has a greater tendency to occur when only natural air movement occurs within a building, while uniform mixing tends to occur more often when the central air fan is operating (provided the locations of the inlet and outlet air registers are adequate to provide uniform air mixing within each room). In the same building, uniform mixing results in dividing the total air exchange to it equally among all rooms. Thus, nonuniform mixing should result in some higher and some lower air exchange rates in different rooms (or zones) within the building in comparison with the house average. This is equivalent to saying that the concentrations of contaminants in different zones will differ and, therefore, so will indoor air quality. In particular, some of the zones will have worse air quality (i.e., higher concentrations due to lower air exchange rates) than the whole house would have if it were fully mixed.

Coupling the ideas of varying air quality under natural air movement and the prevalence of this type of air movement in buildings, it is clear that measuring air exchange rates by artificially making the house uniformly mixed, as if to evaluate energy performance, is not a correct solution. However, most field studies and measurement protocols for indoor quality surveys have measured or specified whole-house infiltration values only [90, 91, 92].

By performing indoor air quality evaluations assuming that it is uniform throughout a building, a potential for serious error is introduced. There is the possibility that measurements made on an average whole-house basis result in good or acceptable indoor air quality, while one or more zones of the house may have concentrations of contaminants above safe levels. The same could, of course, be said of thermal factors capable of resulting in less comfortable conditions in particular zones within a building. Occupants spending significant amounts of time in such zones could suffer unwanted health problems.

In conclusion, natural air exchange rates performed with the purpose of evaluating indoor thermal and mass air quality in a building should be done taking into account the nonuniformity that normally exists in a building. Artificial mixing should not be employed in a tracer-gas technique.

PROPOSED PROCEDURE FOR INDOOR AIR QUALITY EVALUATION

Introduction

The purpose of indoor air quality surveys is to determine if the occupants of the surveyed building are subjected to deleterious health or comfort effects. As different zones of a building can have different environments (i.e., different typical values of thermal and mass factors), it is important to characterize the risk associated with each zone, in particular of those which may cause higher risks.

To determine indoor air quality in all zones of a building, the obviously safe solution is to monitor the value of all pertinent factors for a long enough period of time in all zones simultaneously. Unfortunately, such procedure would be prohibitively expensive, and thus, it is not a viable alternative. Several surveys have been done on this basis, but the cost involved can only be justified on a research basis [93, 94]. Limiting the number of sampling locations and length of the monitoring period is a requirement if widespread surveys are to be conducted on a regular basis.

To limit the number of sampling locations, a logical criterion is necessary. Randomly placed sensors are unacceptable because there would be no guarantee that the highest risk zones would be monitored. To obtain such a criterion, the main processes that affect indoor air quality will be examined next.

Herein, the subsequent emphasis will be put on buildings that do not have continuous forced air supply during occupied periods, which constitute the vast majority of buildings throughout the world. Although the principles behind the search for high risk areas are the same for all buildings, the forcing functions for air movement are dissimilar. In particular, air movement in buildings with forced air systems is dependent on the type of air handling system and location of inlet and outlet air registers. Evaluation of the performance of such systems has been done by standard methods which, in general, involve lengthy room-by-room procedures [95, 96]. Although the following discussion will focus on the buildings without continuous forced air supply, references will be made to denote how to apply the proposed procedure to the other type of buildings.

Locating High-Risk Zones in Buildings

As established in the previous chapter, the condition that can lead to the highest risk throughout a building is when only natural forces cause air movement within. In this case, the potential for nonuniform mixing throughout the building is the greatest, as the various air exchange rates within the house will result in larger ranges of the thermal and mass indoor air quality factors.

However, it is expected that while diffusion might have some influence upon mixing, convection currents within the building will result in relatively good mixing in certain zones, which can then be considered uniformly mixed [97]. These zones can then be characterized by a single value of each pertinent parameter.

The problem of concern is, therefore, to locate the "highest risk" zone among these uniformly mixed zones within the building. For this purpose, mass and thermal factors will be considered separately.

Mass factors

The concentration of a contaminant in a space depends on the amount of contaminant generated within, and on the amount of air exchanged through the boundary of the space. Mathematically, when a contaminant is generated in a space which is assumed to be uniformly mixed, its concentration can be described by a mass balance equation of the form of Eq. (4):

$$-V \frac{dC}{dt} = \dot{V} C - \dot{q} \tag{4}$$

This equation can be written in nondimensional form, by defining the following nondimensional variables:

$$t^* = t R \tag{11}$$

$$C^* = \frac{C}{C_e} = \frac{C R V}{\dot{q}_r} \tag{12}$$

$$\dot{q}^* = \frac{\dot{q}}{\dot{q}_r} \tag{13}$$

The reference values chosen represent the steady-state values of the concentration, generation rate, and ventilation rate, and the time-constant associated with a steady-state decay as per Eq. (2). Substituting Eq. (11) thru Eq. (13) into Eq. (4):

$$-V \left(\frac{\dot{q}_r}{R V}\right) \frac{dC^*}{\left(\frac{1}{R} dt^*\right)} = \dot{V} \left(\frac{\dot{q}_r}{R V}\right) C^* - \dot{q}^* \dot{q}_r \tag{14}$$

or

$$-\frac{dC^*}{dt^*} = C^* - \dot{q}^* \tag{15}$$

Equation (15) shows that the only parameter which influences its solution is $(\dot{q}_r/RV)$, which has the dimensions of a concentration. Therefore, as shown by the steady-state value, the concentration of a particular mass factor in a zone increases as the value of $(\dot{q}/RV)$ increases, that is, as the generation rate per unit volume increases, and as the air exchange rate decreases. Thus, to identify the "highest-risk" zone among the uniformly mixed zones in a building, the relative magnitude of the values of $(\dot{q}/RV)$ for all zones must be known.

The first step is to identify the zones of the building which can be considered to be uniformly mixed. To a greater or lesser degree, natural convection currents are always present in a space and tend to cause uniformity of air properties within that space. If the currents are strong enough,the property gradients in the space will be negligible. However, the larger the space, the larger the potential for nonuniformity to occur. There have been evaluations of the mixing uniformity in rooms performed by the tracer gas method, as listed by Hitchin and Wilson [73], which showed good mixing in some cases and poor mixing in others. The vast majority of cases, however, showed little or no nonuniformity in small rooms, which confirmed earlier observations by Dick [75] that rectangular rooms were usually sufficiently uniformly mixed. Dick also observed that rooms of irregular shape such as hallways showed the largest nonuniformity effects. Measurements conducted in the Iowa State

University Energy Research House (ERH), which will be described in a later section, fully confirmed Dick's observations. Thus, it can be usually assumed that rectangular rooms in a typical building (i.e., about 6 x 4 x 3 m or smaller) can be treated as uniformly mixed by comparison with two different rooms which only communicate through small openings (e.g., doors). Larger rooms, in particular rooms with high ceilings, may show more tendency for nonuniform mixing.

Once the uniformly mixed zones are identified, the values of $(\dot{q}/R\cdot V)$ need to be determined for each zone. If individual values of $\dot{q}$, R, and V were known, this calculation would be trivial. But, while volumes can be evaluated in a more or less direct way[1], and zonal air exchange rates can be measured using a procedure that will be detailed later in this chapter, the evaluation of zonal $\dot{q}$ values is difficult if not impossible to be accurately performed. First, only certain typical types of contaminant generation rates have been fully characterized, and even those carry some uncertainty [37-43]. Second, air exchange between different zones in a building can also introduce or remove contaminants from a particular zone. A mass balance of contaminant for a particular zone (i) in a building can be expressed as (see Fig. 1):

$$-V_i \frac{dC_i}{dt} = \dot{V}_{ia} C_i - \dot{V}_{ai} C_a - \sum_{j=1}^{N} \dot{V}_{ji} C_j + C_i \sum_{j=1}^{N} \dot{V}_{ij} - \dot{q}_i \qquad (16)$$

[1]Due to the presence of furniture in a space, the measurement of the volume of the air in a room may carry significant uncertainty.

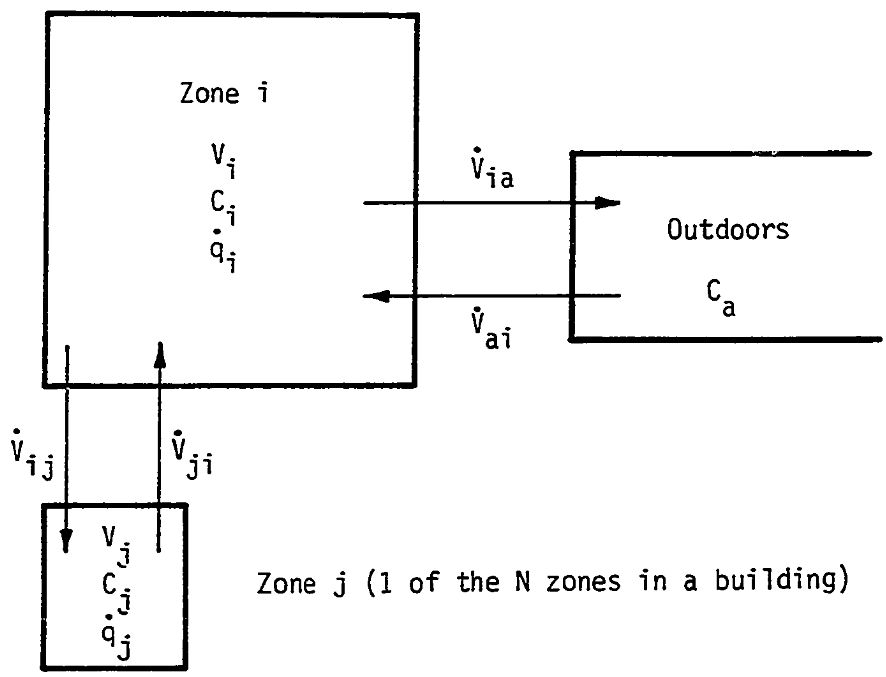


Fig. 1. Schematic diagram of the interactions between zone i and its surroundings

or, if the outdoor concentration is assumed to be zero, as previously postulated (see Eq. (1)), Eq. (16) can be rewritten as:

$$-V_i \cdot \frac{dC_i}{dt} = \dot{V}_{ia} C_i - \dot{q}_{n_i} \tag{17}$$

where $\dot{q}_{n_i}$ is the effective zonal generation rate of contaminant:

$$\dot{q}_{n_i} = \dot{q}_i + \sum_{j=1}^{N} \dot{V}_{ji} C_j - C_i \sum_{j=1}^{N} \dot{V}_{ji} \tag{18}$$

As there is no known method to evaluate the interzone air flows $\dot{V}_{ij}$, direct calculation of the effective zonal generation rates is not possible.

Due to the similarity of Eqs. (4) and (17), locating the highest-risk zone can be accomplished by evaluating $(\dot{q}_n/R\,V)$ rather than $(\dot{q}/R\,V)$. Still, absolute measurements of $(\dot{q}_n/R\,V)$ are difficult because of the natural fluctuations of indoor air movements and because the zonal air exchange rates with outdoors are difficult to evaluate due to the interference of the remaining zones in the building.

However, when an elemental contaminant generation[1] takes place in a zone, it is possible to measure the concentrations which result in each zone over the period following the generation. Analysis of the values of concentration over time will allow an evaluation of the relative magnitude of zonal $(\dot{q}_n/R\,V)$ values which correspond to that

---

[1]For example, a tracer-gas release over a short period of time.

generation. Indeed, a constant concentration can be assumed which, over some period of time, would result in equal exposure to an occupant in a zone:

$$C_e \tau = \int_0^\infty C\,dt \tag{19}$$

Noting that, in steady-state, the equilibrium concentration is given by Eq. (6):

$$C_e = \frac{\dot{q}}{R\,V} = \frac{\dot{q}_n}{R\,V} \tag{20}$$

the integral in Eq. (19) is a direct measure of the wanted $(\dot{q}_n/R\,V)$ parameter. As τ is the same for all zones, the value of this integral at a particular zone can be taken as a reference and the relative magnitudes of $(\dot{q}_n/R\,V)$ for all zones can then be determined:

$$E_i = \frac{C_{e_i}}{C_{e_r}} \tag{21}$$

where E_i will herein be designated as the "Relative Exposure Index" for zone i. Although Eq. (21) is similar in form to Eq. (10), (i.e., the definition of ventilation efficiency (ε)), these two quantities are distinct: the ventilation efficiency depends only on the zonal air exchange rates and it is independent of contaminant generation; conversely, the relative exposure index depends on both zonal air exchange rates and the location where contaminants are generated. These differences are also reflected in the way they can be determined: E values are calculated from tests where the actual contaminant (i.e., tracer gas) is generated in a zone only, whereas ε values are calculated from tests which start with equal concentrations of tracer gas in all zones.

If E values such as these are calculated for situations when generation occurs in each of the zones of the building, resultant zonal values can be obtained for any combination of contaminant release ($\dot{q}$) in the house because Eq. (17) is linear, and, thus, superposition applies.

Unfortunately, this method is not suitable for field use because of the amount of time required to conduct a number of tests to determine zonal contributions to ($\dot{q}_n/RV$), each test requiring relatively long periods[1]. In addition, effects of outdoor weather (i.e., wind and temperature) would have to be taken into account. Thus, a simplification is necessary.

To simplify the determination of the highest ($\dot{q}_n/RV$) value within a house, it is noted that, in general, a particular zone in a building exchanges a significant amount of air with the zones that surround it. Under these conditions, $\dot{q}_n$ values throughout the building tend to have very similar orders of magnitude. The exception would be if contaminant generation occurs in a zone of low air exchange rate, which would only result in small values of ($\dot{q}_n/RV$) throughout the house. Thus, it might suffice to measure the air exchange rates in all zones of the building to obtain information about the highest-risk zones in the building.

---

[1]Tests in the ERH showed that 6 to 8 hours were a minimum required per test, with 24 hours or more being desirable. This duration would be smaller in buildings with higher air exchange rates.

To measure the zonal air exchange rates, a tracer gas procedure is proposed. It consists of injecting tracer gas into the different zones of the building to obtain concentrations as uniform as possible throughout, and then monitoring the decay of the concentrations in the different zones. The decay in each zone is governed by an equation of the type of Eq. (16), with no generation term. Such an equation can be written for each of the N uniformly mixed zones in a building, resulting in a system of N simultaneous linear, first-order differential equations assuming that the interzone flows are constant in time. Under these conditions, the solution for the concentration is given by an equation of the type of Eq. (22):

$$C_i = C_o + \sum_{j=1}^{N} a_j \, e^{-t/\tau_j} \tag{22}$$

Thus, the general solution is a linear combination of exponential decay terms with time constants (τ_j) which, for a typical building, are of the same order of magnitude. The first conclusion to be obtained from this is that the tracer gas decay must be allowed to occur for a relatively long period of time[1] to obtain results which are free from the interference of any fast transients that may take place and thus isolate only the major air flows.

Another conclusion that can also be obtained is that zones which have large flows between them in both directions (i.e., mutually well mixed zones) tend to decay at the same rate because the major air flow

---

[1]Several time constants for each zone.

in each zone is towards the other. They can actually be considered a single zone for practical purposes.

Once enough time has elapsed from the onset of the decay procedure, a net air exchange rate between the zone and outdoors can be obtained by fitting the complex decay to a least-squares approximation of the type of Eq. (2). Although this method does carry some error, measurements which will be described later show that this error is no greater than errors involved in the measurements themselves. In this way, zonal air exchange rates can be determined.

The major limitation of this method is that the first portion of the decay process is ignored because the least-squares straight-line representation is not valid during the first phase of the decay. However, the short-time transients that are reflected in that portion of the decay process are permanently present in the building, and they do affect occupant exposure to the various indoor air quality factors. Moreover, cases exist in which, once the transients are no longer significant, two or more zones tend to decay at the same rate, but at different concentration levels. Thus, the rate of air change as described by the exponent of the exponential decay term (or by the slope of the decay line when a semilog representation is chosen) seems to be an insufficient means of fully describing the risk associated with a particular zone.

To account for the whole decay process, the concept of ventilation efficiency presented in the previous chapter seems the most appropriate.

As defined by Eq. (10), the ventilation efficiency is based on the total integral of concentration over time. For a particular mass contaminant, this integral represents the integrated total exposure of an occupant in that zone. Thus, to distinguish between zones with similar rates of air exchange in the latter part of the decay process, the "highest-risk" zone among them is the zone with lowest ventilation efficiency (i.e., the zone with the largest concentration integral over the whole decay process).

The combination of rate of air exchange (R) and ventilation efficiency (ε) per zone will then be used to identify the "highest-risk" zones in a building:

1. When contaminant generation occurs in zones with low air exchange rate and low ventilation efficiency, values of $(\dot{q}_n/RV)$ are expected to be the highest in those zones. Thus, those zones would be the "highest-risk" zones.

2. When contaminant generation occurs in zones which have high air exchange rate and high ventilation efficiency, values of $(\dot{q}_n/RV)$ are expected to be lower overall than in case (1) for similar generation magnitudes. The highest values of that parameter may occur in zones other than the zone of production because whatever portion is introduced into other zones with lower air exchange rates may remain there for longer times and result in higher risks than in the zone of production

In conclusion, the highest-risk zone should occur at the zone of production or at a zone with a lower ventilation efficiency than the zone of production.

Thermal factors

When outdoor air is mixed with indoor air, the resulting properties of the indoor air are equilibrium values which depend on the rate at which the outdoor air is introduced (i.e., the air exchange rate). Thus, spaces within a building with different air exchange rates can have different thermal conditions even if under the same control.

To evaluate the thermal environment, four factors should be measured in each group of uniformly mixed zones: dry-bulb temperature, relative humidity, air velocity, and mean radiant temperature. The first three factors can be measured directly, but MRT can only be measured indirectly. The quantity which is usually measured is the globe temperature, which can then be converted to mean radiant temperature using Eq. (23):

$$MRT = TG + 2.27 \sqrt{W} \; (TG - DBT) \qquad (23)^{1}$$

as given by Nishi [98]. In principle, there are no established rules as to where the less comfortable zones in a building are located. Factors such as dry-bulb temperature, air velocity, and relative humidity tend to be extreme in the zones with highest and lowest air exchange rates where the warmest or coldest thermal conditions can occur. But, the mean radiant temperature depends greatly on building orientation due to solar effects and no generalized rules can be used.

---

[1] The air velocity (W) in Eq. (23) is the local velocity around the globe itself, which is related to the convection heat transfer coefficient around the globe thermometer.

Given these facts, the thermal environment should be evaluated in all groups of rooms which constitute uniformly mixed zones.

Summary of the Procedure to Locate High-Risk Zones in a Building

As a bottom line, the main points involved in this procedure will be summarized next. As previously explained, this procedure is intended to locate the zones within a building which pose the highest risk to the occupants:

1. An appropriate tracer gas is introduced into the building such that a uniform concentration is obtained throughout the building.

2. The decay of the tracer gas concentration in the different rooms of the building is monitored until the decays are uniform, as approximated by a straight line in a semilog plot with small error; (Note: Rooms with irregular shapes or of large dimensions may have to be monitored at more than a single point.)

3. The rate of decay (R) and the ventilation efficiency (ε) at each zone are calculated;

4. The zones in which contaminants are produced, and the total rates of production, are identified by observation and available data;

5. The high-risk zones (i.e., where contaminants--mass factors--should be monitored) are identified as those with a ventilation efficiency equal to or lower than the value of ε at the zone of production.

6. For each group of zones with similar air exchange rates, monitoring for indoor air quality factors need only take place in the zone with lowest ventilation efficiency.

DESCRIPTION OF EQUIPMENT AND FACILITIES USED TO VERIFY THE PROPOSED INDOOR AIR QUALITY PROCEDURE

Summary Description of the Iowa State University Energy Research House (ERH)

The measurements which were made to validate the proposed procedure and verify the correctness of any assumptions made were conducted in the ERH. This building is a single-family detatched frame-construction residence with three levels which is fully described elsewhere [99]. Its schematic floor plan is shown in Fig. 2. The dimensions and volume of each room are listed in Table 3.

The ERH was built in 1977 and special care was taken to ensure that the envelope was sufficiently tight to minimize infiltration. This house has a central forced air heating and cooling system. Heating can be supplied by an electrically-driven heat-pump, an electrical furnace, or an active solar energy system. No natural gas is used in the house.

During the measurement periods in the ERH, the house was kept unoccupied except for equipment operators. Outdoor weather conditions were continuously monitored by a Climatronics weather station (wind speed and direction, dry-bulb temperature, and dew point).

Tracer-Gas Equipment

Description

The tracer-gas chosen for these studies was sulfurhexafluoride (SF_6). The advantages of SF_6 were a negligible outdoor ambient concentration (compared to other possible tracers such as methane

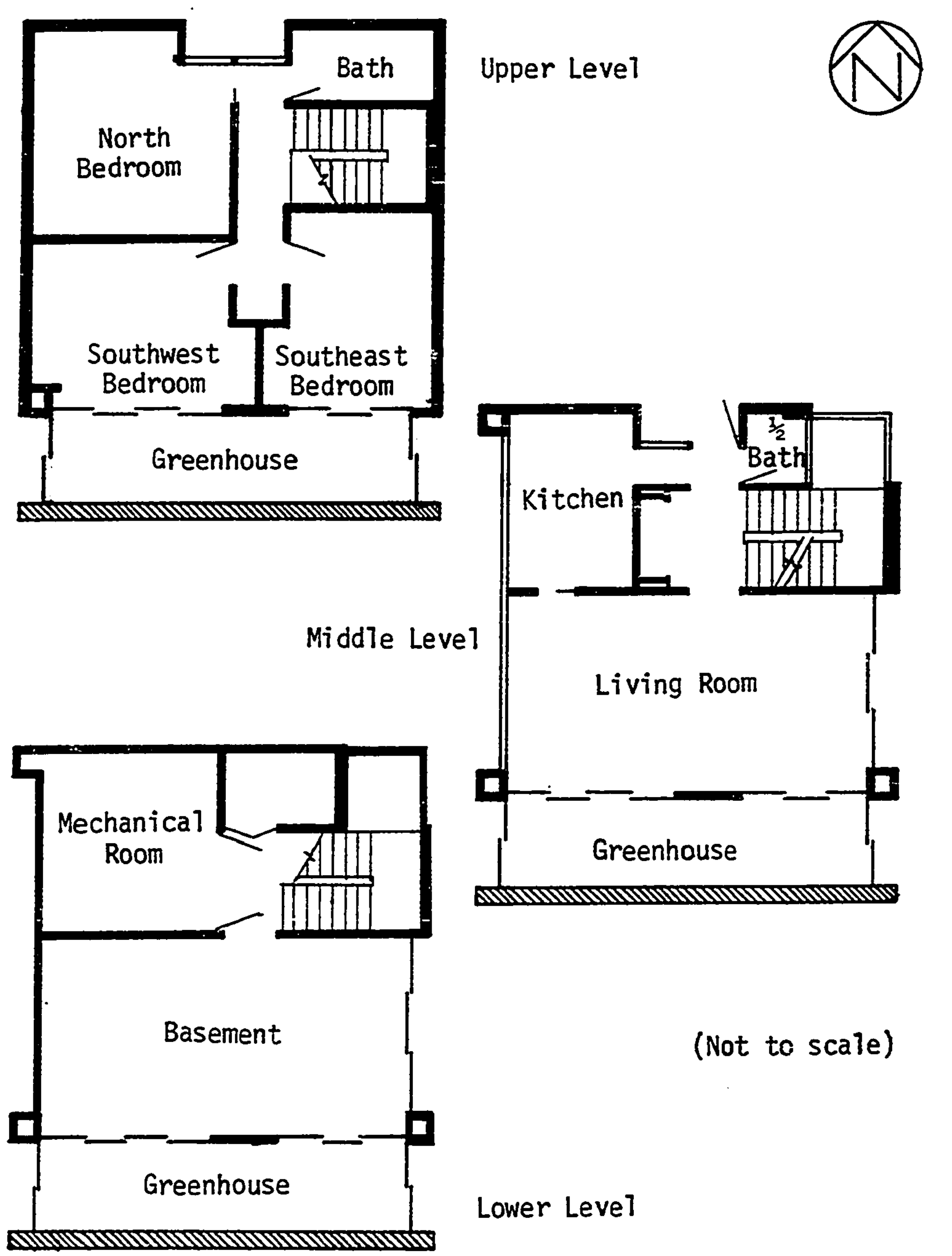


Fig. 2. Floor plan of the Iowa State University Energy Research House

Table 3. Dimensions of interior zones of the Iowa State University Energy Research House

Zone[a]	Floor Area (m^2)	Ceiling Height (m)	Volume[b] (m^3)
Upper bathroom	4.6	2.4	11.3
Upper hallway	5.9	2.4	14.3
North bedroom	18.1	2.4	44.2
Southwest bedroom	15.7	2.4	38.4
Southeast bedroom	14.5	2.4	35.3
Greenhouse	14.8	7.3	108.1
Kitchen	10.0	2.4	24.5
Living room	33.8	2.4	82.5
1/2 bath	1.7	2.4	4.1
Basement	32.6	2.3	74.5
Mechanical room	13.4	2.4	32.6
Laundry	3.7	2.3	9.1
Stairwell	10.8	7.3	78.8
TOTAL	179.6		557.7

[a]See Fig. 2 for location.

[b]Volumes do not take into account furniture.

and carbon dioxide) and the absence of any known physiological consequences for long exposures at high concentrations (Underwriters' Laboratories classification of comparative hazard to life of gases and vapors places SF_6 in group 6, their safest group [100]), which led to rejection of tracers such as carbon monoxide, nitrogen dioxide, and nitrous oxide.

The instrument available to detect SF_6 was a Miran-103 gas analyzer which had the range between 0 and 10 ppm. Although all known applications of SF_6 as a tracer gas have employed concentrations in the ppb range, there was no known restriction upon using the higher range of concentrations. Indeed, the ASTM Standard which regulates tracer-gas studies only recommends that a concentration of 1000 ppm not be exceeded [82].

The SF_6 detector was a single channel unit and, as concurrent sampling was necessary at different locations in a building, a 12-channel multiplexing unit was designed. This multiplexing unit consisted of two manifolds (one for sample inlet, the other for outlet) where solenoid valves controlled by a timer allowed the inlet and outlet valves for each sampling point to be open in a predetermined sequence while all others were closed. The length of sampling at each point was chosen based on the time needed to purge the incoming sample line as well as the response time required by the Miran for a correct reading. The air flow rate necessary for proper operation of the Miran was 20-30 l/min, and 1/2 inch (1.27 cm) inside diameter tubes were used, which resulted in a purge time of 0.76 seconds[1] per meter of sampling tube. As the longest line used was 16 meters in length, the total purge time was established as about 12 seconds. Furthermore, the response time of the Miran was measured to be between 15 and 20 seconds. Thus, to ensure that correct readings were obtained, a one minute cycle was chosen in which a reading was taken during the second half-minute section of the cycle. This cycle period allowed the measurement of the tracer gas concentration five times per hour at each of the 12 sampling locations.

The reason why two manifolds (inlet and outlet) were necessary was to avoid significant transport of SF_6 from one zone to another within the house. Even when the Miran operates at the minimum sampling rate of 20 l/min, this air supply to the room where the instrument would be located would result in a significant rate of air exchange for that room. For example, a 50 m^3 room, which is the size of a normal room in a house, would sustain 0.024 air changes per hour. The total air exchange rate in the ERH had previously been measured on occasion as low as 0.20 air changes per hour [101], and thus, the forced internal air change would be about 10 percent of the total house air exchange rate. It was felt that this forced air movement throughout the house would cause undue disturbances to normal indoor patterns. Moreover, the forced air movement would seriously impair the capability of this procedure to detect between-room or within-room differences in tracer decay.

---

[1] This was twice the time required for the sample to travel the length of the tube.

Thus, it was decided to return the sample collected at each point to the same location through the outlet manifold.

It should be pointed out that the multiplexing system did allow a small amount of interzone air exchange due to the storage capacity of the Miran itself (2 liters). With five samples per hour, this corresponds to about 0.002 air changes per hour (ACH), which would only account for a 1 percent variation in a house with 0.2 ACH. It was felt that this interzone contamination was acceptable and would not be noticeable in a test.

The tracer-gas analyzing system is schematically represented in Fig. 3, and a view is shown in Fig. 4.

Calibration

The SF_6 analyzer required only occasional calibration checks. No internal calibration changes were detected in all checks performed. As the measurements were always made indoors, the ambient temperature surrounding the Miran varied only between 15°C and 20°C, and no temperature drift was observed. The whole calibration procedure was internal to the instrument itself, except for the requirement of a true-zero sample which was obtained by circulating bottled nitrogen through the Miran. All measurements were made at least one hour after the Miran was turned on to avoid warm-up drifts.

Because there had been no previous knowledge of the accuracy of this instrument beyond manufacturer's claims, and because SF_6 was not known to ever having been used in such large concentrations for a

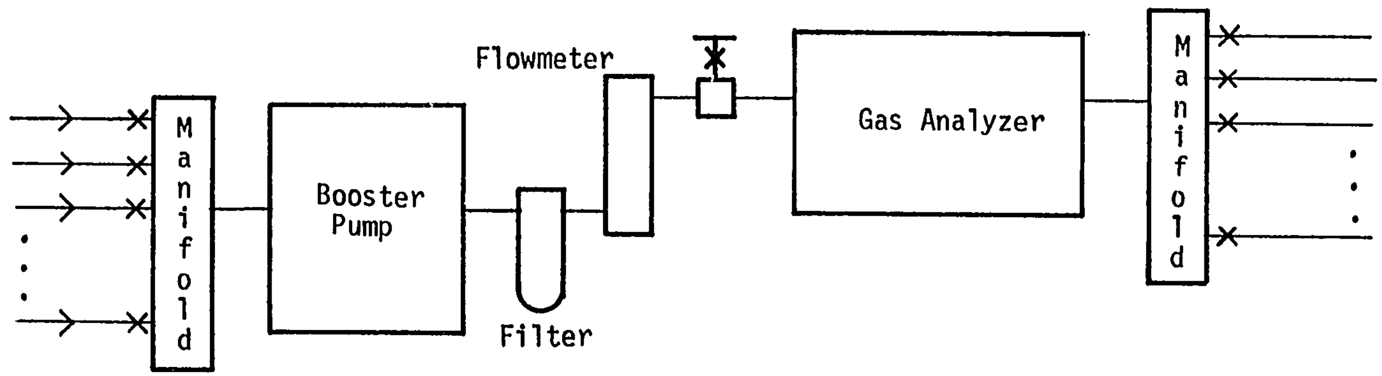


Fig. 3. Schematic diagram of tracer-gas analyzing system

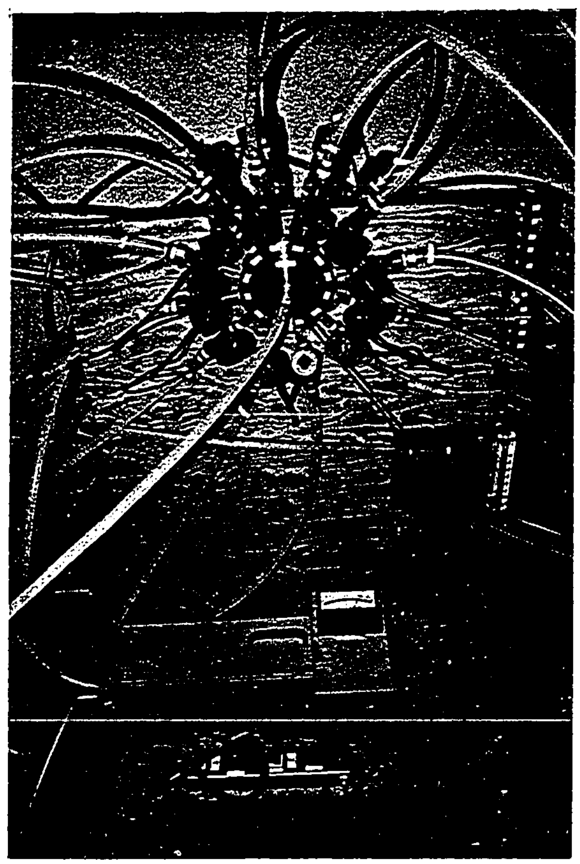


Fig. 4. Frontal view of the tracer-gas analyzing system

tracer-gas study, it was deemed necessary to directly compare measurements obtained by this equipment and by another established method of air exchange rate measurement.

Thus, the SF_6 system was placed in the ERH and 12 sampling locations chosen throughout the house. These locations are listed in Table 4, and some are shown in Figs. 5 thru 8. All sampling was done at 1.60 meters above the floor level, which approximates the average respiratory level of an average standing person, and the samples were returned at floor level.

Also, Mr. John E. Janssen, who has performed numerous air exchange rate measurements as described elsewhere [74, 102], brought his equipment to the ERH to run a comparison test between the two sets of equipment. Janssen's equipment consisted of an ANARAD methane analyzer model AR-400 with a range from 0 to 1000 ppm, which collected a single point sample.

The procedure which was followed consisted of initially uniformly mixing methane to 440 ppm and sulfurhexafluoride to 7 ppm throughout the house. To do this, both gases were simultaneously injected in the forced air duct just ahead of the supply fan (see Fig. 9). The supply fan was kept running continuously during the mixing procedure which took approximately 20 minutes. Decay data of the concentrations of both tracers were subsequently measured for the following 5-1/2 hours.

During this decay, four different periods were observed:

1. During the first 50 minutes, the supply fan ran continuously. Methane was sampled in the main return duct.

Table 4. Sampling locations in the Energy Research House

Zone #	Location[a]
1	Southeast bedroom, upper level
2	Southwest bedroom, upper level
3	North bedroom, upper level
4	Upper stairwell
5[b]	East living room, middle level
6[b]	West living room, middle level
7[c]	Kitchen, middle level
8[d]	Lower stairwell
9	West basement
10	East basement
11[e]	Upper level of the greenhouse
12	Lower level of the greenhouse

[a]Probe placed in geometrical center of the floor (or as close as possible to it if furniture was in the way) 1.6 meters above floor level.

[b]See Fig. 5.

[c]See Fig. 6.

[d]See Fig. 7.

[e]See Fig. 8.

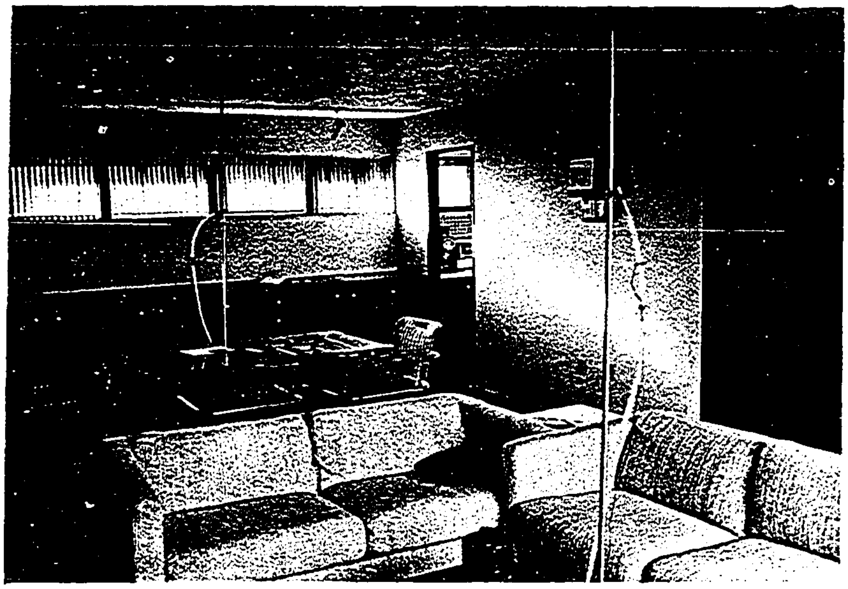


Fig. 5. View of the two sampling ports in the living room of the ERH

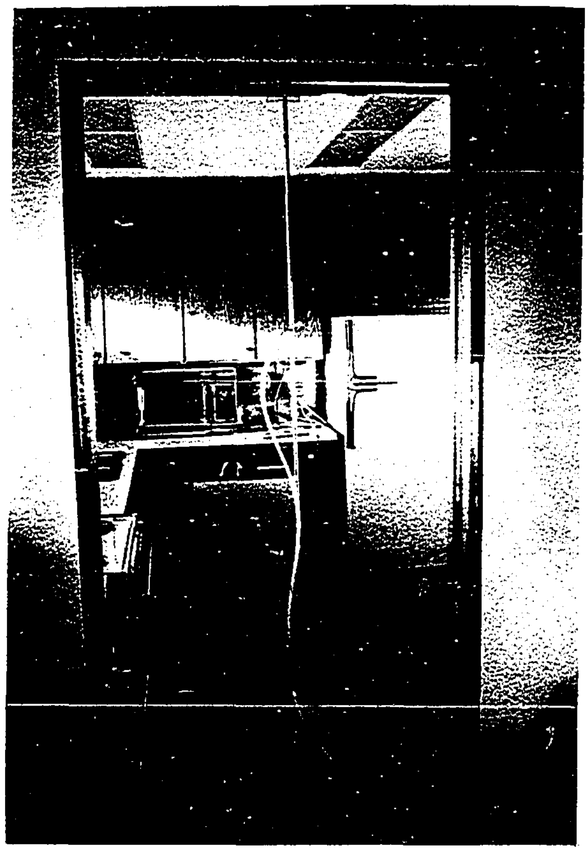


Fig. 6. View of the sampling port in the kitchen of the ERH

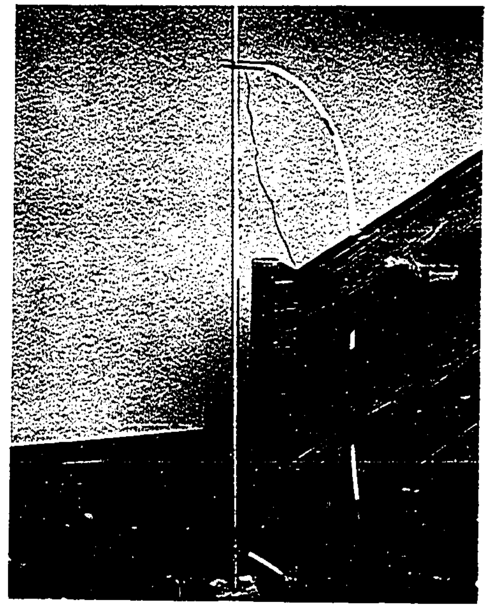


Fig. 7. View of the sampling port in the lower stairwell of the ERH

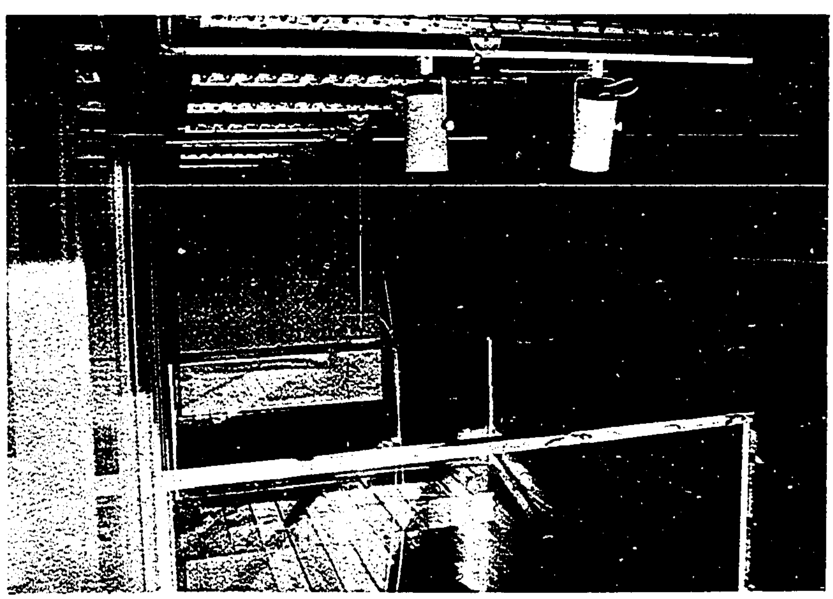


Fig. 8. View of the sampling port in the upper level of the greenhouse of the ERH

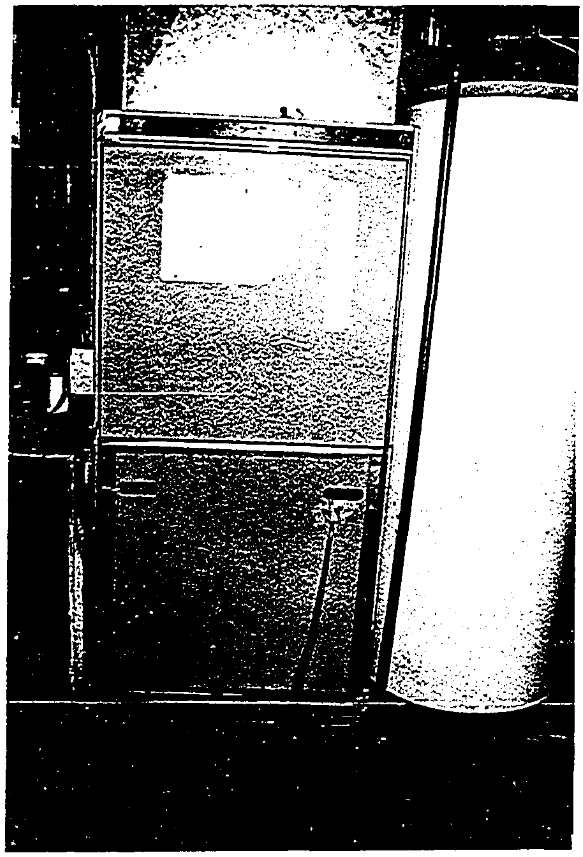


Fig. 9. View of the electric heating furnace in the ERH showing the location where injection of the tracer-gas was made

2. During the following two hours, the central air fan was de-energized, and the concentration of methane was monitored at the bottom of the stairwell.

3. During the fourth hour, the central air fan was re-energized. During the period, methane sampling continued at the bottom of the stairwell.

4. Finally, methane sampling was moved again to the main return duct. This move coincided with an increase in wind speed, as shown by the summary outdoor conditions listed in Table 5.

During these 5-1/2 hours, the decay of SF_6 was monitored at all 12 locations previously specified in Table 4. The measured concentrations of methane are shown in Fig. 10, and, in Fig. 11, the concentrations of SF_6 in several locations throughout the house are also given.

Figure 11 shows that the concentrations of SF_6 were fairly uniform and decayed at the same rate throughout the house whenever the central air fan was in operation. The same did not occur, however, when the fan was not in operation. Figure 11 shows that, between 50 and 170 minutes after the start of the procedure, the concentrations of SF_6 diverged from a common value with different decay rates. This divergence shows that, without the central air fan operating, severe nonuniformity occurred inside the ERH. The decay of concentration of methane should then be compared only to the decay of concentration of SF_6 in the basement during this period (methane was sampled at the bottom of the stairwell, at the boundary between zones 8 and 10 as per Table 4).

Table 5. Outdoor weather summary for calibration measurements[a]

Time (minutes after test start)	Dry-Bulb Temperature (°C)	Wind Speed (m/s)	Wind Direction (degrees clockwise from north)
15	7.7	3.0	149
30	7.8	5.5	146
45	7.9	4.0	154
60	8.0	5.3	146
75	8.3	4.2	150
90	8.4	4.3	150
105	8.8	5.6	153
120	8.9	3.3	162
135	9.1	2.9	173
150	9.1	3.8	183
165	9.4	3.0	166
180	9.6	3.7	158
195	9.6	2.5	161
210	9.9	2.3	169
225	9.9	2.5	173
240	10.3	1.1	172
255	10.5	1.9	170
270	10.8	4.4	170
285	9.7	4.8	176
300	9.7	3.8	150
315	9.9	3.6	143
330	10.6	4.1	151

[a]Data are averages for the 15 minute period preceding the stated time.

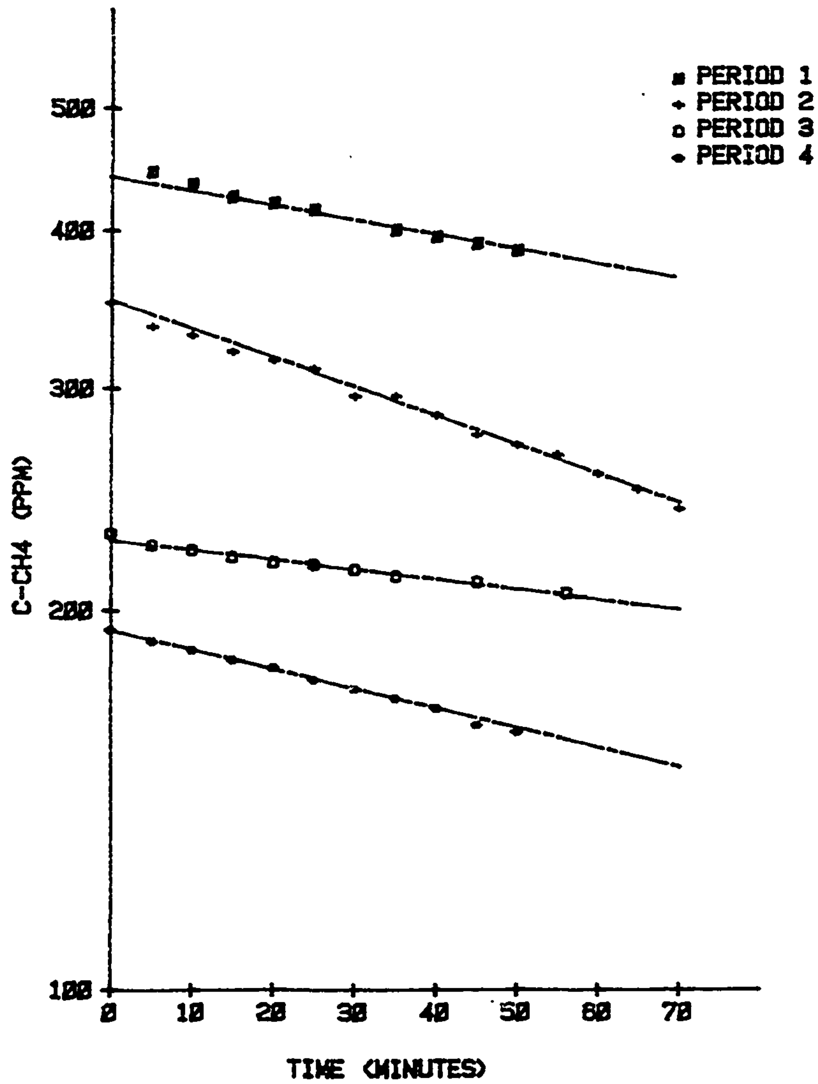


Fig. 10. Concentration of methane in the Energy Research House during calibration test (from Janssen)

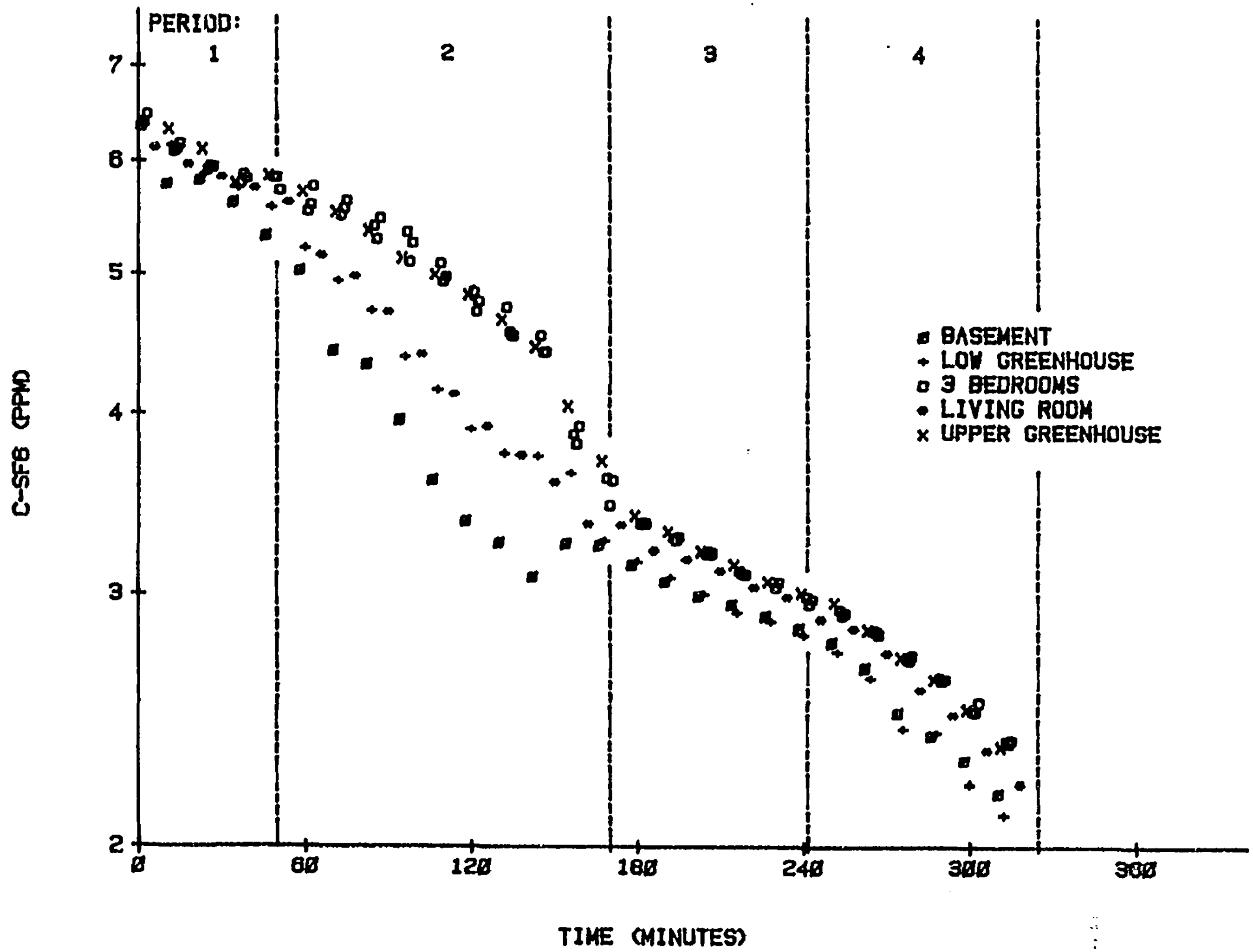


Fig. 11. Concentration of SF_6 in the Energy Research House during calibration test

The rates of decay[1] of methane and SF_6 in each of the four different periods are listed in Table 6. The SF_6 values are whole-house averages when the methane was sampled in the return air duct (first and last period) and the average of zones 8 and 10 when methane was sampled at the bottom of the stairwell. Although the sample size for each test was too small for statistical analyses, Table 6 shows that excellent agreement was obtained, thus validating the accuracy of the equipment used to measure air exchange rates.

Equipment to Measure Thermal and Mass Factors of Indoor Air Quality

Measurements of the thermal factors of indoor air quality were performed with the following equipment:

1. Dry-bulb temperatures were measured on occasion with calibrated mercury thermometers. But, in general, copper-constantan thermocouples were used with a Fluke 2204A datalogger (resolution of 0.1°C).

2. Relative humidities were measured by combination of dry-bulb and wet-bulb temperatures.

3. Air velocities were measured with a DISA 55D81 low velocity hot-wire anemometer with an accuracy of ± 1 cm/sec in the 0 to 30 cm/sec range [103].

---

[1] The rates of decay were obtained as the negative of the slope of the plot of concentration versus time in a semilog plot. The equations for the lines were calculated using a least-squares fitting procedure.

Table 6. Rates of decay of methane and sulfurhexafluoride during calibration test

Period (min)	Rate of Decay (ACH)	
	Methane (Janssen)	SF_6 (Maldonado)
0 - 50	0.16	0.14[a]
60 - 170	0.32	0.33[b]
180 - 240	0.11	0.10[b]
250 - 310	0.22	0.23[a]

[a]Whole-house.

[b]Basement only.

Measurements of mass factors were performed with integrating sensors:

1. Formaldehyde measurements were performed with 3-M monitors (3-M reference number #3750) which has a resolution of 0.8 ppm x hours and a capacity of 72 ppm x hours (see Fig. 12).

2. Radon measurements were performed with TERRADEX type B TRACK ETCH sensors (see Fig. 13), which have been extensively used in indoor radon monitoring programs [104].

3. Other gaseous contaminants were measured using colorimetric length-of-stain MSA tubes (available for carbon monoxide, carbon dioxide, sulfur dioxide, ammonia, ozone, and nitrogen dioxide) through which a sample is pulled by a constant-flow pump (see Figs. 14 and 15).

4. Respirable suspended particulates were collected in an MSA gravimetric dust sampling kit (see Figs. 14 and 15). Samples were weighed in a Fisher microbalance with 5 μg direct reading resolution (1 μg by visual interpolation).

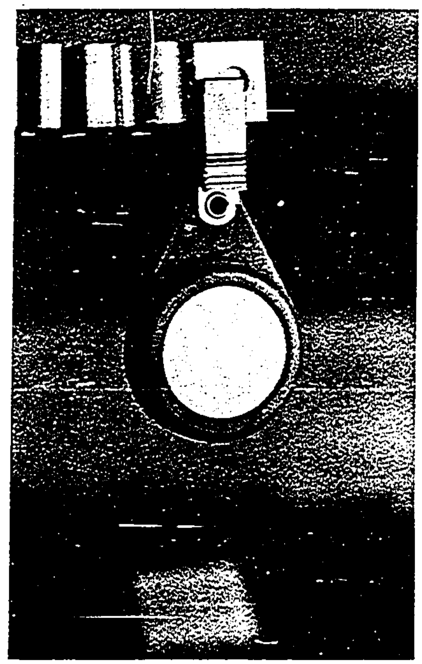


Fig. 12. View of the 3-M formaldehyde sensor

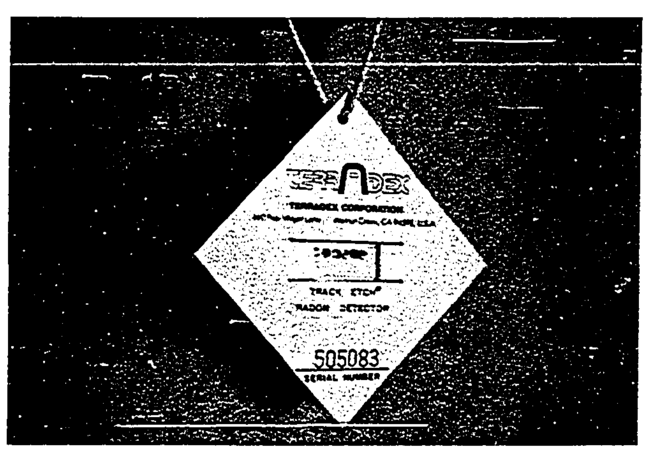


Fig. 13. View of the TERRADEX TRACK ETCH radon sensor

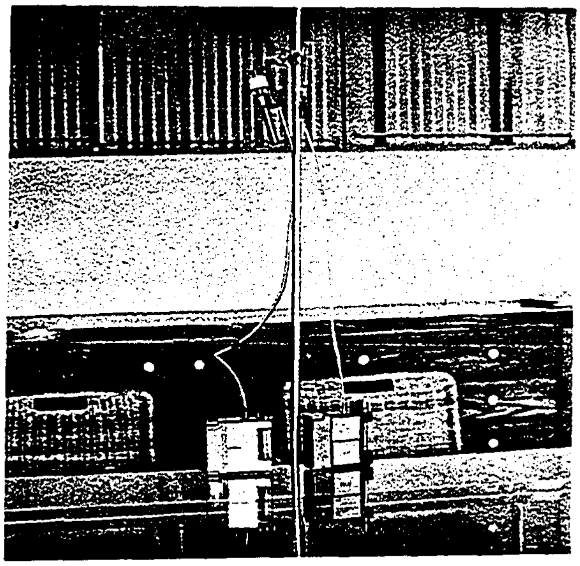


Fig. 14. View of the MSA samplers for suspended particulates and gaseous contaminants

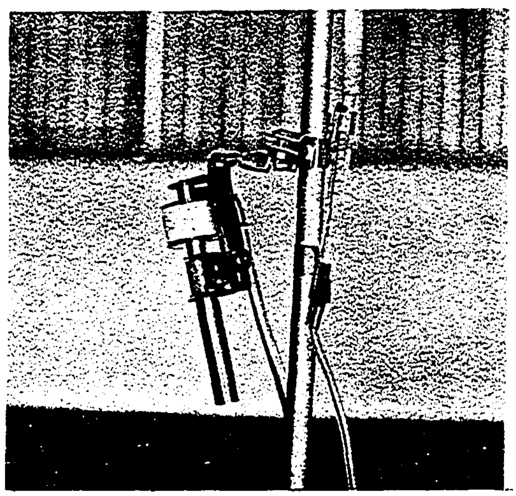


Fig. 15. Detail of the MSA dust collector and colorimetric tube sampler

VALIDATION OF THE TRACER-GAS PROCEDURE TO LOCATE "HIGH-RISK" ZONES IN BUILDINGS

This section will describe the measurements and results which were obtained in the Energy Research House to verify the assumptions and other statements made in a previous chapter. Also described and discussed are the data concerning the use of the procedure as proposed.

Verification of Uniform Mixing in Rooms

A major step in this procedure consists of locating the zones within a building which can be considered to be uniformly mixed. In an earlier section, it was hypothesized that rectangular rooms which were not too large could be considered to be uniformly mixed. This hypothesis was based on earlier reported data, although slight nonuniform mixing had also been reported under the same circumstances [73, 75]. However, for the purpose of indoor air quality evaluation, small spatial variations (e.g., 5%) of concentrations or thermal factors may be tolerated compared to the expected large variations (e.g., 100%) which could result in serious underestimation of risk to the occupants. Given these uncertainties, it was important to directly verify which spaces could or could not be treated as uniformly mixed in a residence.

To do so, five spaces in the ERH were selected for multipoint analysis: the southwest bedroom in the upper level (characteristic of a small room), the living room in the middle level and the basement in the lower level (characteristic of normal large sized rooms in a residence), the stairwell (characteristic of irregularly shaped spaces), and the greenhouse (characteristic of rooms with high ceilings). Due to the limited number of available sampling ports (12), complete sets of data in the five rooms could not be obtained simultaneously. Thus, five separate tests were run in which different sampling locations were used. In all tests, SF_6 was injected into the forced air supply duct ahead of the supply fan to obtain a uniform concentration throughout the house. The gas was then allowed to decay with the central air fan de-energized. The concentrations that were measured in all five tests and the locations where they were measured are shown in Figs. 16 thru 20[1]. A detailed analysis of these five tests will be done next, concentrating on each of the five spaces listed earlier in this paragraph, one at a time. Although comparisons were made between tests conducted at different times, analysis of the results included consideration that the air exchange rates were not the same in all tests due to different outdoor conditions. So, rather than comparing absolute magnitudes from test to test, comparisons of the patterns were made. To facilitate the comparison, at least one channel in each of the five spaces listed was monitored in tests #1 thru #4.

Living room: Analysis of the uniformity of mixing within the living room was made in a two-step procedure. In test #1, shown in Fig. 16, six probes were placed in the living room, 1.6 m above the floor, to investigate horizontal variations of concentrations. Two of

---

[1]These tests will subsequently be designated by test #1 thru test #5, respectively.

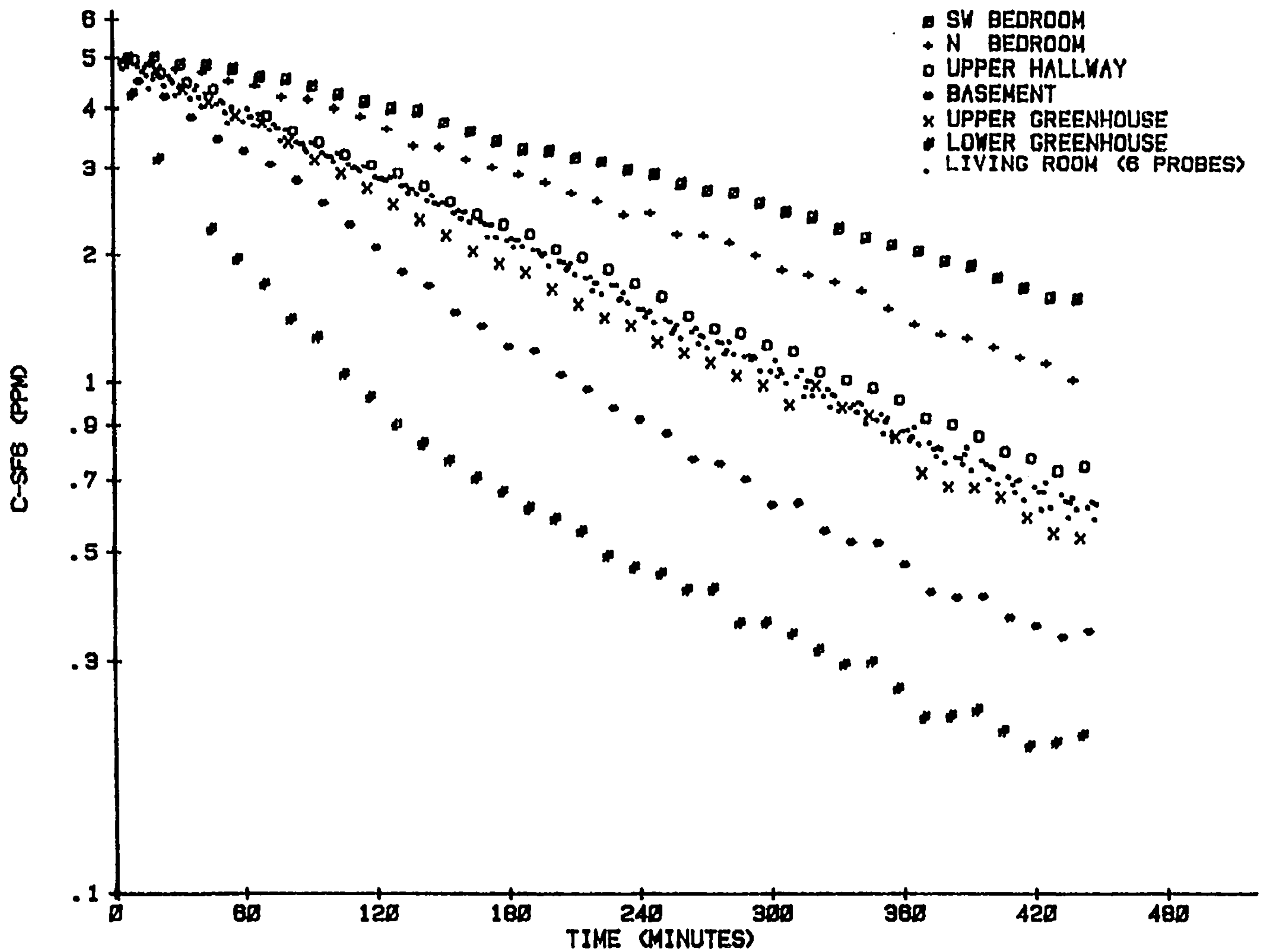


Fig. 16. Concentrations of SF_6 in the ERH during uniform mixing test #1

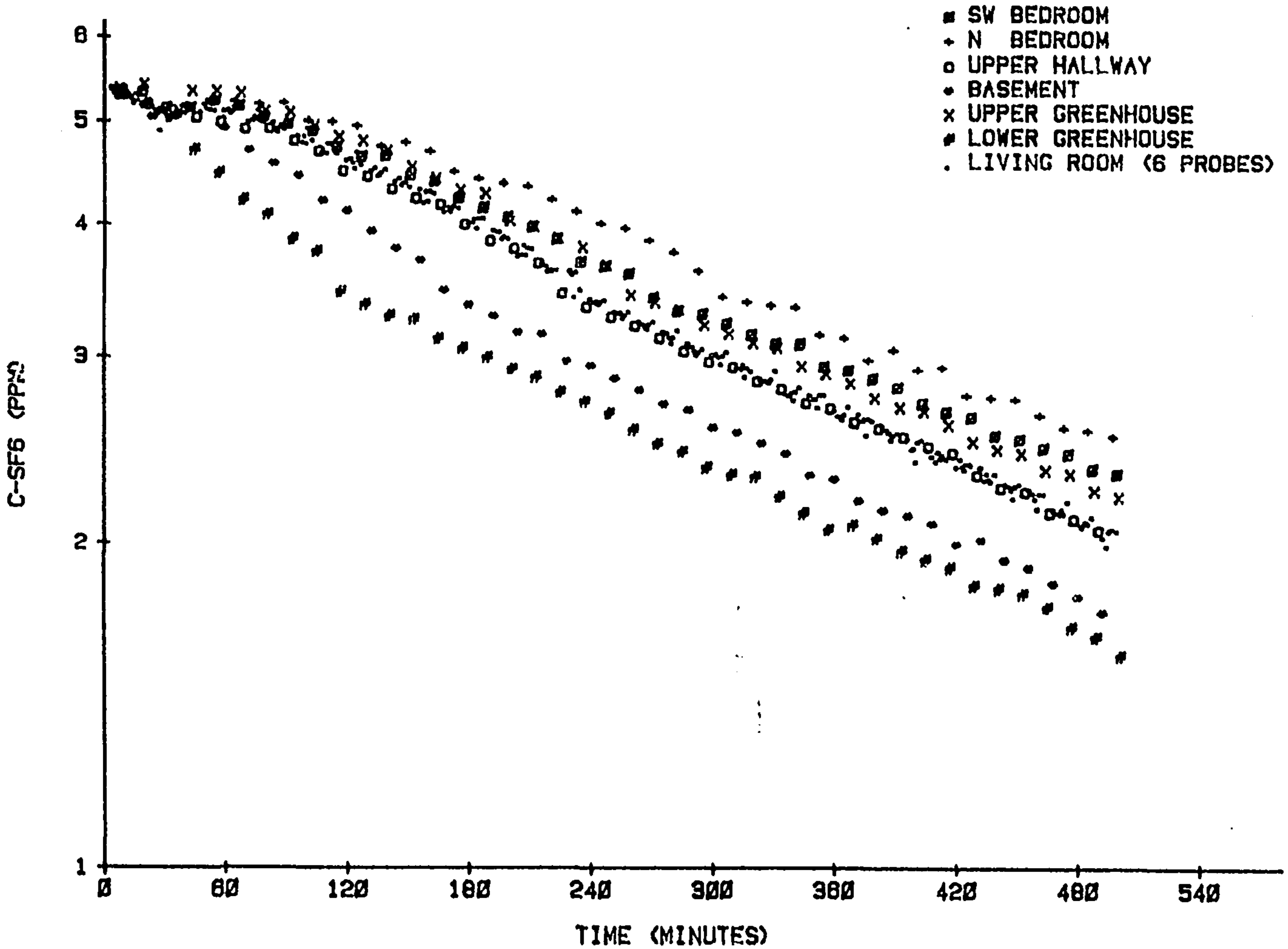


Fig. 17. Concentrations of SF_6 in the ERH during uniform mixing test #2

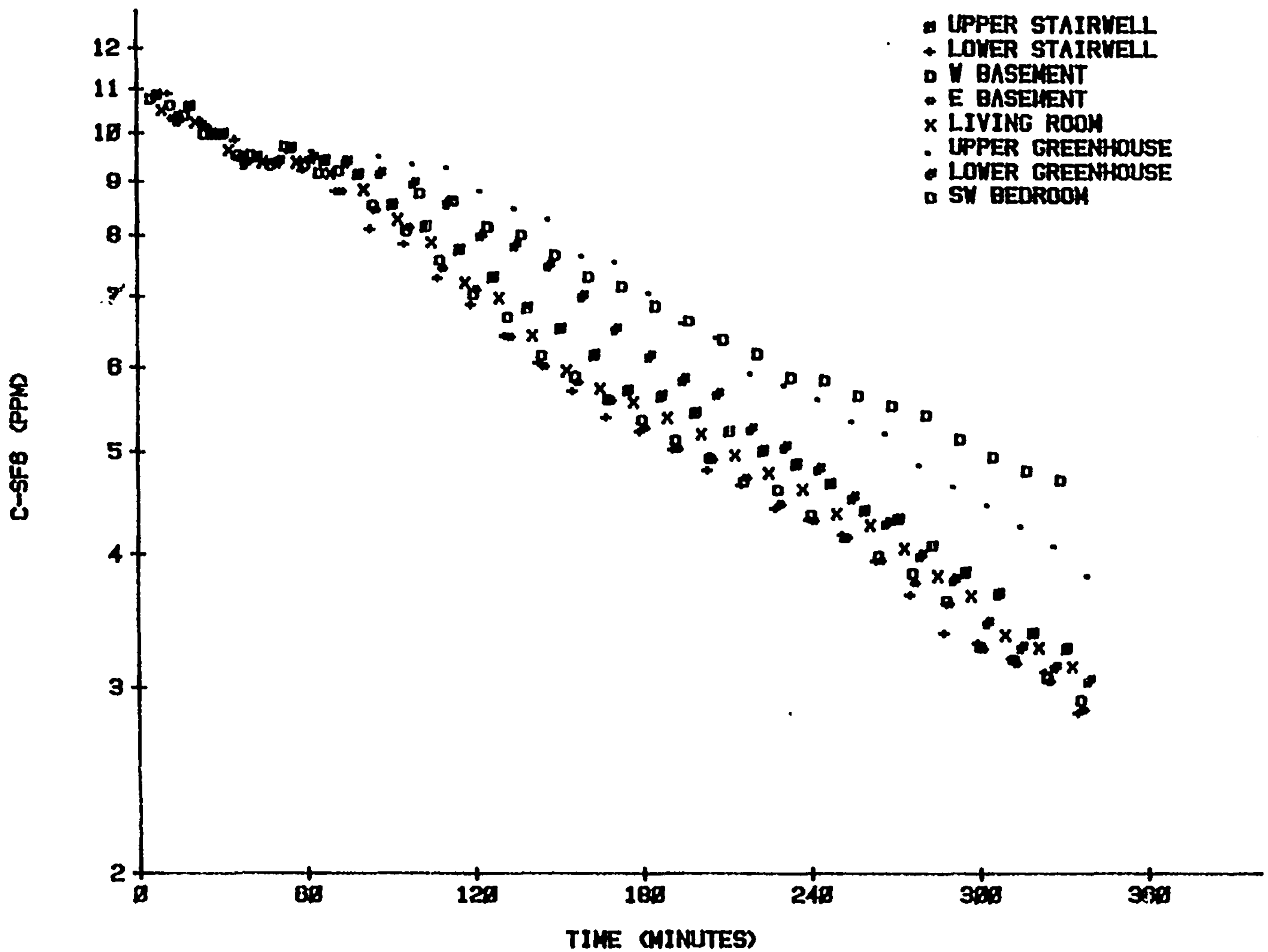


Fig. 18. Concentrations of SF_6 in the ERH during uniform mixing test #3

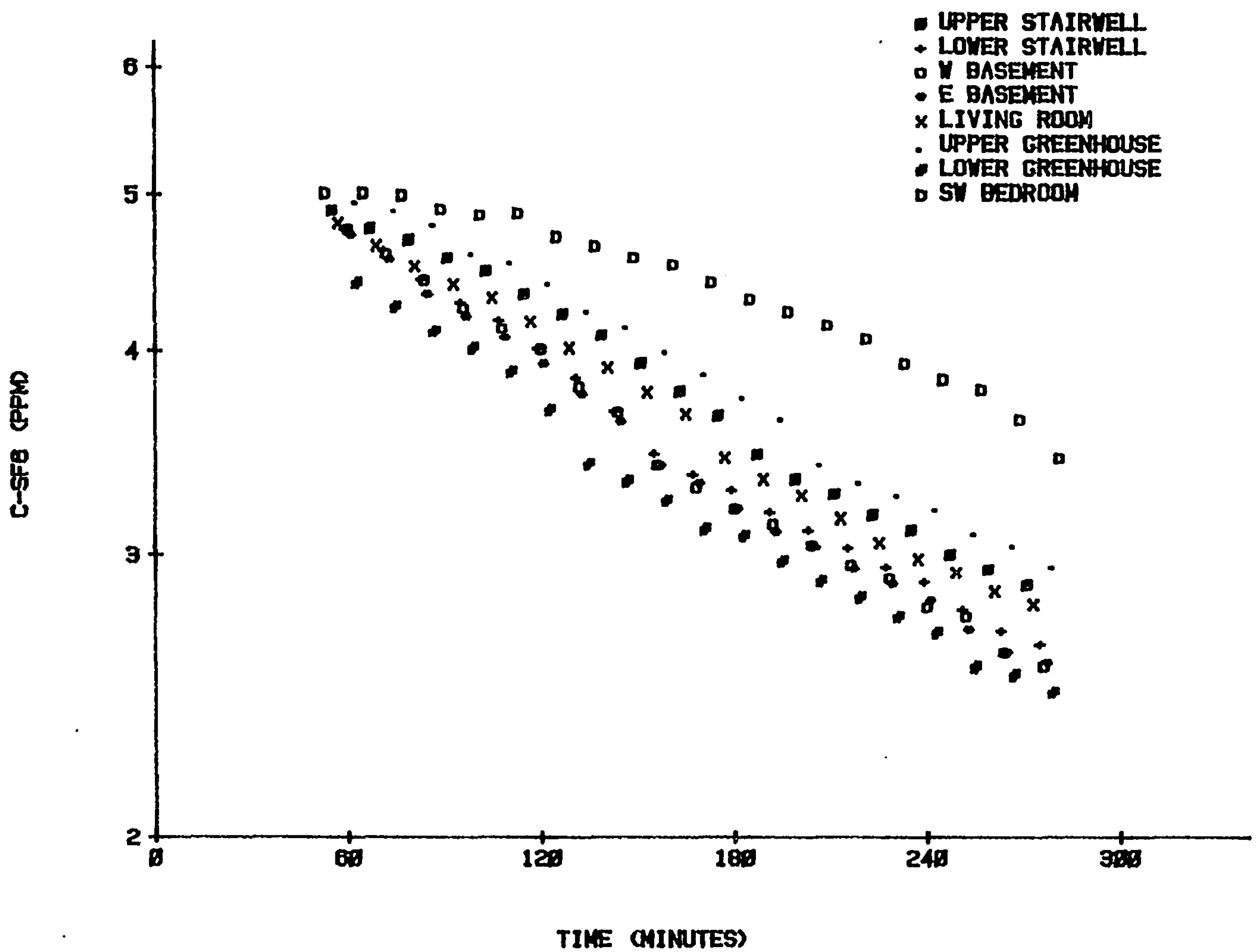


Fig. 19. Concentrations of SF_6 in the ERH during uniform mixing test #4

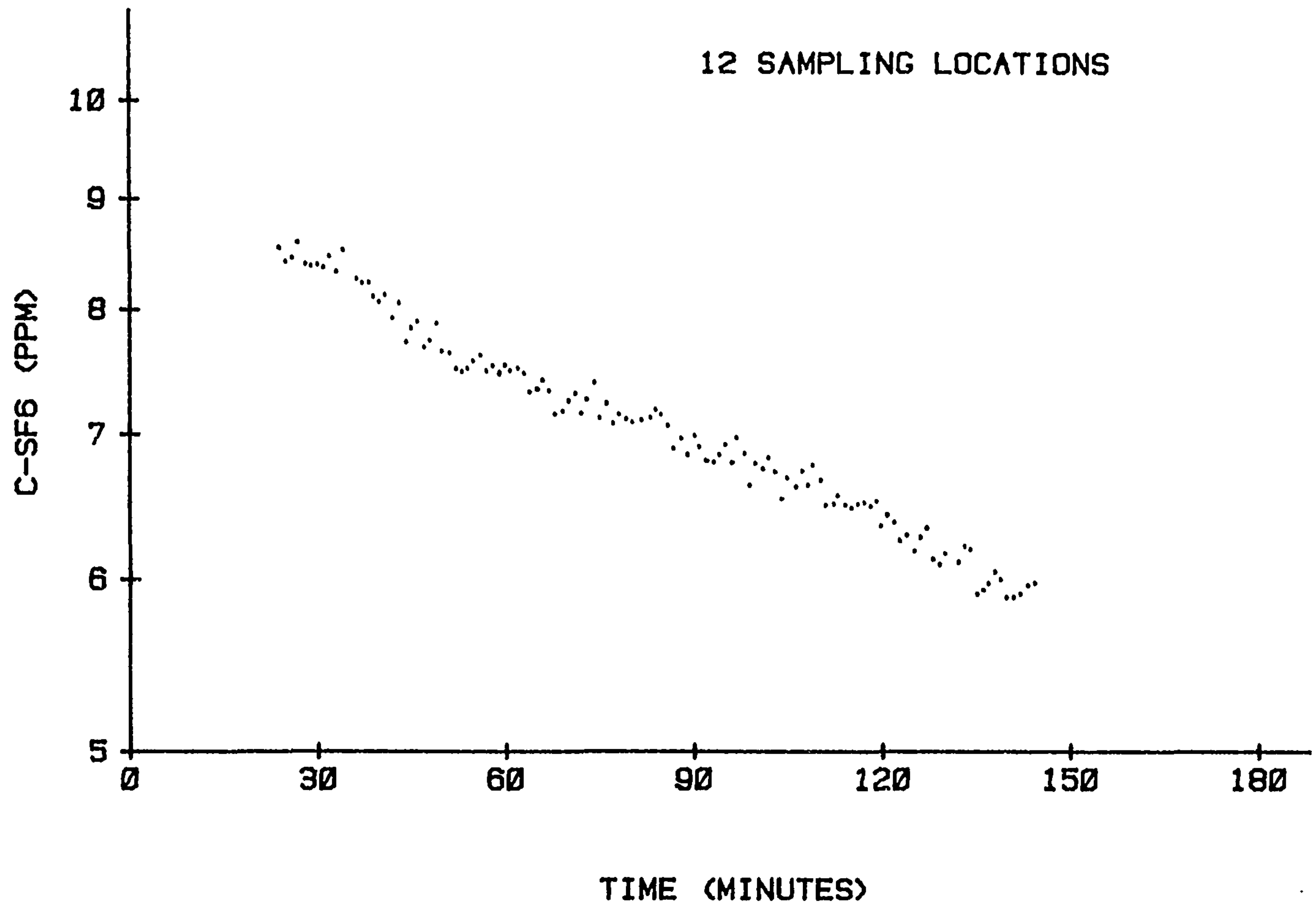


Fig. 20. Concentrations of SF_6 in the southwest bedroom during uniform mixing test #5

the probes were placed in the geometrical center of the east and west halves of the floor plan, and the remaining four were placed within 10 cm of the four corners of the room. The samples were returned at floor level. In test #2, shown in Fig. 17, six probes were also placed in the living room, but three probes each were placed at the geometrical centers of the east and west halves of the floor plan at three different levels, i.e., 5 cm above floor level, 1.6 m above floor level, and 5 cm below ceiling level. The samples were returned at the same level where they were collected. Care was taken to avoid direct recirculation between collection and return air currents by placing the supply and return ports in opposite directions and 20 cm apart, horizontally, from each other.

The concentrations of SF_6 measured at each of the six sampling locations within the living room in tests #1 and #2 are plotted separately in Figs. 21 and 22, respectively. In both cases, it can be seen that there was some scatter in the data obtained in the living room. Figure 22 shows that the west floor level tended to have the lowest concentration in the living room during test #2, and that the east ceiling level tended to have the highest concentration, but the differences were small. At the end of the monitoring period, the concentrations in the six sampling locations in the living room, Fig. 22, varied from 1.99 to 2.07 ppm, which means that there was a 2% deviation from the midpoint of the range (2.03 ppm). Figure 21 shows no specific pattern to indicate a systematic nonuniformity in some part of the room.

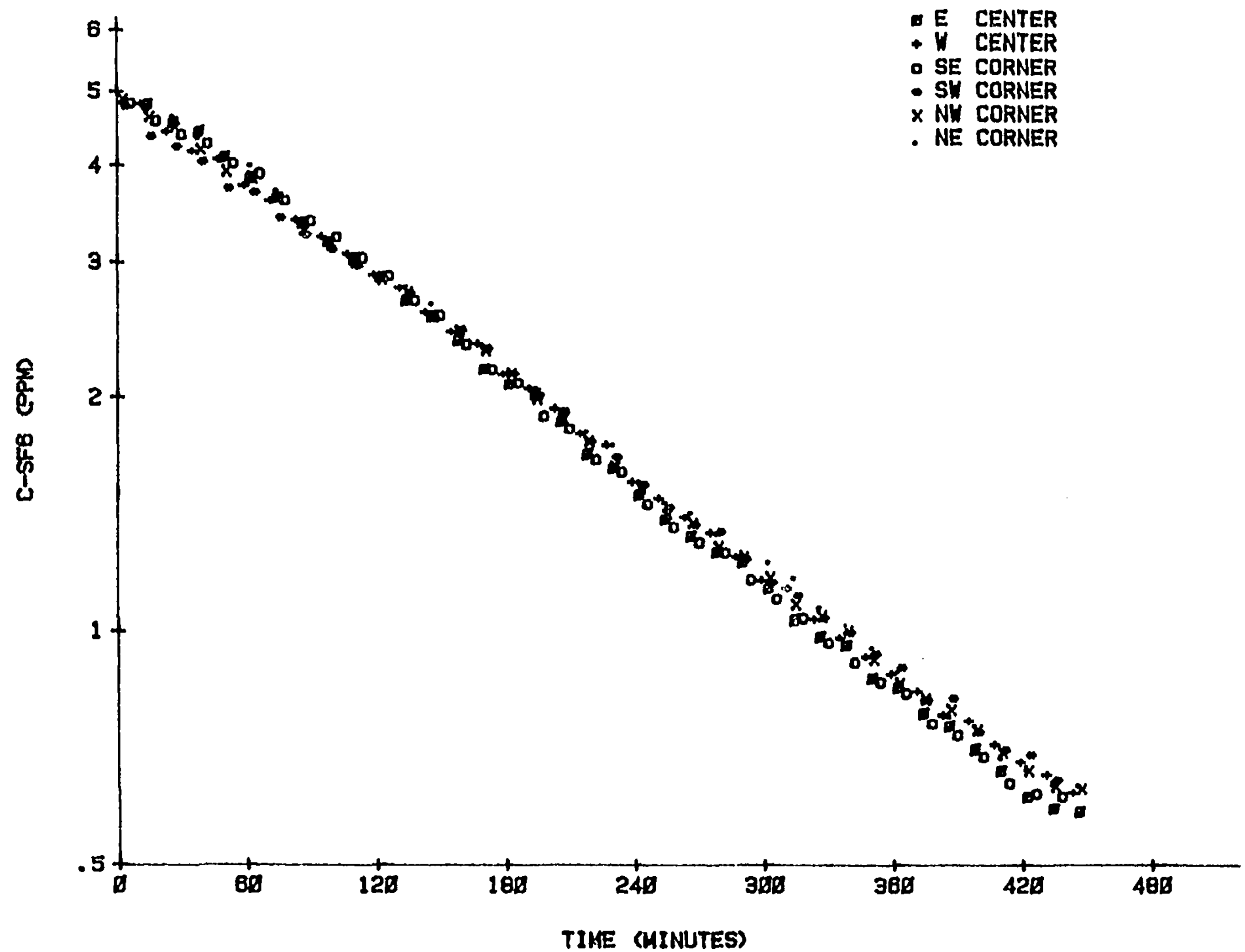


Fig. 21. Concentrations of SF_6 in the ERH living room, test #1

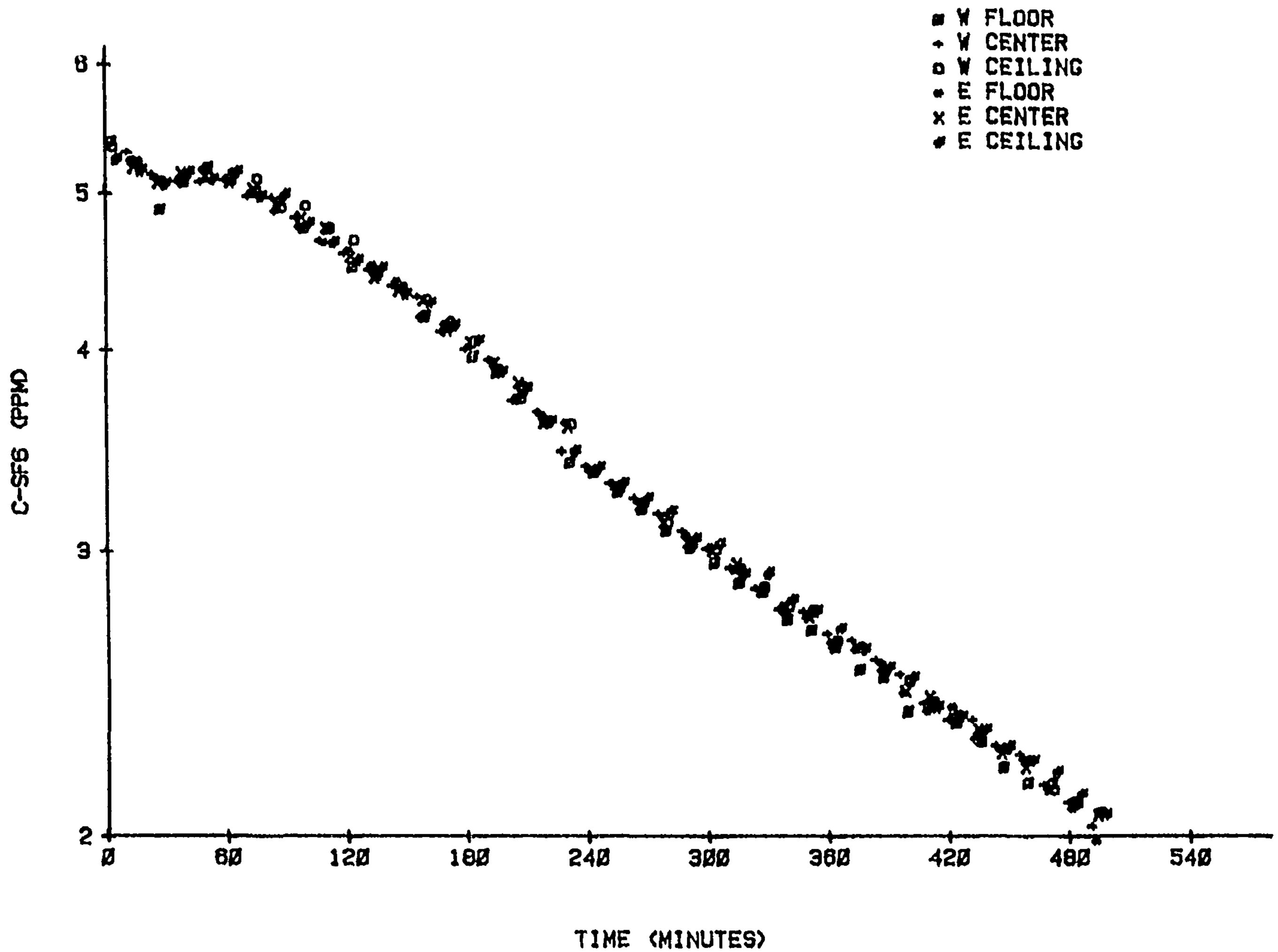


Fig. 22. Concentrations of SF_6 in the ERH living room, test #2

Moreover, the deviation of concentrations at the end of the monitoring period represented 3% from the midpoint of the range, which is of the same order of magnitude as the previous case.

Conversely, the concentrations throughout the house varied substantially during these tests. In test #1, the concentrations at the end of the monitoring period varied from 0.21 ppm to 1.63 ppm and, in test #2, from 1.58 ppm to 2.53 ppm[1]. As summarized in Table 7, these variations correspond to deviations of 77% and 23% from the midpoint of the range, respectively. Thus, the variations that were measured in the living room were quite small with respect to the total variation that was measured within the house. Moreover, the scatter in the data obtained at the six points in the living room in both tests was of the same order of magnitude as the scatter obtained in tests conducted with the central air fan continuously on and all internal doors open, as shown in Fig. 23. In this latter case, the range of the concentrations was from 0.92 to 0.98 ppm, or a deviation of 3% from the midpoint of the range.

These results confirm earlier resports of measured nonunformities in rectangular rooms, but, given the relative mangitudes of the nonuniformities "within a room" and "between rooms", it seems appropriate to assume that the living room was uniformly mixed during both tests.

---

[1]The maximum and minimum concentrations were known from trial tests conducted in the ERH to always occur in the southwest and north bedrooms (maximum) and lower greenhouse (minimum). Thus, these three locations were monitored in tests #1 thru #4.

Table 7. Variation of concentrations throughout the Energy Research House during tests #1 and #2[a]

	Whole house (12 probes)	Living room (6 probes)	Greenhouse (2 probes)
Test #1	0.21-1.64 (77%)	0.59-0.63 (3%)	0.21-0.54 (44%)
Test #2	1.58-2.53 (23%)	1.99-2.07 (2%)	1.58-2.22 (17%)
Fan on (Fig. 23)	0.92-0.98 (3%)	--	--

[a]Values listed are minimum and maximum measured in the space. Values in parentheses are the relative magnitudes of the deviations from the midpoints of the ranges compared to the values of the midpoints of the ranges.

Table 8. Concentrations of tracer gas at the end of the tests #3 and #4[a]

	Number of Samples	Test #3	Test #4
Stairwell	2	2.84-3.27 (7%)	2.64-2.87 (4%)
Greenhouse	2	3.05-3.83 (11%)	2.47-2.95 (9%)
Living room	2	3.10-3.14 (1%)	2.75-2.80 (1%)
Basement	2	2.86-2.92 (1%)	2.56-2.57 (0%)
Whole-house	12	2.84-4.98 (27%)	2.47-3.45 (17%)

[a]Values listed are minimum and maximum measured in the space. Values in parentheses are the relative magnitudes of the deviations from the midpoints of the ranges compared to the values of the midpoints of the ranges.

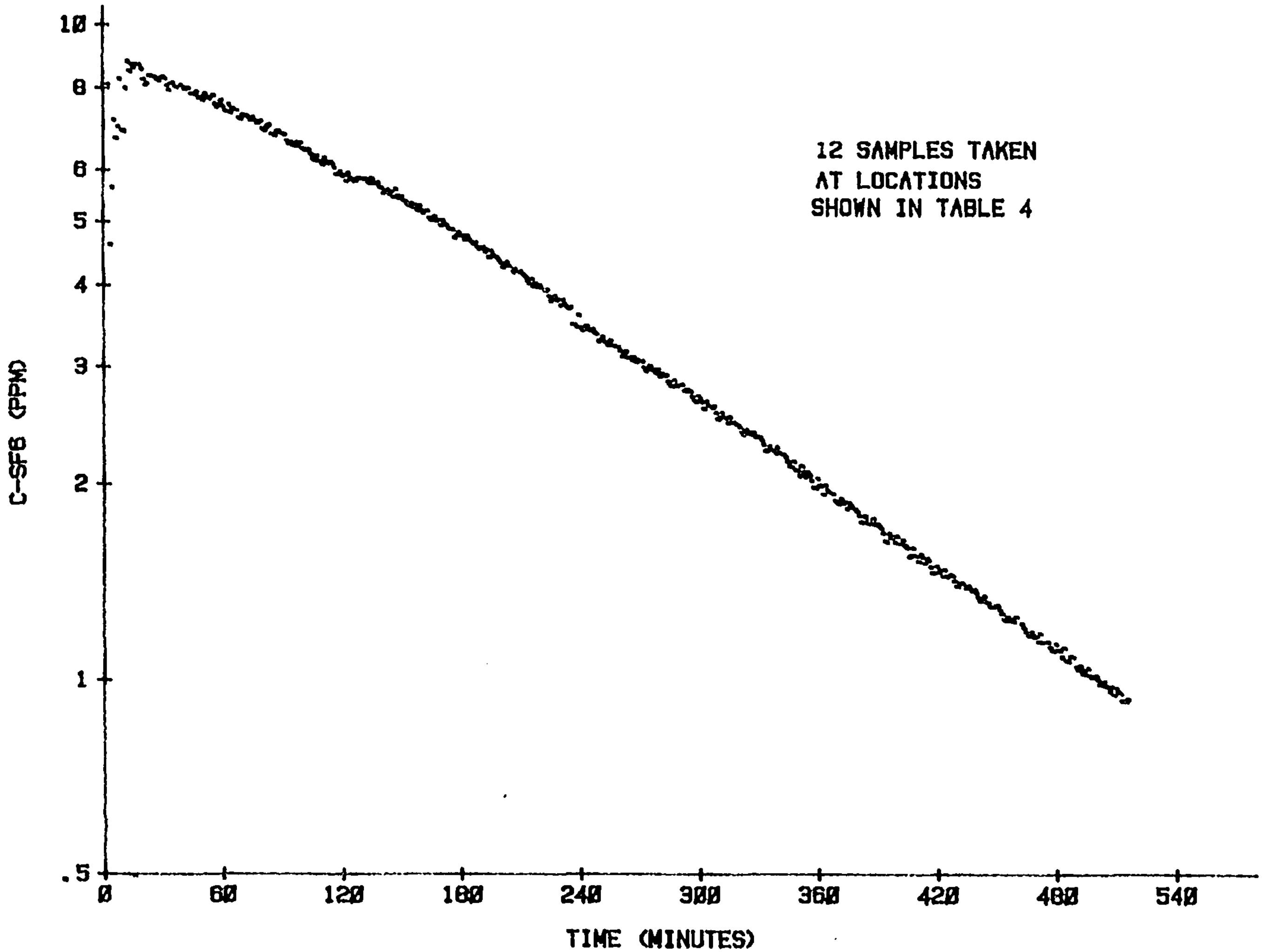


Fig. 23. Concentrations of SF_6 in the ERH with central air fan energized

Greenhouse: One probe was placed in the upper level of the greenhouse and another at the lower level, both at 1.6 m above floor, in tests #1 thru #4 to investigate vertical variations in SF_6 concentrations between the two levels. In Figs. 16 thru 19, the concentration of SF_6 in the upper level was higher than at the lower level of the greenhouse. At the end of the monitoring period, the deviations from the midpoint of the range ranged from a high of 44% in test #1 to a low of 9% in test #4 (see Tables 7 and 8). These deviations represent stratification that was probably of thermal origin, as the average temperature at the upper level of the greenhouse in test #1 was 14.2°C and, at the lower level, the average was 12.1°C. Similar temperature differentials were observed in all tests. This stratification probably resulted from cold air infiltration[1] which tended to move toward the lower level of the greenhouse while the warmer indoor air tended to remain at the upper level for a longer period.

These results show that the greenhouse could not be considered uniformly mixed because large variations (up to 44%) in concentrations were detected. Thus, the greenhouse required more than a single sampling point in all tests to evaluate indoor air quality.

Stairwell: One probe was placed in the upper portion of the stairwell 1.6 m above the upper landing and another in the lower portion, 1.6 m above the lower landing, in both tests #3 and #4 to investigate

---

[1]Average outdoor air temperature ranged from a high of 4°C in test #1 to -5°C in test #4.

vertical variations in SF_6 concentrations within the stairwell. The deviations of the two measured concentrations in tests #3 and #4 were 4% and 7%, respectively. Although this was a relatively small deviation, compared to the greenhouse, the concentrations in the upper level of the stairwell always remained higher than in the lower level, thus indicating that stratification was also present in this space. Thus, the stairwell could not be considered to be a uniformly mixed space.

Basement: Two probes were placed in the geometrical centers of the east and west halves of the floor plan of the basement 1.6 m above floor level during tests #3 and #4. As shown in Table 8, the ranges of concentrations of SF_6 at these two points were similar to the ranges obtained from the two probes which were placed in corresponding positions in the living room during these two tests. Therefore, given the similar geometry of both basement and living room, it was concluded that the basement was also a uniformly mixed space.

Southwest bedroom: Twelve probes were placed in the southwest bedroom at different positions and levels throughout the room to investigate horizontal and vertical variations of concentrations within this room. The results of this test (#5), shown in Fig. 20, indicate that, at the end of the monitoring period, the variation in concentration among the various sampling locations deviated only 1% from the midpoint of the range. This pattern and deviation was similar to that found in the living room. Thus, this room was concluded to be a uniformly mixed space.

In conclusion, the tests conducted to determine the validity of the "uniformly mixed spaces" assumption showed that, although differences occurred within rooms of rectangular shapes with low aspect ratios, these differences represented deviations of at most 3% from their mean values and, thus, small compared to the differences that occurred among the different spaces of the house. These results obtained in the ERH confirm those reported in the literature [73, 74]. Thus, to evaluate indoor air quality in a residence, little error is committed by treating rectangular rooms with low aspect ratios as uniformly mixed spaces. Exceptions are those spaces which span more than one level in a house (typically 2.4 m high). In these spaces, large variations in concentrations can occur due to thermal stratification.

Verification of the Consequences of the Use of the Central Air Fan

Current practice is to measure whole-house air exchange rates by forcibly mixing the house with the central air fan, or with conveniently placed portable fans. In the ERH, tests indicate that this practice would result in overestimation of the air exchange rates.

When the central air fan was not used and the greenhouse was isolated from the rest of the house, the lower part of the greenhouse consistently showed the highest air exchange among all zones within the ERH. This fact is clearly shown in Figs. 16 thru 19. However, when the greenhouse was isolated from the rest of the house by closing all of its doors[1], and the central air fan was kept running, the decay

---

[1]In the ERH, there was no forced air supply to the greenhouse.

throughout the house was faster than at the lower level of the greenhouse, as shown in Fig. 24.

Analysis of these results indicated that operation of the central air fan increased the rate of air exchange between the house and outdoors. The cause for this increase is not self-evident, but, at least in part, it appears that it was due to leakage through exhaust dampers in the ductwork. Although this situation may not be common in most residences, it is certainly a factor that must be kept in mind when a measurement of air exchange rate is made in a building.

Location of High-Risk Zones

The high-risk zones in a building are those with the largest values of $(\dot{q}_n/RV)$. To locate these zones, the concept of Relative Exposure Index (E) was introduced in a previous chapter[1]. In that chapter, it was also hypothesized that similar conclusions could also be obtained from the air exchange rates (R) and ventilation efficiencies (ε) determined for the various zones of a building. The measurements that were taken in the ERH to determine values for R, ε, and E will be detailed next.

Measurement of zonal ventilation efficiencies and air exchange rates with outdoors

To measure R and ε values in the ERH, SF_6 was introduced into the supply air duct just ahead of the central air fan, as shown in Fig. 9. Once an appropriate uniform concentration of SF_6 was obtained throughout

---

[1]Proposed procedure for indoor air quality evaluation.

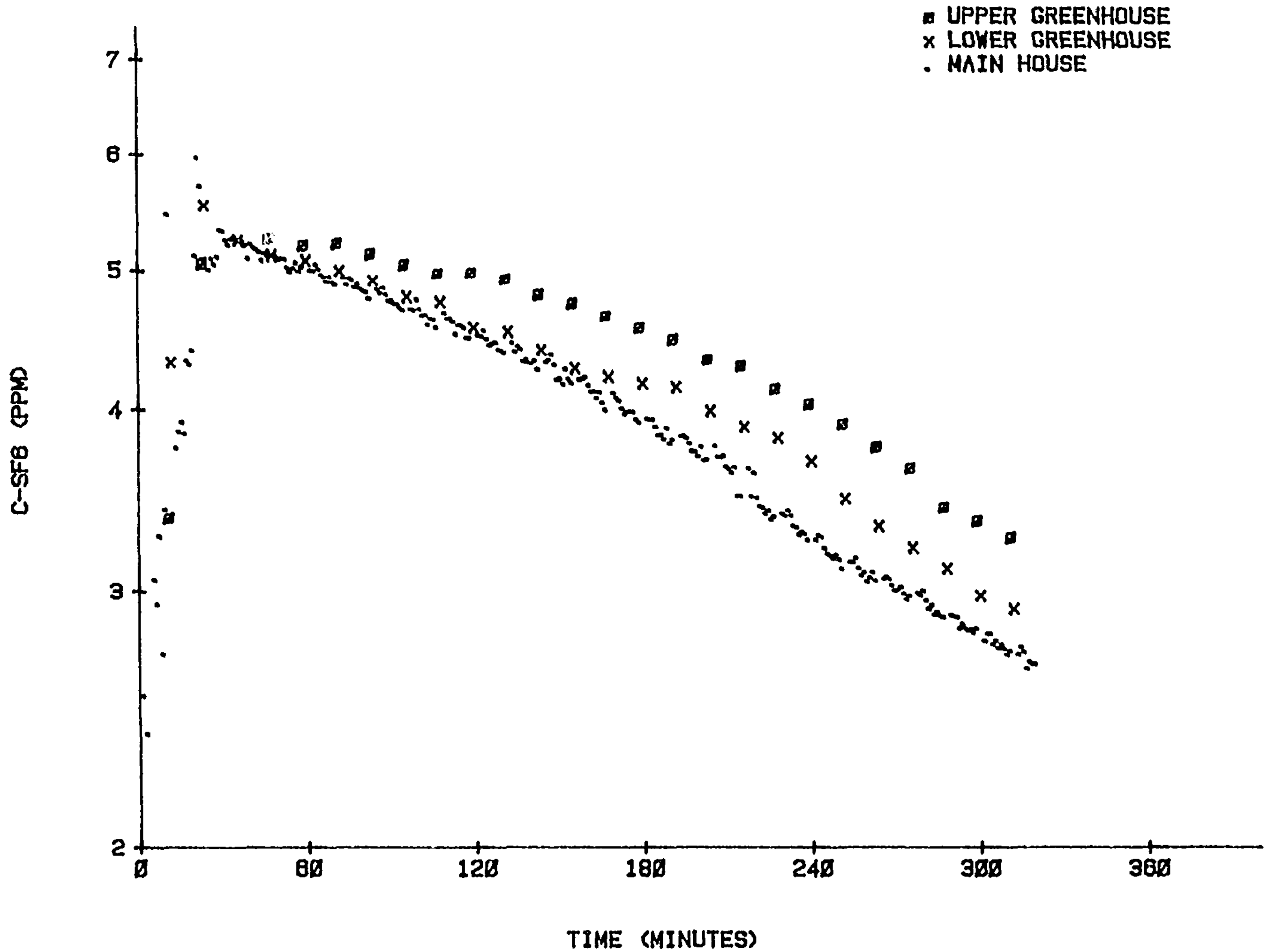


Fig. 24. Concentrations of SF_6 in the ERH with central air fan on, greenhouse doors closed

the ERH, the central air fan was turned off, and all doors to the greenhouse were closed. The mechanical room door, the laundry room door, and the doors between the bedrooms and the hallway were also closed, but the bathroom doors were left open because the concentrations within those rooms were not monitored. The bathrooms were thus treated as a part of the stairwell, with which they were in direct communication.

The decay of the SF_6 concentration in all zones was monitored for sufficient time to separate the effects of transients with short time constants. The zonal air exchange rates were obtained by determining the slope of the loglinear plot of concentration versus time for each zone (see Appendix A), and the zonal ventilation efficiencies were obtained from Eq. (10) in which the integrals of the concentrations were calculated by stepwise integration of the measured data.

As the magnitudes of the air exchange rates and ventilation efficiencies depend on outdoor weather conditions (i.e., dry-bulb temperature, wind speed and wind direction), measurements of R and ε values were made for five distinct outdoor weather patterns. The concentrations of SF_6 measured during these five tests are shown in Figs. 16 thru 19 and in Fig. 25[1]. For these five tests, the resultant zonal air exchange rates are listed in Table 9 and zonal ventilation efficiencies are listed in Table 10.

Air exchange rates   Analysis of the air exchange rates listed in Table 9 shows that there was a strong effect of wind speed and wind

---

[1]Note that air exchange tests #1 thru #4 were obtained at the same time as uniformity of mixing tests #1 thru #4.

Table 9. Zonal air exchange rates

Zones	Air Exchange Rates (ACH)				
	Test #1[a]	Test #2[b]	Test #3[c]	Test #4[d]	Test #5[e]
Southeast bedroom	--	--	0.17	0.15	0.11
Southwest bedroom	0.17	0.11	0.16	0.13	0.10
North bedroom	0.22	0.11	0.23	0.14	0.11
Upper stairwell	0.27	0.13	0.22	0.15	0.12
East living room	0.30	0.13	0.23	0.14	0.14
West living room	0.29	0.13	0.22	0.14	0.14
Kitchen	--	--	0.22	0.15	0.13
Lower stairwell	--	--	0.23	0.14	0.14
West basement	--	--	0.24	0.14	0.17
East basement	0.33	0.13	0.24	0.14	0.16
Upper greenhouse	0.29	0.13	0.23	0.15	0.13
Lower greenhouse	0.29	0.12	0.28	0.14	0.17

[a]See Fig. 16.
[b]See Fig. 17.
[c]See Fig. 18.
[d]See Fig. 19.
[e]See Fig. 25.

Table 9. Continued

Zones	Air Exchange Rates (ACH)				
	Test #1[a]	Test #2[b]	Test #3[c]	Test #4[d]	Test #5[e]
Average Indoor Temperature (°C)					
Upper level	16.1	18.8	20.3	16.6	19.2
Middle level	16.0	18.5	20.2	15.8	19.3
Lower level	16.4	19.2	20.5	15.8	19.0
Upper greenhouse	14.2	15.7	26.0	11.9	20.7
Lower greenhouse	12.1	13.8	22.1	10.1	19.0
Average Outdoor Temperature (°C)	4.1	-0.4	6.6	-4.8	1.7
Average wind speed (m/s)	5.8	0.4	3.8	5.8	2.7
Prevalent wind direction[f]	ESE	SSE	W	ENE	SE

[f]Wind blowing from the direction listed.

Table 10. Zonal ventilation efficiencies

Zone	Ventilation Efficiencies[a]				
	Test #1[b]	Test #2[c]	Test #3[d]	Test #4[e]	Test #5[f]
Southeast bedroom	--	--	0.80	0.90	0.85
Southwest bedroom	0.60	0.91	0.88	0.81	0.82
North bedroom	0.74	0.88	0.88	0.82	0.84
Upper stairwell	0.92	0.99	0.95	0.95	0.96
East living room	1.00	1.00	0.99	1.00	1.00
West living room	1.00	1.00	1.00	1.00	1.00
Kitchen	--	--	1.00	0.99	0.98
Lower stairwell	--	--	1.06	1.05	0.97
West basement	--	--	1.04	1.07	1.06
East basement	1.45	1.12	1.05	1.09	1.05
Upper greenhouse	1.05	0.95	0.88	0.96	1.22
Lower greenhouse	2.92	1.22	0.96	1.16	1.11

[a]See Table 9 for average indoor temperatures and outdoor weather conditions.
All values are referenced to the west living room, which was chosen due to its central location in the Energy Research House.

[b]See Fig. 16.

[c]See Fig. 17.

[d]See Fig. 18.

[e]See Fig. 19.

[f]See Fig. 25.

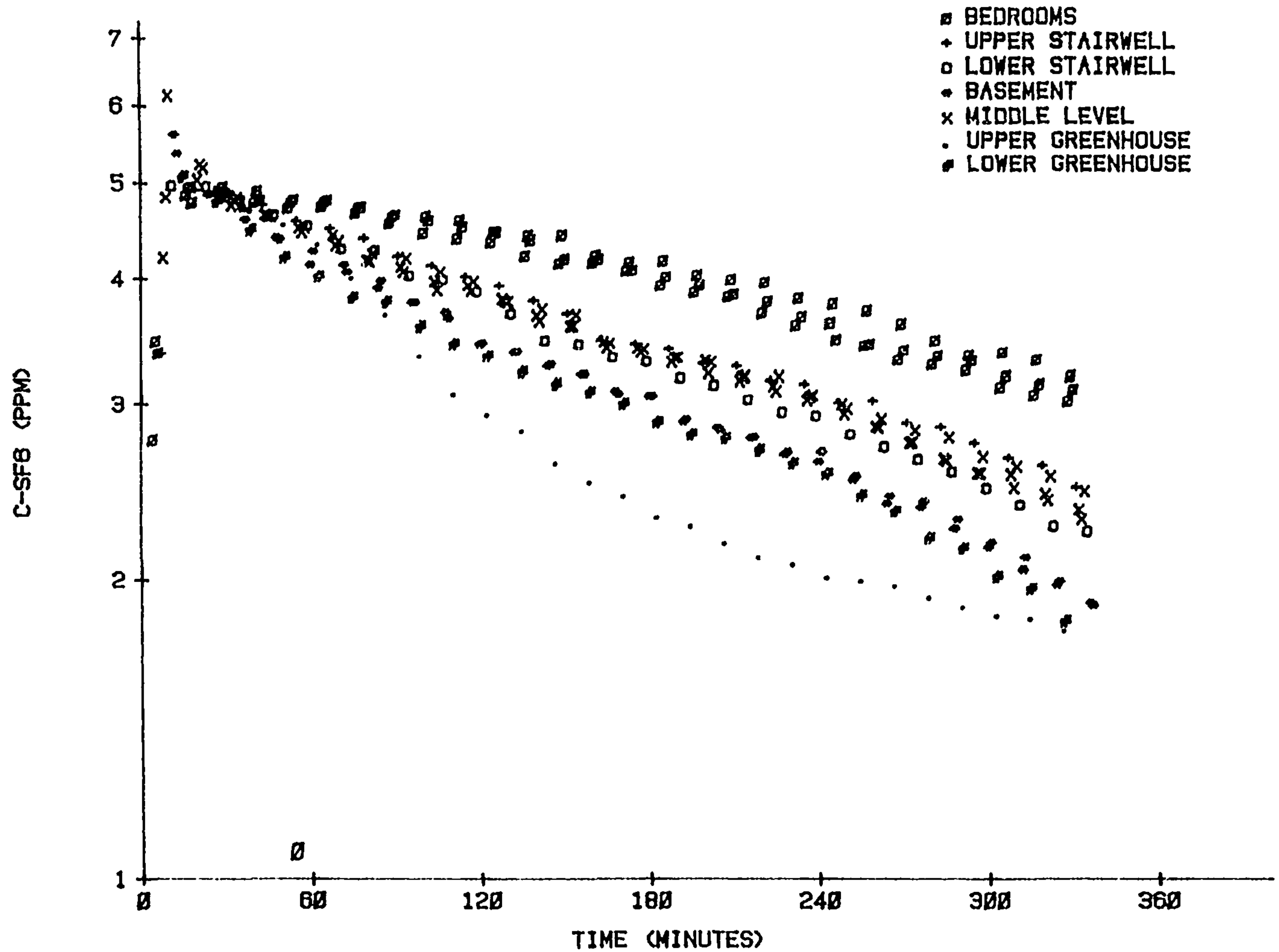


Fig. 25. Concentrations of SF_6 in the ERH during air exchange rate test #6

direction upon the magnitudes of the air exchange rates:

1. In test #1, the wind had the same speed as in test #4. As the temperature difference between indoors and outdoors was larger in test #4, it would be expected that, if directional effects did not exist, larger air exchange rates would have been obtained in test #4 than in test #1. However, the opposite occurred, which indicated that the ERH was more susceptible to east-southeast winds than to east-northeast winds. Although these two wind directions are separated by only 45°, the difference in air exchange rates may be due to the design of the ERH, which attempted to shield the house from the prevalent winterly northwest winds [99], and to the shielding effect of the garage which is located to the northeast of the ERH.

For practical purposes, test #4 had a similar behavior as test #2, in which there was little wind: in both cases, the ratio of the maximum to the minimum air exchange rates was 1.2. Conversely, in the other three cases, the ratios varied from 1.7 to 1.9, an increase in range of about 50%.

2. In tests #1, #3, and #5, similar patterns of air exchange rates were observed: the lowest air exchange rates occurred in the upstairs bedrooms and the highest rates occurred in the lower level. Moreover, the magnitudes of the air exchange rates increased as the wind speed increased.

Ventilation efficiency The values of the ventilation efficiencies, listed in Table 10, were less dependent on wind characteristics, as, most of the time, the zones in the upper level had ventilation efficiencies smaller than unity and those in the lower level had values greater than unity. However, some wind dependency was evidenced by the fact that the lowest ventilation efficiency always occurred in the upper level zone furthest downwind: the southwest bedroom had the lowest ε in tests #1, #4, and #5, when the wind came from the east-southeast, east-northeast, and southeast, respectively; the north bedroom had the lowest ε in test #2, when the wind came from the south-southeast; and the southeast bedroom had the lowest ε in test #3, when the wind came from the west.

In conclusion, given the sensitivity of R and ε values to the direction of the wind, all studies involving replicate tests should be performed under similar wind conditions.

Measurement of the zonal values of the Relative Exposure Index

In this section, the measurements that were made to obtain zonal values of the Relative Exposure Index will be described. The procedure consisted of releasing bottled SF_6 at 4 psi (0.27 atm) above atmospheric pressure for 30 seconds in a particular zone. This amount of SF_6 was chosen because it resulted in adequate values of SF_6 concentrations in the house, but results should be independent of the amount of SF_6 used. Subsequently, the concentrations of SF_6 throughout the ERH were monitored for periods of 6 to 20 hours following the tracer gas release.

Figure 26 shows the results of such a test (#7) when the gas was released in the lower level of the greenhouse[1]. Immediately following

[1]In this figure, and in the next four figures, only typical channels are shown. All other channels behaved like one of those shown and, therefore, were omitted for simplicity of reading.

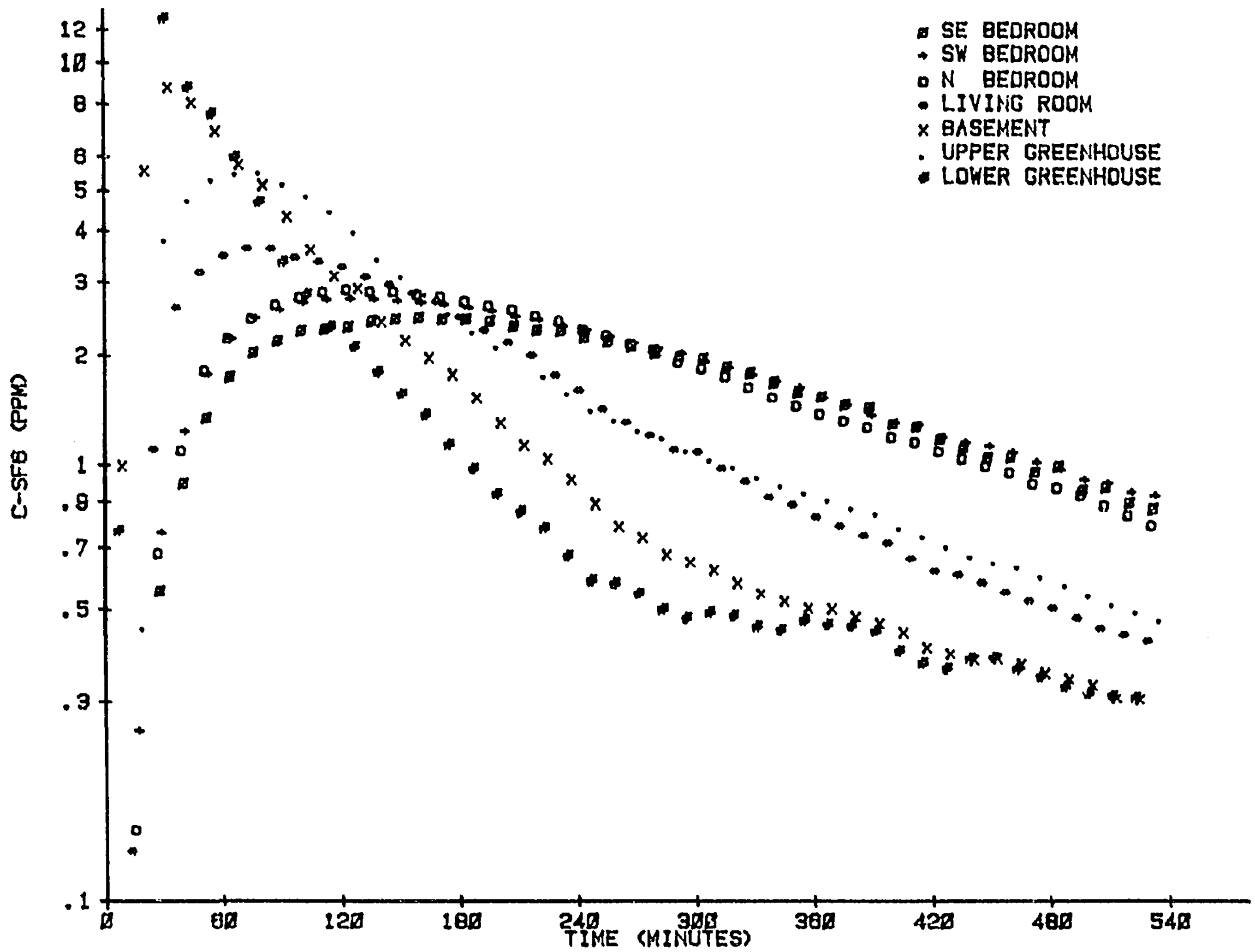


Fig. 26. Concentrations of SF_6 in the ERH following tracer release in lower greenhouse, test #7

the gas release, the concentration in the lower greenhouse rose to high levels. In the other zones, the rise was slower, requiring from 35 minutes (in the basement) to 3 hours (in the southeast bedroom) to reach peak concentrations. Also, the longer rise times resulted in lower peak concentrations. After the peaks were reached, the concentrations decreased at different rates. In the zones with large early peaks, a high rate of decay occurred initially due to the exchange not only with outdoors but also with all the other zones in the house. Once all time-to-peak concentrations were reached, the decay rate in each zone was slower. This test thus confirmed that, even though actual contaminant production, $\dot{q}$, took place only in the lower level of the ERH, effective contaminant generation, $\dot{q}_n$, took place in all zones of the ERH due to the natural air movement which existed between zones.

Quantification of the effective zonal generation rates was done through evaluation of the integral in Eq. (19):

$$\frac{\dot{q}_n}{R\,V} \propto \int_0^\infty C\,dt = \int_0^{t_f} C\,dt + \int_{t_f}^\infty C\,dt \tag{24}$$

where t_f is the length of the monitoring period. Following the end of the monitoring period, the concentrations were approximated by equations of the form:

$$\ln C = I - S\,t \tag{25}$$

which were obtained by least-squares fitting of the last portion of the decay curves. The values of the slope are identified as S rather than

R because these decay rates result not only from air exchange with outdoors, but also from interzonal exchanges due to the lack of uniform mixing in these tests. The value of the Relative Exposure Index (E) for each zone, as defined by Eq. (21), was calculated using for the reference value the integrated area obtained at the zone where the tracer-gas was released.

For the test shown in Fig. 26, the results obtained by this method are summarized in Table 11. These results show that, when actual contaminant generation occurred in the lower level of the ERH, the critical zones were in the upper level of the house. In this particular test, the southwest bedroom was the critical zone, but the comments on wind directionality made in the previous section should also be applicable to this test. In other words, the critical zones in other tests were those furthest downwind in the upper level of the ERH.

It should be realized that these Relative Exposure Index values are weather dependent because of the corresponding changes in R values. When the test shown in Fig. 26 was conducted, the wind was from the south-southeast at 4.3 m/s, and the outdoor temperature averaged -7.1°C. The air exchange rates (S), as listed in Table 11, are indeed in agreement with those listed in Table 9. The differences can be explained by the interzonal air exchanges: the lower values of S for the zones in the lower level were caused by transfer of SF_6 from the higher levels during the last portion of the test.

Table 11. Zonal values of the Relative Exposure Index for tracer-gas injection in the lower greenhouse (test #7)[a]

Zone	T^b (°C)	S^c (ACH)	I^c	$A_1{}^d$ (ppm·min)	$A_2{}^d$ (ppm·min)	A^d (ppm·min)	E^e
Southeast bedroom	13.7	0.216	1.78	868	252	1120	1.13
Southwest bedroom	14.2	0.191	1.62	928	302	1230	1.24
North bedroom	14.1	0.210	1.65	918	241	1159	1.17
Upper stairwell	14.4	0.256	1.45	921	109	1030	1.04
East living room	13.7	0.262	1.34	795	90	885	0.89
West living room	14.1	0.245	1.27	809	105	914	0.92
Kitchen	14.3	0.245	1.27	847	104	951	0.96
Lower stairwell	13.2	0.203	0.61	761	93	854	0.86
West basement	13.4	0.181	0.37	772	100	872	0.88
East basement	13.1	0.187	0.44	839	98	937	0.95
Upper greenhouse	12.4	0.234	1.32	997	126	1123	1.13
Lower greenhouse	10.1	0.157	0.17	775	116	991	1.00

[a]The length of the monitoring period was 8-1/2 hours. The wind was from the SSE at 4.3 m/s and the average outdoor air temperature was -7.1°C.

[b]Average zone temperature during the test.

[c]See Eq. (25). Values are least-squares fits for the period > 360 minutes in Fig. 26.

[d]Eq. (24) is represented by $A = A_1 + A_2$; A_1 was obtained by piecewise integration and A_2 by calculation of $[1/S\ e^{(I-St)}]$.

[e]The reference is the A-value for the lower greenhouse.

To provide some degree of assurance that E values were somewhat similar for similar wind direction but different wind speed and outdoor temperature, another test (#8) was run. In this test, the southeast wind was at 1.8 m/s, and the average outdoor temperature was 2.3°C. Another purpose of test #8 was to evaluate the effect of different lengths of monitoring periods upon the values of the Relative Exposure Index. Thus, test #8 was conducted for 20 hours to compare the values of the Relative Exposure Index obtained with the full 20 hours of data with those obtained from the same test but evaluated with only the first 8-1/2 hours of data. The concentrations measured during test #8 are shown in Fig. 27.

Table 12 lists the calculated values of E as if the test had only been 8-1/2 hours long as in the previous case (Fig. 26). Table 13 lists the corresponding values taking into account the whole test[1]. Comparison of the total integrated areas from both tables shows that there was good agreement for the largest areas but as much as 20% error in estimation took place at the smallest areas. This error was probably due to the uncertainty in the air exchange rate due to wind changes 12 hours after the onset of the test. So, despite the desirability of long testing periods, the variability of the outdoor weather also poses a problem that indicates that the use of shorter periods might be more appropriate. Moreover, except for some variability in the magnitudes of the Relative

---

[1]The value of the air exchange rates (S) are smaller in Table 13 because the wind was calm during the last 8 hours of the study.

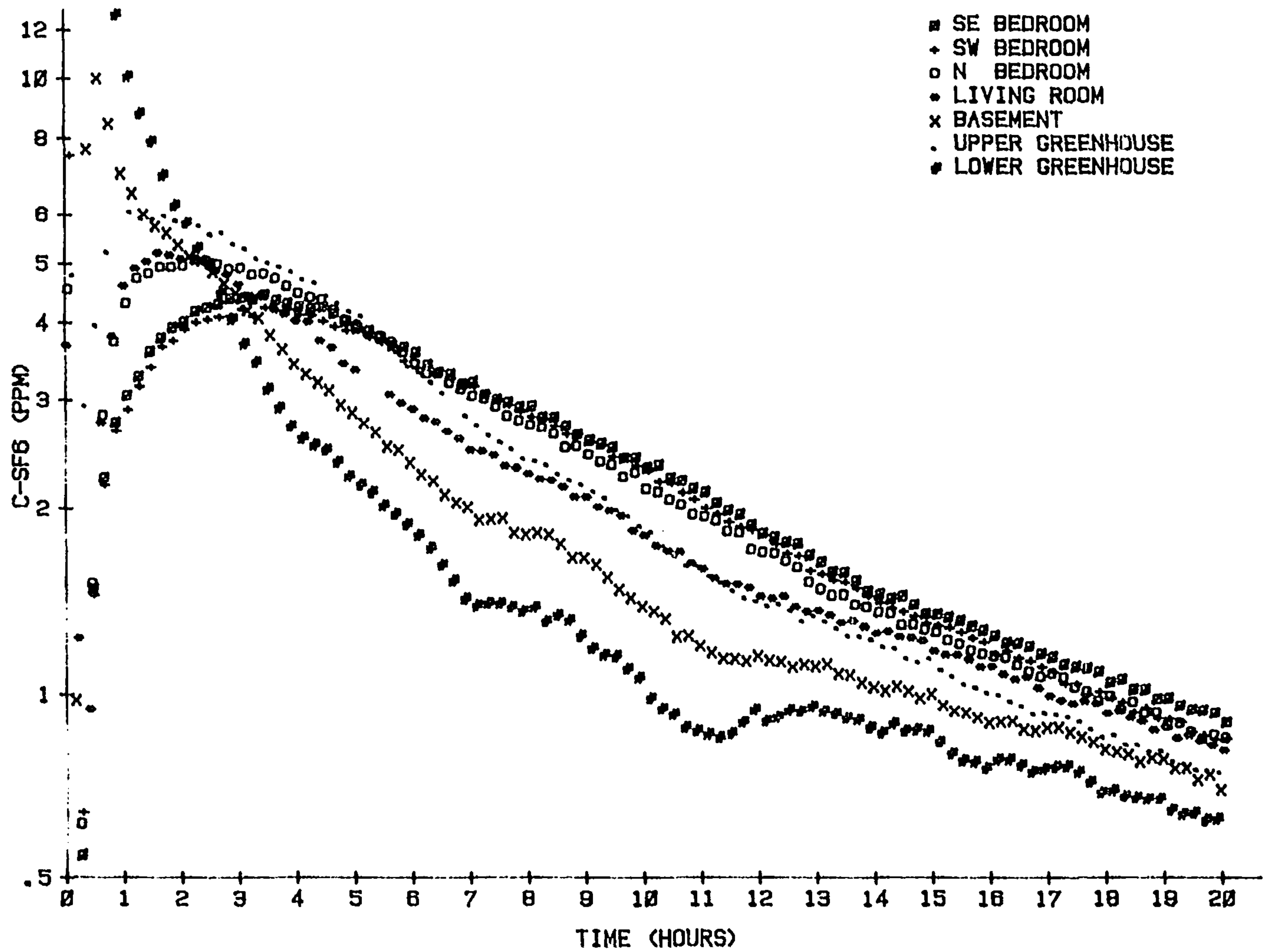


Fig. 27. Concentrations of SF_6 in the ERH following tracer release in lower greenhouse, test #8

Table 12. Values of the zonal Relative Exposure Index for tracer-gas injection in the lower greenhouse (test #8--8-1/2 hour case)[a]

Zone	T^b (°C)	S^c (ACH)	I^c	$A_1{}^d$ (ppm·min)	$A_2{}^d$ (ppm·min)	A^d (ppm·min)	E^e
Southeast bedroom	17.4	0.104	1.89	1751	1584	3335	1.30
Southwest bedroom	17.5	0.102	1.86	1697	1595	3292	1.29
North bedroom	17.6	0.123	1.99	1910	1258	3168	1.24
Upper stairwell	18.4	0.125	1.83	1785	1028	2813	1.10
East living room	18.4	0.126	1.81	1723	998	2721	1.06
West living room	18.6	0.123	1.80	1739	1040	2779	1.09
Kitchen	19.0	0.124	1.78	1749	997	2746	1.07
Lower stairwell	17.5	0.148	1.84	1677	719	2396	0.94
West basement	17.9	0.157	1.84	1789	631	2420	0.95
East basement	17.5	0.136	1.67	1818	740	2558	1.00
Upper greenhouse	16.5	0.109	1.76	2079	1260	3339	1.30
Lower greenhouse	12.9	0.167	1.60	2126	433	2559	1.00

[a]The wind was from the SE at 1.8 m/s, and the average outdoor air temperature was 2.3°C.

[b]Average zone temperature during the test.

[c]See Eq. (25). Values are least-squares fits for the period 300-510 minutes in Fig. 27.

[d]Eq. (24) is represented by $A = A_1 + A_2$; A_1 was obtained by piecewise integration and A_2 by calculation of $[1/S\ e^{(I-St)}]$.

[e]The reference is the A-value for the lower greenhouse.

Table 13. Values of the zonal Relative Exposure Index for tracer-gas injection in the lower greenhouse (test #8--20 hour case)[a]

Zone	T^b (°C)	S^c (ACH)	I^c	$A_1{}^d$ (ppm·min)	$A_2{}^d$ (ppm·min)	A^d (ppm·min)	E^e
Southeast bedroom	16.1	0.085	1.60	2800	631	3431	1.08
Southwest bedroom	16.3	0.093	1.67	2702	534	3236	1.02
North bedroom	16.3	0.086	1.53	2870	581	3451	1.09
Upper stairwell	16.9	0.075	1.30	2677	659	3336	1.05
East living room	16.8	0.074	1.25	2574	649	3223	1.02
West living room	16.9	0.074	1.27	2604	640	3244	1.03
Kitchen	17.3	0.072	1.23	2586	673	3259	1.03
Lower stairwell	16.0	0.064	0.99	2415	695	3110	0.98
West basement	16.4	0.060	0.88	2438	717	3155	1.00
East basement	16.1	0.060	0.87	2449	722	3171	1.00
Upper greenhouse	13.9	0.085	1.37	2899	514	3413	1.08
Lower greenhouse	11.8	0.056	0.66	2492	672	3164	1.00

[a]The wind was from the SE at 1.8 m/s, and the average outdoor air temperature was 2.3°C.

[b]Average zone temperature during the test.

[c]See Eq. (25). Values are least-squares fits for the period > 720 minutes in Fig. 27.

[d]Eq. (24) is represented by $A = A_1 + A_2$; A_1 was obtained by piecewise integration and A_2 by calculation of $[1/S\ e^{(I-St)}]$.

[e]The reference is the A-value for the lower greenhouse.

Exposure Index, the critical zones were consistently the same: the zones in the upper level of the ERH.

Other similar tests were run in which the tracer-gas was released in the basement, living room, and southwest bedroom to check for the respective zonal E values. Results of these tests are shown in Figs. 28, 29, and 30, respectively, and the results are listed in Tables 14 thru 16. All these tests were run when the wind was within 45° from the southeast.

Analysis of these and the previous results leads to the following observations:

1. In all cases, as shown in Table 17, the high-risk zone obtained from the E values either occurred in the zone where the gas was released or in a zone which had lower air exchange rate and lower ventilation efficiency than the zone of release, as obtained in test #6. When the gas was released in the southwest bedroom, the zone with the lowest air exchange rate and ventilation efficiency within the house for southeast winds (see Table 9), very little tracer gas penetrated the remainder of the house and the southwest bedroom was indeed the highest-risk zone in the house. When the gas was released in the basement and in the living room, only very minor increases on the values of the Relative Exposure Index over its value in the zone of release occurred. The maximum increase when the gas was released in the basement occurred in the southeast bedroom, and when the gas was released in the living room, the maximum increase occurred in the upper stairwell.

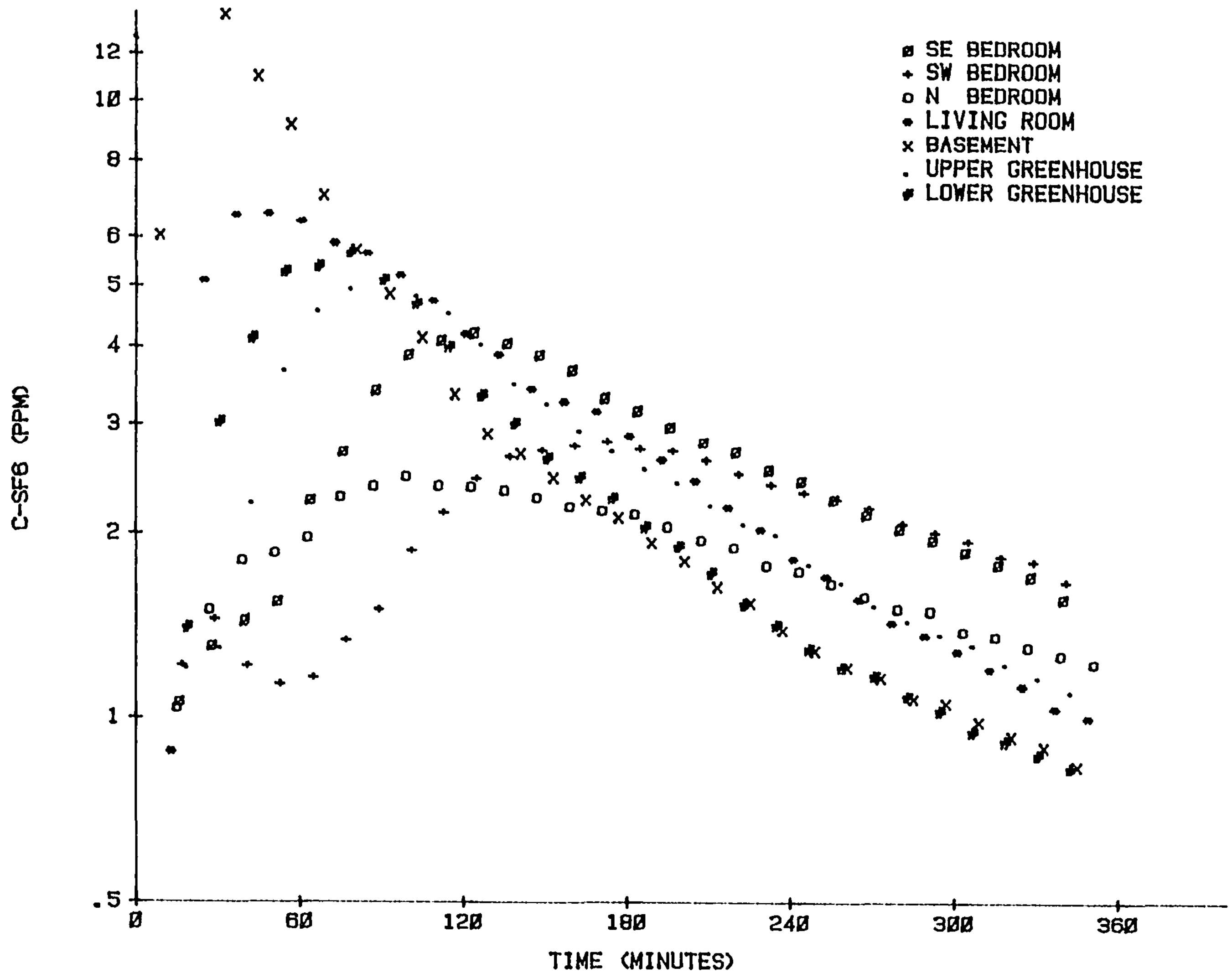


Fig. 28. Concentrations of SF_6 in the ERH following tracer release in basement, test #9

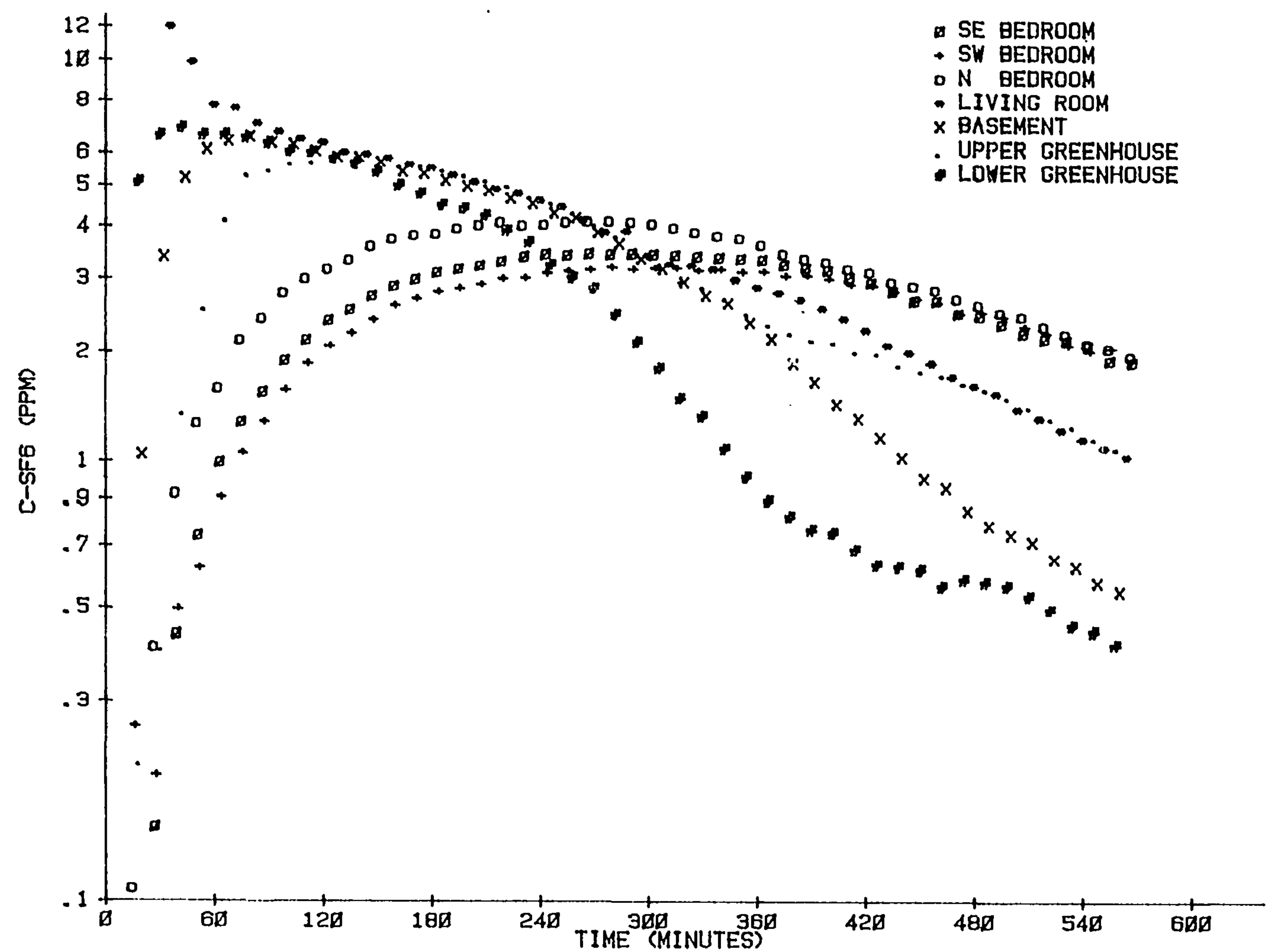


Fig. 29. Concentrations of SF_6 in the ERH following tracer release in living room, test #10

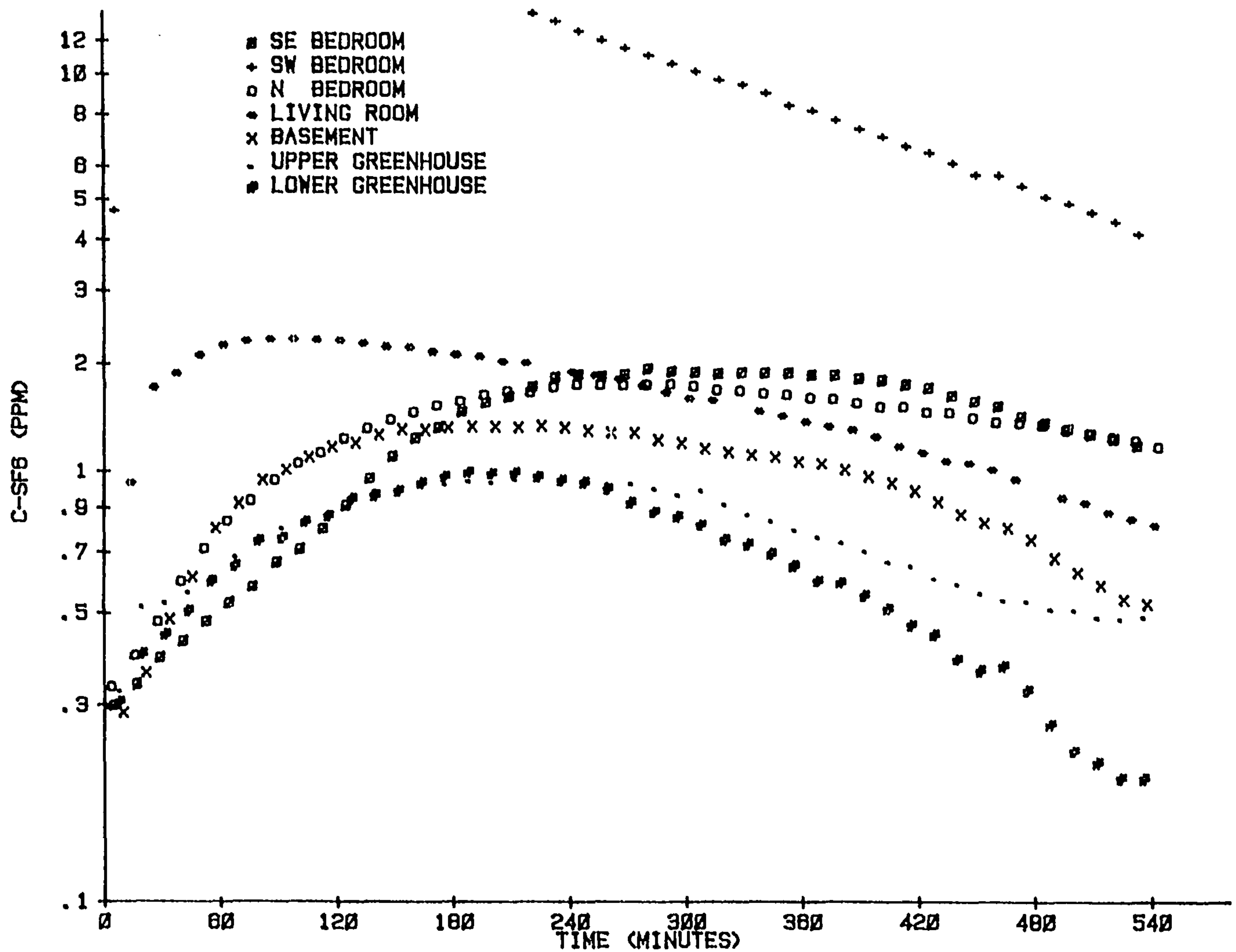


Fig. 30. Concentrations of SF_6 in the ERH following tracer release in SW bedroom, test #11

Table 14. Values of the zonal Relative Exposure Index for tracer-gas injection in the basement (test #9)[a]

	T^b (°C)	S^c (ACH)	I^c	$A_1{}^d$ (ppm·min)	$A_2{}^d$ (ppm·min)	A^d (ppm·min)	E^e
Southeast bedroom	16.6	0.260	1.94	825	366	1191	1.01
Southwest bedroom	15.9	0.194	1.64	641	531	1172	0.99
North bedroom	15.1	0.195	1.33	578	388	966	0.82
Upper stairwell	16.2	0.382	2.17	989	158	1147	0.97
East living room	17.2	0.358	2.04	950	169	1119	0.95
West living room	17.1	0.357	2.05	954	172	1126	0.95
Kitchen	16.9	0.362	2.08	947	171	1118	0.95
Lower stairwell	16.7	0.328	1.67	910	149	1059	0.90
West basement	17.3	0.293	1.50	1009	174	1183	1.00
East basement	17.3	0.295	1.51	989	172	1161	0.98
Upper greenhouse	18.2	0.322	1.91	837	203	1040	0.88
Lower greenhouse	17.0	0.320	1.61	801	153	954	0.81

[a]The wind was from the east at 4.9 m/s, and the average outdoor air temperature was -3.6°C.

[b]Average zone temperature during the test.

[c]See Eq. (25). Values are least-squares fits for the period >210 minutes in Fig. 28.

[d]Eq. (24) is represented by $A = A_1 + A_2$; A_1 was obtained by piecewise integration and A_2 by calculation of $[1/S\ e^{(I-St)}]$.

[e]The reference is the A-value for the west basement.

Table 15. Values of the zonal Relative Exposure Index for tracer-gas injection in the living room (test #10)[a]

Zone	T^b (°C)	S^c (ACH)	I^c	$A_1{}^d$ (ppm·min)	$A_2{}^d$ (ppm·min)	A^d (ppm·min)	E^e
Southeast bedroom	18.1	0.178	2.32	1386	674	2060	0.87
Southwest bedroom	18.5	0.170	2.27	1294	723	2017	0.85
North bedroom	16.6	0.200	2.56	1638	624	2262	0.95
Upper stairwell	17.6	0.304	3.11	2217	274	2491	1.05
East living room	17.1	0.314	2.95	2114	153	2267	0.96
West living room	17.4	0.284	2.78	2118	252	2370	1.00
Kitchen	17.6	0.320	3.08	2213	217	2430	1.03
Lower stairwell	16.5	0.322	2.49	1846	118	1964	0.83
West basement	16.9	0.313	2.32	1768	111	1879	0.79
East basement	16.7	0.336	2.52	1770	102	1872	0.79
Upper greenhouse	19.7	0.252	2.51	1728	293	2021	0.85
Lower greenhouse	15.6	0.214	1.14	1515	124	1639	0.69

[a]The wind was from the south at 30 m/s, and the average outdoor air temperature was 0.5°C.

[b]Average zone temperature during the test.

[c]See Eq. (25). Values are least-squares fits for the period > 450 minutes in Fig. 29.

[d]Eq. (24) is represented by $A = A_1 + A_2$; A_1 was obtained by piecewise integration and A_2 by calculation of $[1/S\ e^{(I-St)}]$.

[e]The reference is the A-value for the west living room.

Table 16. Values of the zonal Relative Exposure Index for tracer-gas injection in the southwest bedroom (test #11)[a]

	T^b (°C)	S^c (ACH)	I^c	$A_1{}^d$ (ppm·min)	$A_2{}^d$ (ppm·min)	A^d (ppm·min)	E^e
Southeast bedroom	22.2	0.151	1.60	713	530	1243	0.17
Southwest bedroom	21.9	0.234	3.53	6286	1142	7428	1.00
North bedroom	20.4	0.088	1.05	718	915	1633	0.22
Upper stairwell	20.8	0.158	1.50	896	433	1329	0.18
East living room	20.4	0.189	1.55	805	288	1093	0.15
West living room	20.7	0.200	1.61	822	265	1087	0.15
Kitchen	20.7	0.176	1.52	824	341	1165	0.16
Lower stairwell	19.0	0.221	1.55	587	189	776	0.10
West basement	19.3	0.275	1.87	541	131	672	0.09
East basement	19.1	0.293	2.00	542	120	662	0.09
Upper greenhouse	23.8	0.172	0.75	395	166	561	0.08
Lower greenhouse	20.8	0.436	2.26	351	30	381	0.05

[a]The wind was from the south at 1.8 m/s, and the average outdoor air temperature was -9.7°C.

[b]Average zone temperature during the test.

[c]See Eq. (25). Values are least-squares fits for the period > 360 minutes in Fig. 30.

[d]Eq. (24) is represented by $A = A_1 + A_2$; A_1 was obtained by piecewise integration and A_2 by calculation of $[1/S\ e^{(I-St)}]$.

[e]The reference is the A-value for the southwest bedroom.

Table 17. High-risk zones in the Energy Research House for different locations of tracer-gas release

Zone of Tracer-Gas Release	Highest-Risk Zone	Air Exchange Rates (ACH)[a]		Ventilation Efficiencies[b]	
		Zone of Release	Highest-Risk Zone	Zone of Release	Highest-Risk Zone
Lower greenhouse[c]	Southwest bedroom[c]	0.17	0.10	1.11	0.82
Basement[d]	Southeast bedroom[d]	0.16	0.11	1.05	0.85
Living room[e]	Upper stairwell[e]	0.14	0.12	1.00	0.96
Soutwest bedroom[f]	Southwest bedroom[f]	0.10	0.10	0.82	0.82

[a]From test #6 (see Table 9). This case was chosen because of similarity of weather conditions with all cases shown here.

[b]From test #6 (see Table 10).

[c]From test #7 (see Table 11).

[d]From test #9 (see Table 14).

[e]From test #10 (see Table 15).

[f]From test #11 (see Table 16).

2. As shown in Table 18, values of E greater than unity usually occurred in zones with lower air exchange rates and ventilation efficiencies than those in the zone where the tracer gas was released. This result supports the hypothesis that contaminant monitoring need only take place in the zone of production and in zones with lower air exchange rates or ventilation efficiencies.

3. As shown in Table 18, zones which had similar air exchange rates and ventilation efficiencies usually had also similar E values: 1) the three upstairs bedrooms were within 10% of each other in most tests; 2) the upper stairwell and the middle level zones always formed a consistent group and seldom differed more than 5%; 3) the lower level zones (except the greenhouse) were also very close to each other in all tests. Conversely, typical E values for each of these groups of zones usually differed considerably from each other, up to 30%[1]. Therefore, a single monitoring point should suffice for each group of zones.

4. In conclusion, combining observations 2 and 3, contaminant monitoring should only be needed in the zone of production and in the zone with lowest air exchange rate and lowest ventilation efficiency. One of these two zones will be the highest-risk zone for the contaminant under study. Thus, a single tracer gas study such as outlined in the previous section together with the determination of where contaminants are generated should suffice to locate the highest-risk zones in a building.

---

[1]See test when injection was in the greenhouse, where the range of E values was 0.86-1.24.

Table 18. Summary of air exchange rates, ventilation efficiencies, and Relative Exposure Indices in the Energy Research House for southeast winds

Zone	R (ACH)	ε	E			
			Lower Green-house[a]	Basement[a]	Living Room[a]	Southwest Bedroom[a]
Southeast bedroom	0.11	0.85	1.13	1.01	0.87	0.17
Southwest bedroom	0.10	0.82	1.24	0.99	0.85	1.00
North bedroom	0.11	0.84	1.17	0.82	0.95	0.22
Upper stairwell	0.12	0.96	1.04	0.97	1.05	0.18
East living room	0.14	1.00	0.89	0.95	0.96	0.15
West living room	0.14	1.00	0.92	0.95	1.00	0.15
Kitchen	0.13	0.98	0.96	0.95	1.03	0.16
Lower stairwell	0.14	0.97	0.86	0.90	0.83	0.10
West basement	0.17	1.06	0.88	1.00	0.79	0.09
East basement	0.16	1.05	0.95	0.98	0.79	0.09
Upper greenhouse	0.13	1.22	1.13	0.88	0.85	0.08
Lower greenhouse	0.17	1.11	1.00	0.82	0.69	0.05

[a]Location where the tracer-gas was released.

Contaminant Measurements

The purpose of the measurements described in this section was to try to confirm the results of contaminant distributions observed throughout the ERH that were obtained using the concept of Relative Exposure Indices (E). Exact quantification for indoor air quality evaluation was not desired and thus, relative rather than absolute magnitudes of the concentrations were desired.

The Energy Research House (ERH) is an all-electric house and the only occupancy was occasional visits by research teams. Under these circumstances, there were only small amounts of combustion-generated contaminants. To overcome this difficulty, combustion-related contaminants were generated by having a volunteer smoke two cigarettes per hour for three hours in the living room. The central air fan was kept off during the three sessions that took place. The concentrations of carbon monoxide, carbon dioxide, and nitrogen dioxide, which are three of the most common combustion-generated contaminants, were monitored in the living room and in the southwest bedroom. These two zones were the zones of production and lowest air exchange rate, respectively. Due to the availability of only one MSA pump to measure the concentrations of the three contaminants previously noted, monitoring took place during sequential periods of three hours of smoking and four subsequent hours in each of the locations. The measured concentrations of carbon monoxide, carbon dioxide, and nitrogen dioxide are listed in Table 19.

Table 19. Concentrations of the smoking-related contaminants in the Energy Research House[a]

	Hours 1 - 3			Hours 4 - 7		
	CO_2 (%)	CO (ppm)	NO_2 (ppm)	CO_2 (%)	CO (ppm)	NO_2 (ppm)
Session #1						
Living room	0.09	2.9	0.06	--	--	--
Southwest bedroom	--	--	--	0.06	2.2	0.03
Session #2						
Living room	--	--	--	0.11	3.8	0.05
Southwest bedroom	0.08	2.9	0.08	--	--	--
Session #3						
Living room	0.08	5.0	0.06	--	--	--
Southwest bedroom	--	--	--	0.11	7.5	0.02

[a]Two cigarettes/hour smoked in the living room for the first three hours.

The results show that, in most cases, the concentrations in the living room were generally higher than in the southwest bedroom, but their values were similar in magnitude. This confirms the values listed in Table 15, as the values of the Relative Exposure Index were larger in the living room than in the southwest bedroom.

The only contaminants that were normally produced in the greenhouse were thought to be formaldehyde and radon. Formaldehyde could have been released by a number of varnishes and wood finishes which were common throughout the ERH. Radon could have been introduced by exhalation through concrete walls, in particular in the basement.

Formaldehyde was believed to be produced almost uniformly throughout the house. Thus, the highest-risk zone should have been in the upper level. Samples were collected in the greenhouse, the living room, and the southwest bedroom. The results, listed in Table 20, confirm the earlier conclusion that more contaminant should be collected in zones with lower air exchange rates and ventilation efficiencies when uniform generation occurs within the house. Following this test, the floor of the living room was resurfaced, which was believed to increase formaldehyde levels in the ERH. More samples were thus collected, this time only in the living room and southwest bedroom. The results, listed in Table 21, show that an increase did indeed occur, but levels were still well below the 0.1 ppm level listed in Table 2. However, the concentrations were once again higher upstairs.

Table 20. Formaldehyde concentrations in the Energy Research House

Sample Location	Sampling Time (hrs)	Weight Collected (μg)	Concentration (ppm)
Greenhouse	36	1.9	0.03
Living room	36	2.1	0.03
Southwest bedroom	36	2.5	0.03

Table 21. Formaldehyde concentration in the Energy Research House following resurfacing of the living room floor

Sample Location	Sampling Time (hrs)	Weight Collected (μg)	Concentration (ppm)
Living room	12	< 1.5[a]	< 0.03
Living room	24	1.87	0.03
Living room	36	2.51	0.03
Southwest bedroom	12	1.65	0.03
Southwest bedroom	24	2.34	0.03
Southwest bedroom	36	4.30	0.03

[a]1.5 μg is the minimum detectable weight for this monitor.

Finally, radon was monitored in the basement, where the rate of production was assumed to be the highest, and in the southwest bedroom, where the air exchange rate and ventilation efficiency were the lowest. Contrary to the previous tests, the central air fan could not be disabled during the exposure due to its length (36 days). The results indicated 3.17 pCi/l in the southwest bedroom and 2.21 pCi/l in the basement. The higher value obtained in the southwest bedroom should be interpreted as a combination of two phenomena: on the one hand, radon generation in the basement should result in similar concentrations in the basement and in the southwest bedroom, as shown by the magnitude of the Relative Exposure Indices listed in Table 14; on the other hand, when the central air fan was on (intermittently), the net generation of radon was made uniform throughout the house and, thus, higher concentrations should be expected in zones with lower air exchange rates and ventilation efficiencies (i.e., the southwest bedroom).

In conclusion, all these measurements confirmed that sampling only in the zone where the contaminants are produced may not be enough to correctly characterize the exposure of the occupants. Monitoring should thus also take place in the zone of lowest air exchange rate and lowest ventilation efficiency to ensure that the highest-risk zone in the building is identified.

FIELD VALIDATION

Introduction

The two main purposes of this section are, first, to verify the feasibility of practical field use of the proposed indoor air quality evaluation procedure and, second, to gather data from other types of buildings for comparison with the results obtained in the ERH. Because energy-efficient buildings are more likely to have indoor air quality problems due to their usually lower air exchange rates, only this type of building was studied. Futhermore, all four buildings selected were single-family residences.

For all residences, the procedure consisted of performing the multipoint tracer gas test as described earlier[1] to quantify the air exchange rates and ventilation efficiencies in the various uniformly mixed zones throughout each building. The zones where contaminants were generated or released were located by physical examination of the building and from the results of a questionnaire that the building occupants were asked to complete. This questionnaire, given in Appendix A, inquired about typical house activities and products used that might affect indoor air quality, and was used to determine the zones which were normally occupied. On a subsequent day, contaminant measurements were performed in the zone with the lowest air exchange

---

[1]In chapter "Proposed Procedure for Indoor Air Quality Evaluation".

rate and ventilation efficiency and in the zone where each contaminant was released at the highest rate.

The main characteristics of the four residences that were tested are summarized in Table 22.

House #1

This house was located in Ames, Iowa. Its floor plan is schematically shown in Fig. 31. It was a house designed to satisfy a portion of its energy requirements by passive collection of solar energy. To do so, the south facade included a large glazed area, the east part of which formed an attached greenhouse. This house had no central forced air distribution system except for a ceiling fan located in the upper level just west of the greenhouse. The backup heating system was a perimeter hot-water baseboard radiating/convecting system fueled by propane. Air-to-air heat exchangers were located in the two bathrooms and in the kitchen.

Eleven sampling locations were used for the tracer gas study. These locations are listed in Table 23. Tracer gas was injected into the kitchen and mixed throughout the house through the use of the ceiling fan. Although this method is not as effective as a central air distribution system to obtain complete mixing uniformity, good results were obtained with the ceiling fan except in the basement, which never reached the same concentration of SF_6 as the rest of the house. However, as the basement was not a normally occupied part of the house, no special effort was made to obtain the same concentration in the basement as in the rest of the house.

Table 22. Summary of the characteristics of the houses tested in the field validation

	House #1	House #2	House #3	House #4
Number of stories[a]	3	2	2	2
Net floor area (m^2)[b]	190	320	230	150
Primary heating system	solar	gas furnace	gas furnace	gas furnace
Secondary heating system	perimeter hot water	wood stove	portable electric heater	---
Air Conditioning	1 window unit[c]	central	central	central
Kitchen range	electric	gas	gas	gas
Number of occupants	2	2	6	2
Comments	3 heat exchangers[d]	1 heat exchanger[e]	exhaust fans in baths[f]	--

[a]Including basement.

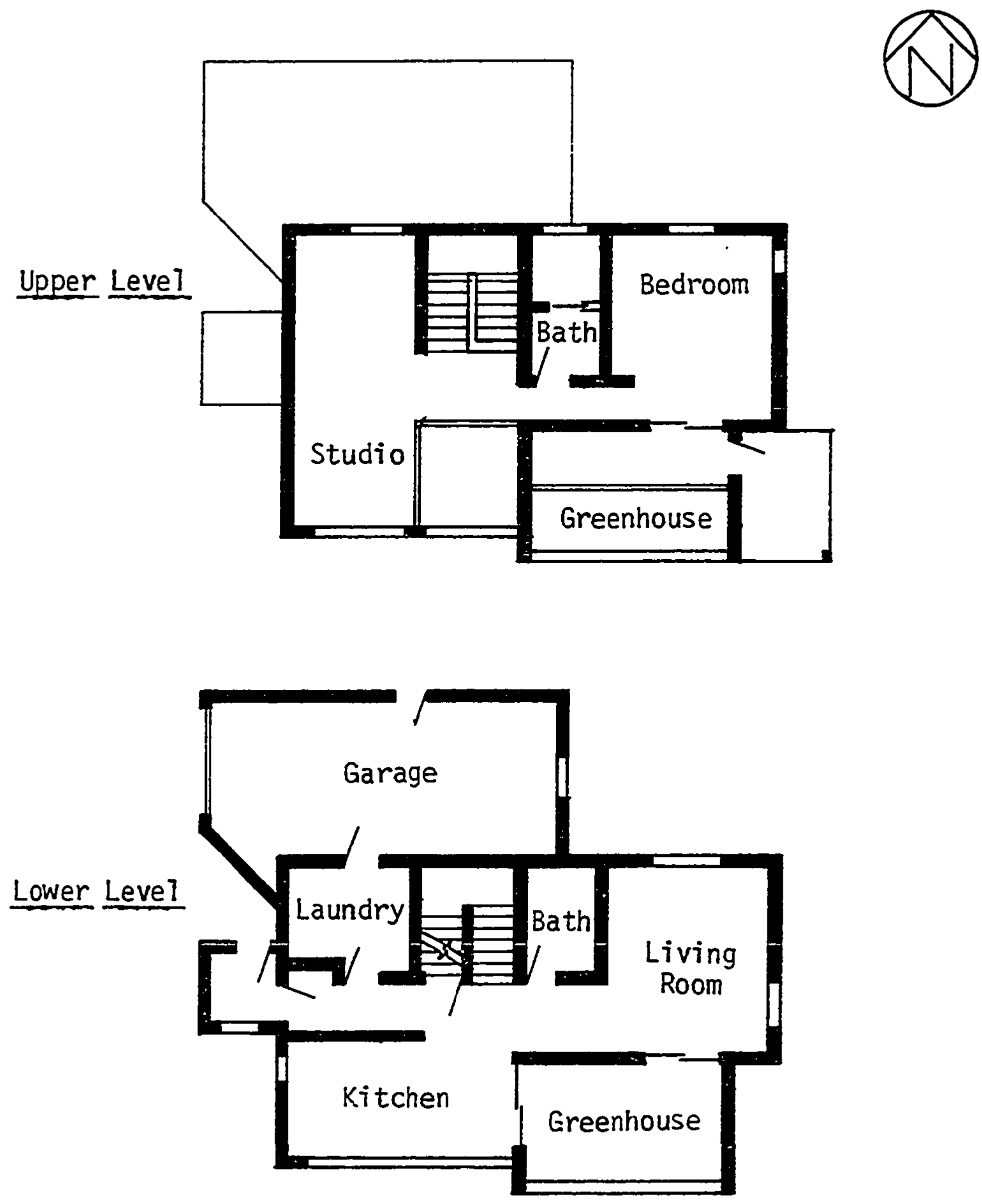
[b]Includes finished basement.

[c]Located in the bedroom.

[d]Air-to-air heat exchangers located in the kitchen and in the two bathrooms.

[e]Air-to-air heat exchanger connected to the central air system.

[f]Wired in parallel with light switch.



(Not to scale)

Fig. 31. Floor plan of house #1

Table 23. Results from the tracer-gas study for House #1[a]

Zone	T^{b} (°C)	R (ACH)	A^{c} (ppm·min)	ε^{d}
Lower hallway	16.3	0.27	599	0.98
Kitchen	17.4	0.24	585	1.00
Living room	17.1	0.27	613	0.95
Laundry	16.2	0.26	596	0.98
Basement	15.4	0.26	487	--[e]
Bedroom	17.2	0.25	626	0.93
Upper studio	17.7	0.26	647	0.90
Upper hallway	17.8	0.25	607	0.96
Lower bathroom	21.4	0.28	521	1.12
Upper bathroom	16.8	0.33	390	1.50
Greenhouse	13.8	0.26	589	0.99

[a]Test conducted with calm wind and average outdoor temperature of -2°C.

[b]Average temperature during the study.

[c]Integral of the measured concentrations during the test.

[d]Ventilation efficiency as per Eq. (10). The reference zone was arbitrarily taken as the kitchen.

[e]This value is not significant because the initial concentration in the basement was lower than in the rest of the house.

The decay of SF_6 in typical zones is shown in Fig. 32[1]. The values of the zonal air exchange rates and ventilation efficiencies obtained from the test are listed in Table 23.

The results of the tracer gas study show that the largest air exchange rates and ventilation efficiencies occurred in the two bathrooms, particularly in the upper level. The reason for such high values is probably leaky ducting for the air-to-air heat exchangers[2]. Although all the air exchange rates except that in the upper level bathroom were similar (0.24 to 0.28 hr^{-1}), the ventilation efficiency in the zone where the third heat exchanger was located was also the third highest. This indicated that ducting to the heat exchangers was the major cause of infiltration air to this house.

As most of the house had similar air exchange rates, the highest-risk zone in the house was that which had the lowest ventilation efficiency, i.e., the upper level studio. To determine contaminant monitoring locations in addition to this zone, contaminant generation locations had to be identified. Except for cooking, any other contaminant was assumed to be uniform throughout the house[3]. In addition,

---

[1] Due to a malfunction of the data-acquisition equipment, the first 45 minutes of the data were not recorded.

[2] The leak in the upper level bathroom resulted in an easily felt cold draft.

[3] Radon was not monitored in the field studies due to the length of time required by the TERRADEX sensors. In an actual field test, the sensor(s) could be placed in the appropriate location when other contaminants were being monitored. TERRADEX sensors come with adequate mailing materials and, thus, the sensors could then be mailed on the correct date by the house occupant.

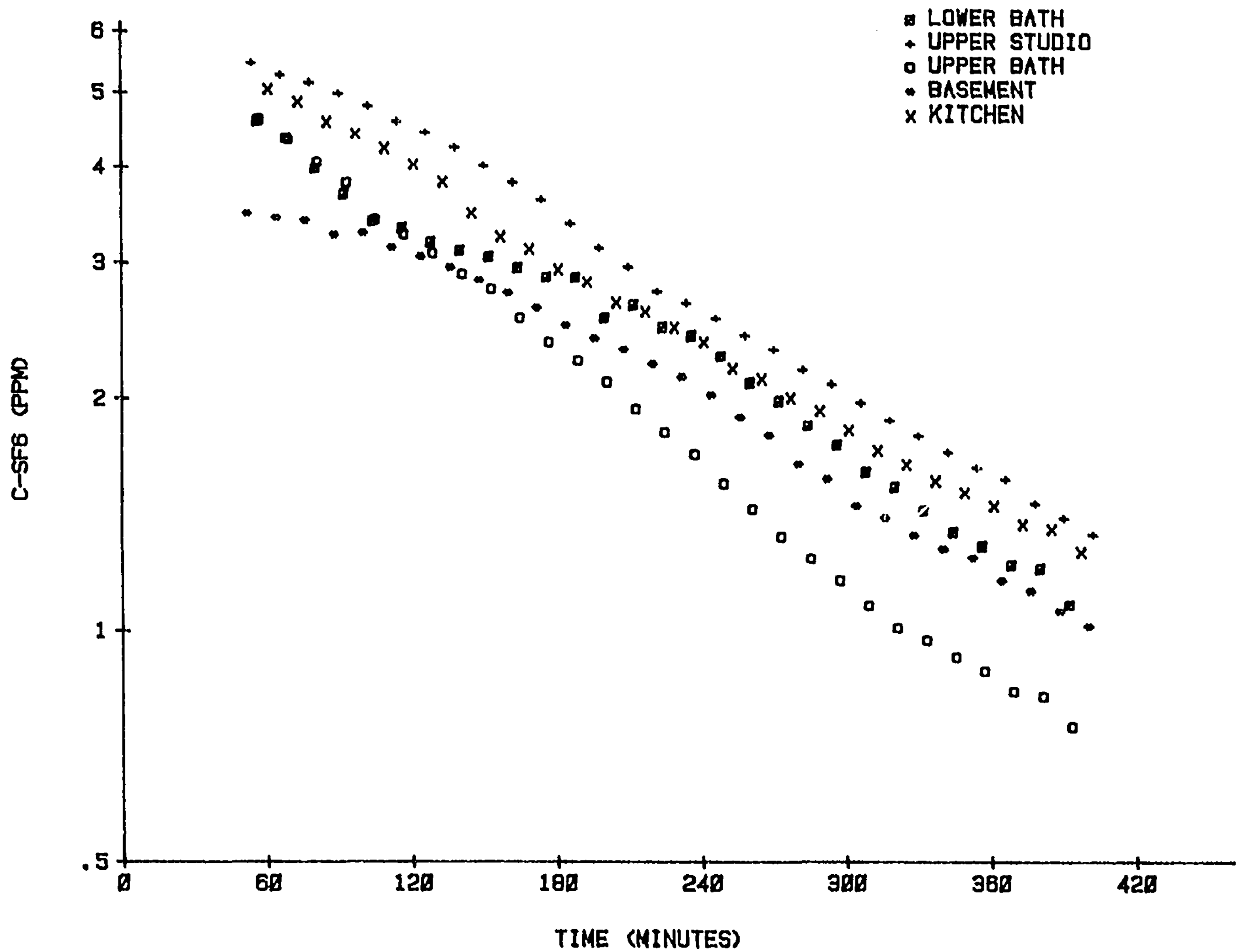


Fig. 32. Concentrations of SF_6 in house #1

contaminants related to cooking were associated with a warm plume which would rise through the open kitchen ceiling to the upper level studio. Thus, in this particular house, the zone where contaminants were generated at the highest rate was also the zone with lowest ventilation efficiency. Thus, monitoring for contaminants took place in a single zone. Measurement of thermal factors was done throughout the house.

The results of the contaminant measurements are listed in Table 24, which show that no levels in excess of the recommended values listed in Table 2 were found. Thermal properties of the air, listed in Table 25, were also within normal levels.

Conclusions obtained from this study indicate that the air exchange rate was adequate to provide a clean indoor environment even without operation of the air-to-air heat exchangers. For periods when no cooking takes place, calculations using ASHRAE Standard 62-1981 [4] result in a minimum recommended ventilation rate of 35 l/sec (5 l/sec per room) which corresponds to an air exchange rate of 0.26 ACH. As 0.25 ACH was also the measured value under calm winds and not extreme outdoor temperature, the house should not have much lower air exchange rates during most of the year. In particular, during milder periods, natural ventilation can simply be accomplished by window or door openings. The additional recommendation in ASHRAE Standard 62-1981 for when cooking takes place (50 l/sec) and for when bathrooms are in use (25 l/sec) can also be handled by the air-to-air heat exchangers. Thus, in this house, no indoor air quality problems were found.

Table 24. Mass air quality factors in House #1[a]

Contaminant	Measured Value
CO	0.15%
CO_2	2.3 ppm
NO_2	0
RSP	0
Formaldehyde	0.06 ppm

[a]Monitoring in the upper level studio.

Table 25. Thermal air quality factors in House #1

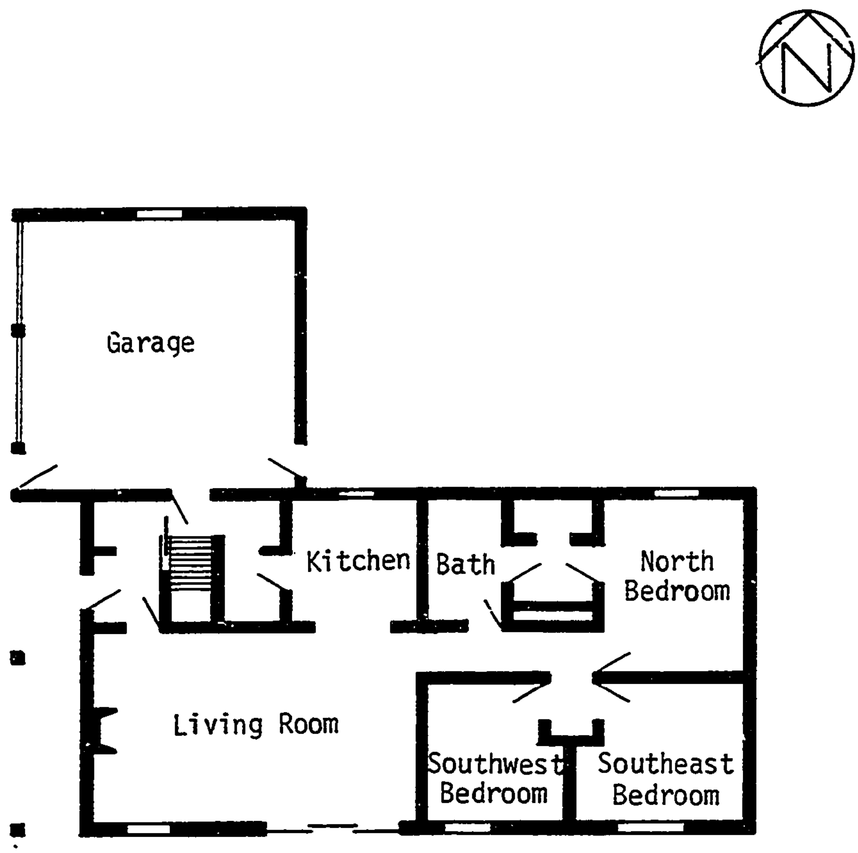
Location	Dry-bulb Temperature (°C)	Relative Humidity (%)	Air Velocity (cm/s)
Upper level[a]	20.0	45	9
Lower level[b]	19.4	55	9

[a]In the upper hallway.
[b]Between the kitchen and the living room.

House #2

This house was located in Clarksville, Iowa. Its floor plan is schematically shown in Fig. 33. It was a single-level double-insulated house with extra wall concrete thickness in its southern facade to provide some passive solar features. This house also had a full basement where a conventional gas-fired central air heating and cooling system was located. In addition, there was a wood stove in the living area of the basement. Although there was an outdoor air supply duct near the wood stove, the duct was not connected to the wood stove and the air supply for combustion came from the basement itself. An air-to-air heat exchanger was also connected to the central air system to provide mechanical ventilation to the building when so desired by the occupants.

Ten sampling locations were used for the tracer gas study. These locations are listed in Table 26. Tracer gas was distributed through the central air system and it was noticed that the concentration in the basement took about one hour to reach a level similar to those in the rest of the house. Because the rate of decay in the basement was not any larger than in the rest of the house, as shown in Fig. 34, it can be concluded that the forced air system did not deliver sufficient amount of ventilation air to the basement. During the decay study, both the central air fan and the heat exchanger were not in operation except during the last hour, when the heat exchanger was turned on to investigate its effectiveness.



(Not to scale)

Fig. 33. Floor plan of house #2

Table 26. Results from the tracer-gas study for House #2[a]

Zone	T^b (°C)	R (ACH)	A^c (ppm·min)	ε^d	R_{HX}[e]
Southeast bedroom	21.7	0.10	918	0.98	0.27
Southwest bedroom	21.9	0.10	893	1.01	0.22
North bedroom	20.3	0.09	910	0.99	0.15
Bathroom	22.2	0.11	892	1.01	0.25
East living room	23.9	0.11	858	1.05	0.26
West living room	23.8	0.11	910	0.99	0.26
Kitchen	24.2	0.10	902	1.00	0.25
Laundry	25.1	0.10	887	1.02	0.27
Hallway	24.3	0.10	897	1.01	0.31
Basement	28.7	0.11	833	--[f]	0.20

[a]Test conducted with easterly 4.5 m/s winds and an average outdoor air temperature of -2°C.

[b]Average temperature during the study.

[c]Integral of the measured concentrations during the test (last hour not included).

[d]Ventilation efficiency as per Eq. (10). The reference zone was arbitrarily taken as the kitchen.

[e]Rate of air exchange after the air-to-air heat exchanger was in operation.

[f]This value is not significant because the initial concentration in the basement was lower than in the rest of the house.

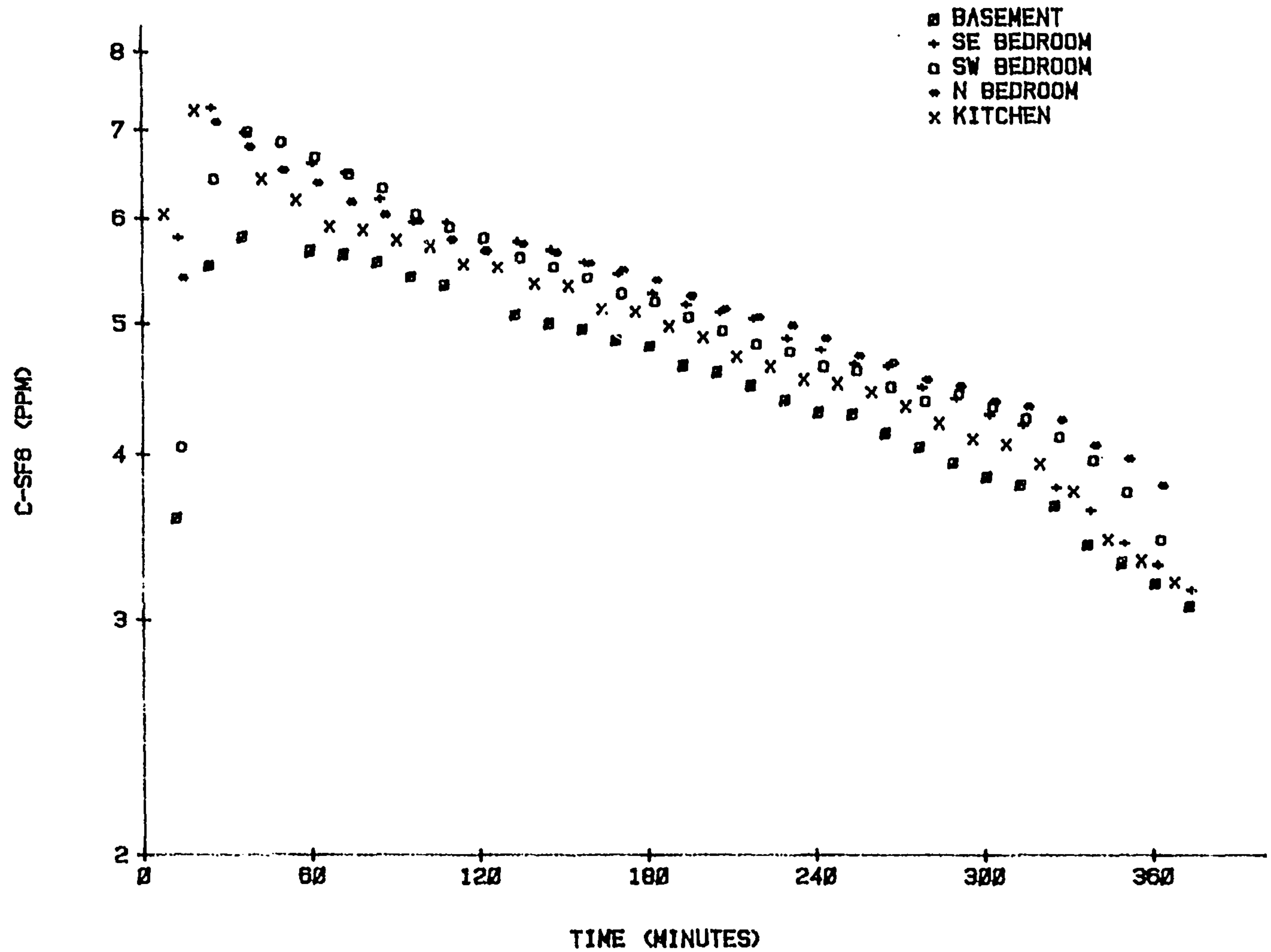


Fig. 34. Concentrations of SF_6 in house #2

Figure 34 and Table 26 show that there were only small differences among the air exchange rates in the different zones of the building. The differences in ventilation efficiencies were also nonsignificant. Thus, for practical purposes, the entire upper level could have been considered to be uniformly mixed, including the large living room. The fact that this large room was uniformly mixed provides further confirmation that large rooms with regular rectangular geometry may be considered uniformly mixed for the purpose of indoor air quality evaluation. Finally, it was observed that the air exchange rates increased approximately 2.5 times when the heat exchanger was turned on[1].

As the upper level could be considered to be uniformly mixed, contaminants were monitored in the kitchen, which was where the highest rate of generation of combustion-related contaminants occurred. Due to the presence of the wood stove in the basement, combustion-related contaminants were also monitored there. The results of the contaminant sampling, which were performed on a subsequent day, are listed in Table 27, as also are the results of the evaluation of thermal factors.

The results listed in Table 27 show large concentrations of carbon monoxide, particularly in the basement, probably the result of incomplete combustion in the wood stove as a consequence of the inadequate supply of fresh air. Other contaminant levels were also near or above the recommended levels listed in Table 2. Thermal conditions in the basement were in the "warm" portion of the comfort envelope.

---

[1]This increase was quantified on the basis of a single hour of data. A better value would have required more data, but it was not possible to do so due to time limitations for the use of the house.

Table 27. Indoor air quality factors in House #2[a]

Factor		Measurements: Upper level[b]	Measurements: Basement[c]
CO	(ppm)	5	25
CO_2	(%)	0.22	0.23
NO_2	(ppm)	0	0.07
RSP	(ppm)	0	0
Formaldehyde	(ppm)	0.08	0.06
Dry-bulb temperature (°C)		23.9	28.7
Relative humidity (%)		55	40
Air velocity (cm/s)		3	--[d]

[a]During the tests, the wood stove was in continuous operation.
[b]Measurements in the morning.
[c]Measurements in the afternoon.
[d]Not measured.

The weather conditions during the measurement period (see Table 26), although not extreme, were characteristic of a major portion of the heating season. Thus, as the air exchange rate in this residence was low, there was a large potential for indoor air quality problems. For this house, calculations using ASHRAE Standard 62-1981 recommendations resulted in 0.15 ACH minimum, a level which could only be attained with significant operation time of the air-to-air heat exchanger. Moreover, this minimum air exchange rate would have to be increased to supply enough combustion air for the wood stove. Thus, unless the air-to-air heat exchanger was in operation most of the time[1], a large potential for indoor air quality problems existed in this building.

House #3

This house was located in Fairfax, Iowa. Its floor plan is schematically shown in Fig. 35. It was a conventionally designed split-level house, although well-insulated and constructed with special care to ensure air tightness. This house had a gas-fired central air heating system. The bathrooms had exhaust fans which were on whenever their lights were turned on.

Twelve sampling locations were used for the tracer gas study. These locations are listed in Table 28. Tracer gas was injected into and distributed through the central air system. Nearly two hours were

---

[1]According to the house occupants, the heat exchanger was in operation only four hours a day.

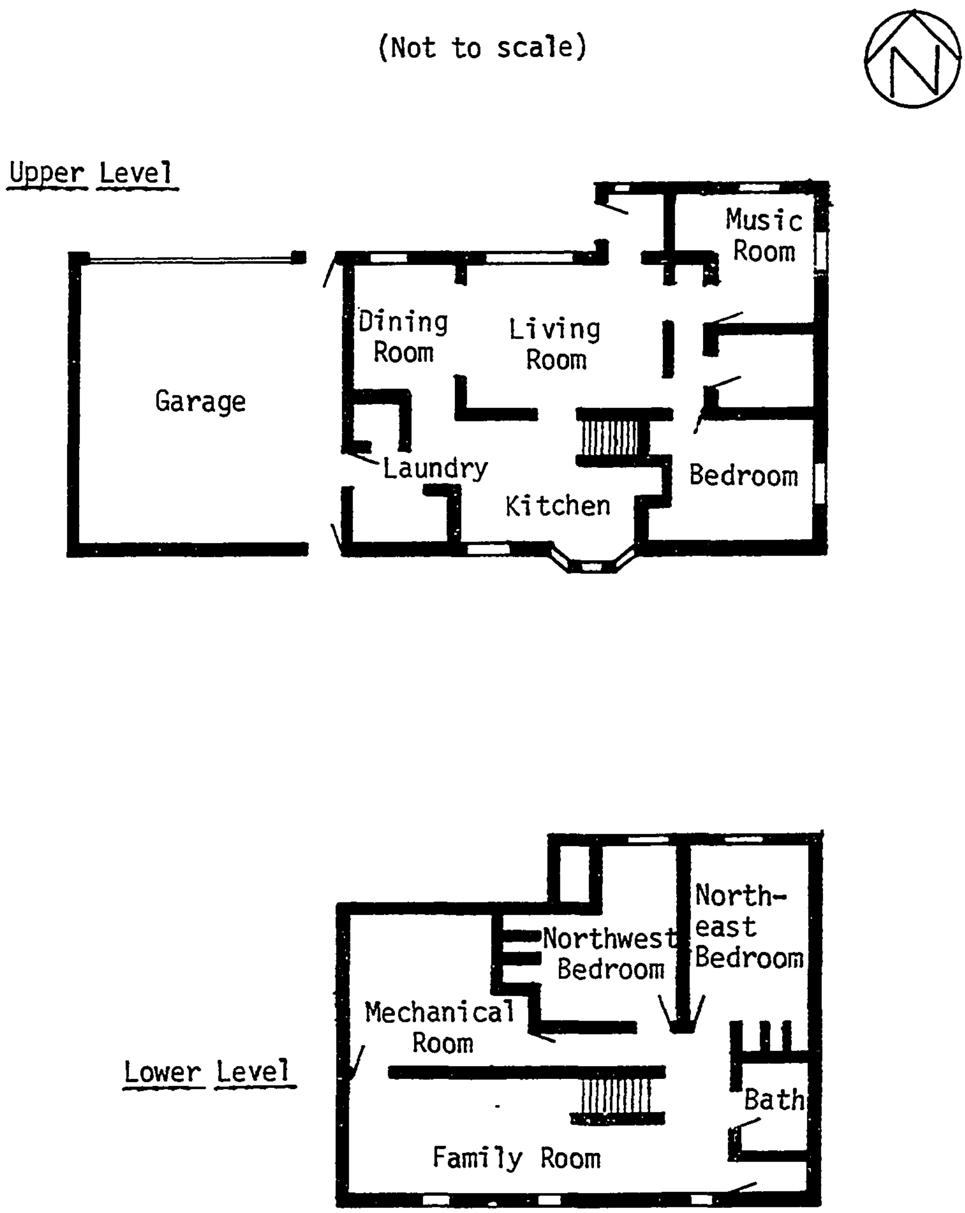


Fig. 35. Floor plan of house #3

Table 28. Results from the tracer-gas study for House #3[a]

Zone	T^b (°C)	R (ACH)	A^c (ppm·min)	ε^d
Northwest bedroom	18.2	0.20	1363	0.90
Upper bedroom	22.9	0.11	1419	0.87[e]
Music room	18.1	0.14	1304	0.95
Laundry	24.9	0.14	1261	0.98
Upper hallway	22.8	0.14	1279	0.96
Living room	22.5	0.14	1280	0.96
Kitchen	23.0	0.14	1257	0.98
Northeast bedroom	22.0	0.17	1224	1.01
Dining room	22.5	0.14	1234	1.00
Family room	--[f]	0.17	1233	1.00
Mechanical room	20.0	0.18	1062	1.16
Lower hallway	17.9	0.18	1258	0.98

[a]Test conducted with northerly 4.5 m/s winds and an average outdoor air temperature of 11°C.

[b]Average temperature during the study.

[c]Integral of the measured concentrations during the test.

[d]Ventilation efficiency as per Eq. (10). The reference zone was arbitrarily chosen as the family room.

[e]The lowest ventilation efficiency despite the initially lower concentration in this room. Had uniformity been achieved earlier, a lower value would be observed.

[f]Not obtained due to a malfunction of the measuring thermocouple.

required for the upper level bedroom to reach the same concentration as the rest of the house. Study of the concentration decay shown in Fig. 36 and summarized in Table 28 shows that the air exchange rate in that bedroom was also significantly lower than in the rest of the house. Thus, the upper level bedroom not only had the lowest air exchange rate but, also, it had inadequate supply of air when the forced air system was in operation. This room was, therefore, clearly identified as the highest-risk zone in the house.

Table 28 shows that the upper level air exchange rates were in all cases lower than those in the lower level. Only the mechanical room exhibited a significantly higher ventilation efficiency.

In addition to the upper level bedroom, contaminant monitoring took place in the kitchen, which was the source of combustion-related contaminants and, also, formaldehyde, due to large wood paneling areas. The downstairs family room was also sampled for formaldehyde because it contained large wood paneling areas too. Although, by similarity to what was observed in the Energy Research House, higher $(\dot{q}_n/R\,V)$ values would still be expected in the upper level as a result of generation downstairs, sampling was nevertheless done for verification. The results of these measurements are listed in Table 29 and they show that the concentrations of formaldehyde upstairs were indeed higher than downstairs. The values of the remaining factors were at acceptable levels, although some, like NO_2 and formaldehyde, were at or just above the levels listed in Table 2.

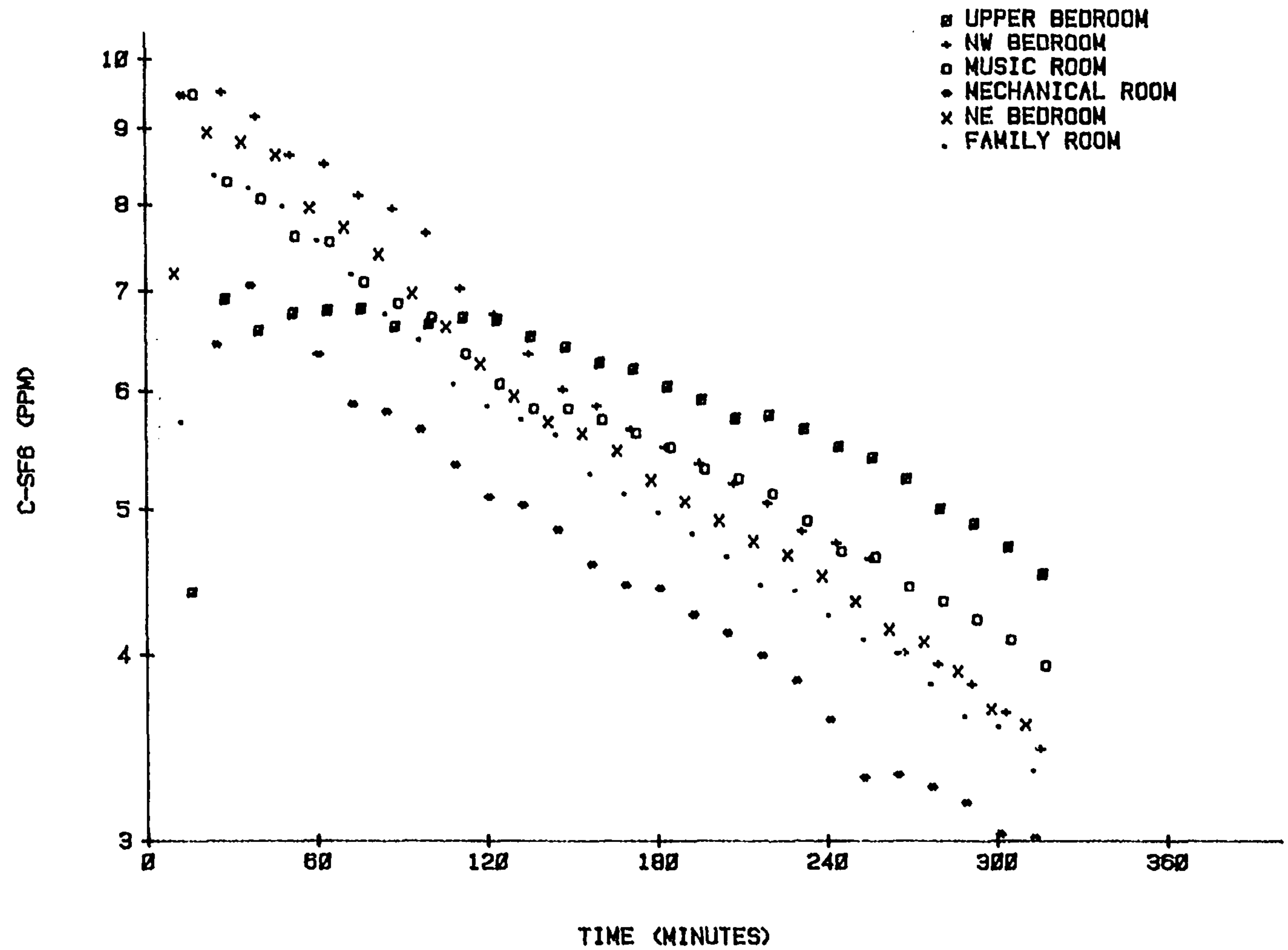


Fig. 36. Concentrations of SF_6 in house #3

Table 29. Indoor air quality factors in House #3

Factor	Measurements		
	Lower Level		Upper Level
	Bedroom	Kitchen[a]	Family Room
CO (ppm)	6.5	5	--
CO_2 (%)	0.16	0.19	--
NO_2 (ppm)	0.02	0.08	--
RSP (ppm)	0	--	--
Formaldehyde (ppm)	0.10	0.11	0.07
Dry-bulb temperature (°C)	23.3	22.2	18.6
Relative humidity (%)	40	50	55
Air velocity (cm/sec)	4.1	3.6	6.1

[a]During these measurements, an electrical crock-pot was left on in the kitchen.

The conclusions obtained for this house indicate that the air exchange rate was too low, thereby creating the potential for unwanted levels of contaminants, as demonstrated in Table 29. The weather conditions when the measurements were taken were quite mild and, thus, during most of the heating season, higher air exchange rates will occur. But the level which results from the recommended levels in ASHRAE Standard 62-1981 is 0.27 ACH, which is twice the measured value in upper level, might not be attained most of the time during the heating season.

House #4

This house was located in Des Moines, Iowa. Its floor plan is schematically shown in Fig. 37. It was a two-story residence of conventional construction that was recently retrofitted by installing urea-formaldehyde foam insulation in the walls. The house had a gas-fired central air heating system.

Nine sampling locations were used for the tracer gas study. These locations are listed in Table 30. Tracer gas was distributed through the central air system and a good uniformity of mixing was obtained throughout the house. Figure 38 shows the decay of the SF_6 concentrations at the different sampling locations. The results of this test are also summarized in Table 30.

The results show that there were three distinct zones within the building: the north wing in the upper level, which showed the lowest air exchange rates (0.36-0.38) and ventilation efficiencies below unity;

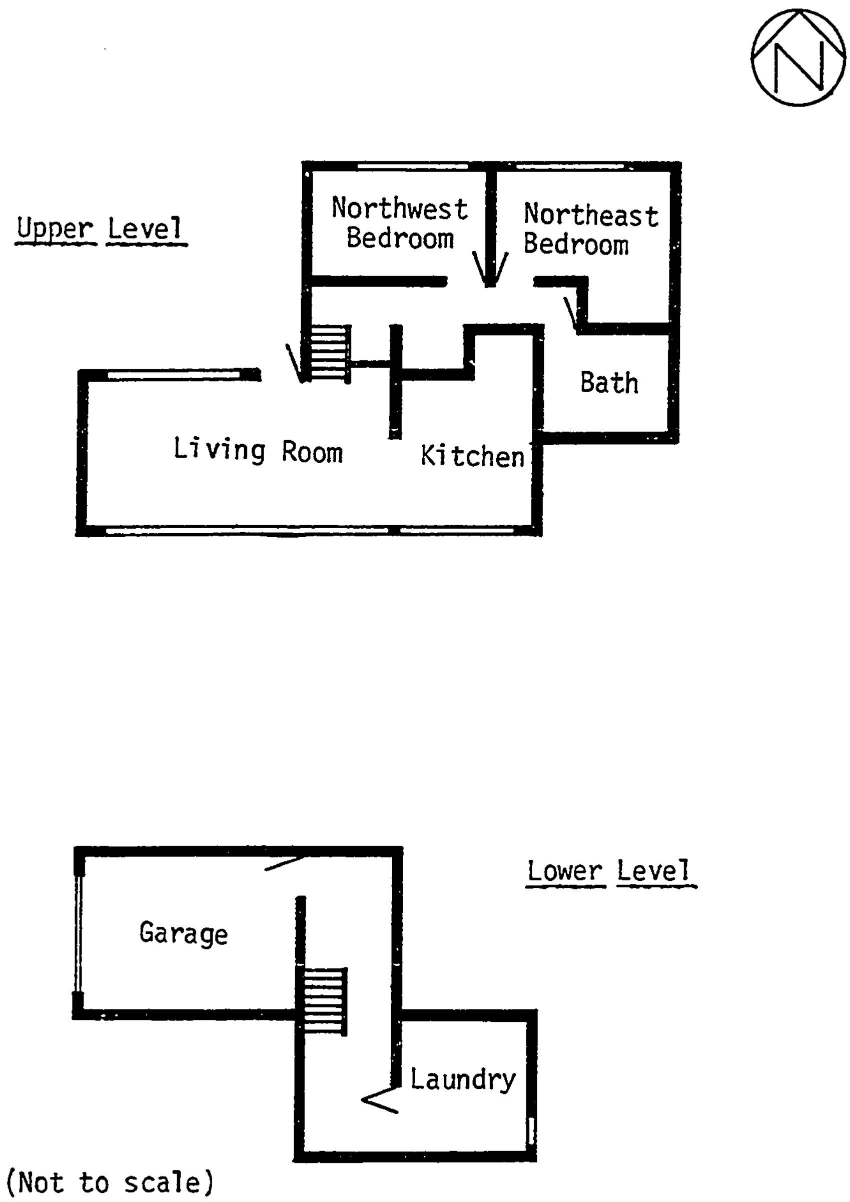


Fig. 37. Floor plan of house #4

Table 30. Results from the tracer-gas study for House #4[a]

Zone	T^b (°C)	R (ACH)	A^c (ppm·min)	ε^d
Upper hallway	18.7	0.38	625	0.83
Kitchen	18.9	0.43	465	1.11
East living room	18.9	0.43	516	1.00
Northeast bedroom	20.2	0.36	656	0.79
Bathroom	20.1	0.36	642	0.80
West living room	18.9	0.43	494	1.04
Northwest bedroom	20.2	0.38	644	0.80
Mechanical room	20.1	0.49	374	1.38
Lower hallway	18.9	0.46	551	1.07

[a]Test conducted with southeast winds at 3.1 m/s, and an average outdoor air temperature of -3°C.

[b]Average temperature during the test.

[c]Integral of the measured concentrations during the test.

[d]Ventilation efficiency as per Eq. (10). The reference zone was arbitrarily chosen as the living room.

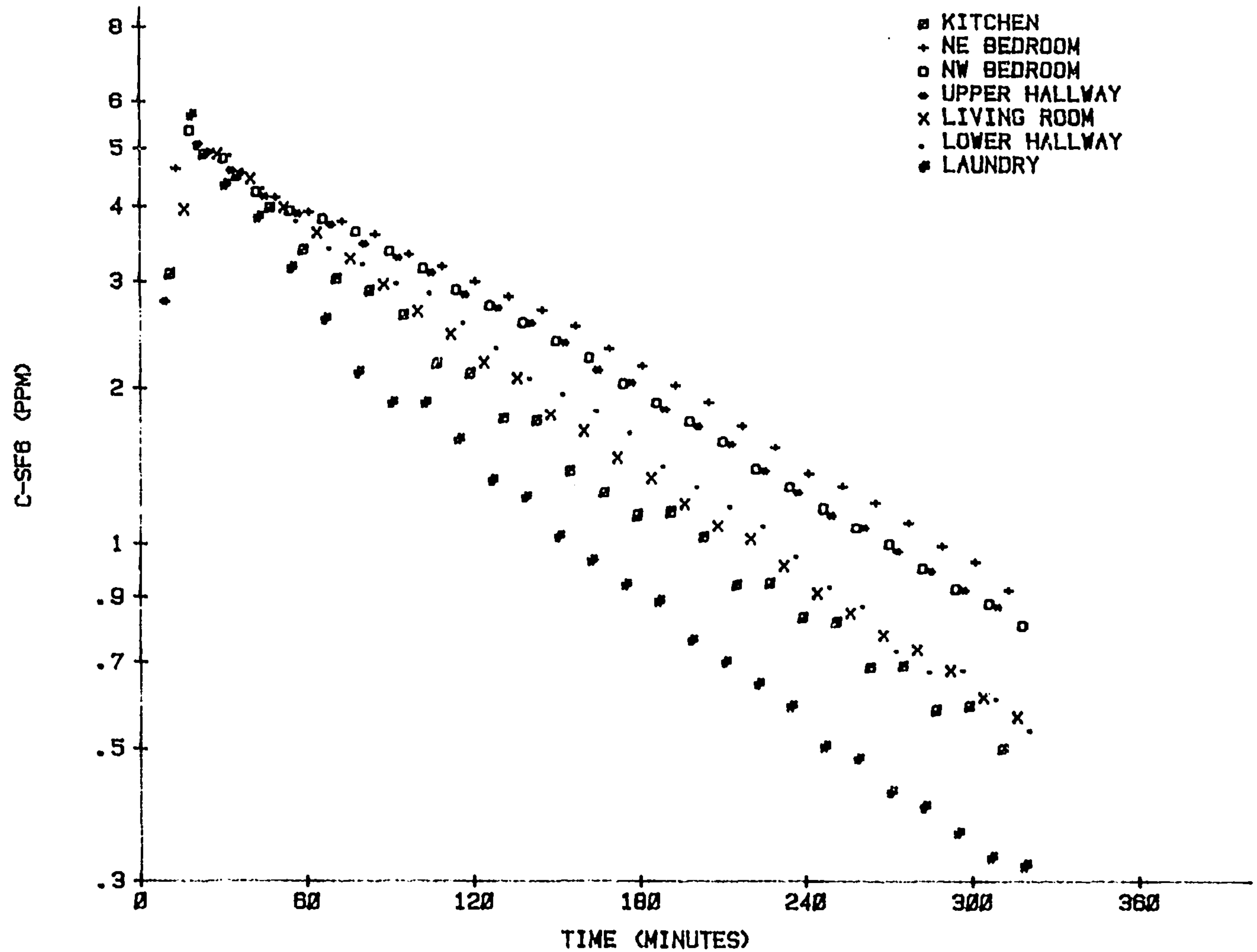


Fig. 38. Concentrations of SF_6 in house #4

the south wing inthe upper level, with intermediate air exchange rates (0.43-0.46); and, finally, the mechanical room, which showed the highest air exchange rate (0.49) and lowest ventilation efficiency.

These results show that the north wing in the upper level, particularly the northeast bedroom, was the highest-risk zone in the building. Since urea-formaldehyde insulation was installed in all walls in the north wing, this was the logical choice for monitoring formaldehyde[1]. For redundancy, given the problems associated with the urea-formaldehyde insulation, sensors were also placed in the other bedroom and in the living room. However, no formaldehyde was found in the air.

This house had an air exchange rate higher than any other in this study and about the same as the recommended level by ASHRAE Standard 62-1981. Thus, no air quality problems were found, and it appears that there is only little potential for such problems to occur.

Conclusions

The field tests conducted in the four houses that were described in this chapter demonstrated the feasibility of the proposed surveying procedure. Furthermore, it was verified that, in all cases, the zone in a building with the lowest air exchange rate and lowest ventilation efficiency was located in the upper level. However, not all zones in the upper levels have proved to have low air exchange rates: see, for instance, the upper level bathroom in House #1.

---

[1]In this house, only formaldehyde was sampled.

The survey further showed that, in some cases, high concentrations of mass factors can occur. In addition to individual levels of some contaminants above those maximum recommended levels listed in Table 2, many contaminants were present simultaneously, and at levels similar to those listed in Table 2, which raises concern about their interactive total effect. However, no comprehensive studies of these interactive effects have been done as pointed out earlier.

Given the experience obtained from the field tests, the final proposed procedure for the indoor air quality surveying is given in detail in Appendix B.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The most important conclusions obtained from this work are:

1. Substantial nonuniform mixing can occur in buildings. This nonuniformity can result in distinct rates of air exchange among the various rooms of the building. However, rooms which have regular rectangular geometries and normal ceiling height (i.e., about 2.4 m) can usually be considered uniformly mixed.

2. Although single point measurements have been used to characterize buildings for energy conservation, single values of air exchange rates are not adequate to describe a building for the purpose of indoor air quality evaluation.

3. The level of exposure for the occupants due to contaminant concentrations can vary markedly throughout the house. To determine if a building has an indoor air quality problem, it is necessary to determine the highest possible exposure of the occupants to the contaminants.

4. For each mass contaminant generated in a particular zone, the highest-risk zone can be determined using the concept of "Relative Exposure Index" (E). To obtain these indices, contaminant generation can be simulated by releasing tracer gas into the appropriate zone over a short period of time.

5. For each mass contaminant, the highest-risk zone always occurs either at the zone where the contaminant is produced or at a zone in the house which has a lower air exchange or a lower ventilation efficiency. Thus, rather than conducting multiple tests to determine values of the Relative Exposure Index which correspond to the various generation locations, quantification of air exchange rates and zonal ventilation efficiencies may provide equivalent information.

6. The air exchange rates and ventilation efficiencies of the different uniformly mixed zones in a building can be determined with a multipoint tracer gas procedure such as described in this work.

7. In the vast majority of the cases, the lowest air exchange rates and ventilation efficiencies in a building occurred in the upper levels. But care must be exercised in this generalization because large differences among rooms in the upper level may occur in a particular building. Moreover, generalization to buildings with cooling systems is cautioned because all measurements reported herein were taken under the heating mode.

8. The procedure for field survey of buildings for indoor air quality problems which was proposed was verified to be feasible for generalized application. Although less complicated and less expensive than the methods that have been used so far only for research programs, it still requires two days of field data collection per building.

9. Besides its application for indoor air quality studies, the proposed multipoint tracer gas technique can also pinpoint distribution deficiencies in the central air handling system of the building and

localized leakage through the building envelope. This information can be used to improve comfort conditions in the affected zones and can lead to identification of energy conservation opportunities in the building studied.

10. Single point measurements of air exchange rates to partially characterize energy consumption in a building should only be used if uniform mixing is artificially ensured within the building. However, the use of the central air fan, or to a lesser degree, of portable fans, to obtain uniform mixing throughout the house can lead to overestimated values due to the increased potential for leakage which may result.

Recommendations

The following are recommended:

1. If the multipoint tracer gas procedure is to be used on a regular basis, a more portable instrument package than that shown in Fig. 3 should be developed.

2. The concepts of R, ε, and E may be useful in modeling total building performance, including the energy and indoor air quality aspects. However, modeling of these zonal values needs further development. Further research is recommended to incorporate them as an integral part of building performance models.

3. If the information about locations of high-risk zones is to be useful in designing new buildings, an expanded data base with values of air exchange rates, ventilation efficiencies, and Relative Exposure Indices in buildings should be obtained.

4. Currently, evaluation of the quality of the indoor air is made by comparing the individual levels of each factor to levels recommended by appropriate standards. Few interactive effects can be considered due to a lack of scientific knowledge on this subject. Future study to better characterize the possible interactive effects of the pertinent factors of indoor air quality is recommended.

REFERENCES

1. Fanger, P. O. Thermal Comfort. New York: McGraw-Hill, 1972.

2. ANSI/ASHRAE Standard 55-1981: Thermal Environmental Conditions for Human Occupancy. Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, 1981.

3. Code of Federal Regulations 29 CFR 1910 (1979). Occupational Safety and Health Standards, subpart Z--Toxic and Hazardous Substances. Washington, D.C.: U.S. Government Printing Office, 1979.

4. ASHRAE Standard 62-1981: Ventilation for Acceptable Indoor Air Quality. Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, 1981.

5. Houghten, F. C.; and Yaglou, C. P. "Determining Lines of Equal Comfort." ASHVE Transactions 29 (1923): 163-176.

6. Houghten, F. C.; and Yaglou, C. P. "Determination of the Comfort Zone." ASHVE Transactions 29 (1923): 361-384.

7. Yaglou, C. P. "Indices of Comfort." In Physiology of Heat Regulation, pp. 277-287. Edited by L. H. Newburgh. Philadelphia: W. B. Saunders Company, 1949.

8. Gagge, A. P.; Stolwijk, J. A. J.; and Nishi, Y. "An Effective Temperature Scale Based on a Simple Model of Human Physiological Regulatory Response." ASHRAE Transactions 77 (part 1)(1971): 247-262.

9. Rohles, F. H.; and Nevins, R. G. "The Nature of Thermal Comfort for Sedentary Man." ASHRAE Transactions 77 (part 1)(1971): 239-246.

10. Nevins, R. G.; and Gagge, A. P. "The New ASHRAE Comfort Chart." ASHRAE Journal 14 (May 1972): 41-43.

11. Gagge, A. P.; Nishi, Y.; and Gonzalez, R. R. "Standard Effective Temperature." CIB Commission W45--Symposium: Thermal Comfort and Moderate Heat Stress, Watford, U.K., September 1972.

12. Nishi, Y.; and Gagge, A. P. "Effective Temperature Scale Useful for Hypo- and Hyperbaric Environments." Aviation, Space, and Environmental Medicine 48 (1977): 97-107.

13. Sprague, C. H.; Jai, R. B.; Nevins, R. G.; and Azer, N. Z. "The Prediction of Thermal Sensation for Man in Moderate Thermal Environments via a Simple Thermoregulatory Model." ASHRAE Transactions 80 (part 1)(1974): 130-141.

14. Azer, N. Z.; and Hsu, S. "The Prediction of Thermal Sensation from a Simple Model of Human Physiological Regulatory Response." ASHRAE Transactions 83 (part 1)(1977): 88-102.

15. Berglund, L. "Mathematical Models for Predicting the Thermal Comfort Response of Building Occupants." ASHRAE Transactions 84 (part 1)(1978): 735-748.

16. Sprague, C. H.; and Munson, D. M. "A Composite Ensemble Method for Estimating Thermal Insulating Values of Clothing." ASHRAE Transactions 80 (part 1)(1974): 120-129.

17. Azer, N. Z. "The Prediction of Thermal Insulation Values of Garments from the Physical Data of Their Fabrics." ASHRAE Transactions 82 (part 1)(1976): 87-106.

18. Rohles, F. H.; Woods, J. E.; and Nevins, R. G. "The Effects of Air Movement and Temperature on the Thermal Sensations of Sedentary Man." ASHRAE Transactions 80 (part 1)(1974): 101-119.

19. McIntyre, D. A. "The Effect of Air Movement on Thermal Comfort and Sensation." In Indoor Climate, pp. 541-560. Edited by P. O. Fanger and O. Valbjorn. Horsholm, Denmark: Danish Building Research Institute, 1978.

20. Fanger, P. O.; and Pedersen, C. J. K. "Discomfort Due to Air Velocities in Spaces." In Institute of International Refrigeration - Commission B1, pp. 289-296. Belgrad, Yugoslavia, 1977.

21. Madsen, T. L. "Limits for Draught and Asymmetric Radiation in Relation to Human Thermal Well-being." In Institute of International Refrigeration - Commission B1, pp. 297-306. Belgrad, Yugoslavia, 1977.

22. Fanger, P. O.; Banhidi, L.; Olesen, B. W.; and Langkilde, G. "Comfort Limits for Heated Ceilings." ASHRAE Transactions 86 (part 2)(1980): 141-156.

23. Berglund, L. G. "Occupant Acceptance of Temperature Drifts." In Indoor Climate, pp. 507-525. Edited by P. O. Fanger and O. Valbjorn. Horsholm, Denmark: Danish Building Research Institute, 1978.

24. Nielsen, B.; Oddershede, I.; Torp, A.; and Fanger, P. O. "Thermal Comfort During Continuous and Intermittent Work." In Indoor Climate, pp. 477-490. Edited by P. O. Fanger and O. Valbjorn. Horsholm, Denmark: Danish Building Research Institute, 1978.

25. Woods, J. E. "Climatological Effects on Thermal Comfort and Energy Utilization in Residences and Offices." In Proceedings of the 7th International Biometeorological Congress, pp. 95-105. College Park, Maryland, 1975.

26. McNall, P. E.; and Schlegel, J. C. "The Relative Effects of Convective and Radiation Heat Transfer on Thermal Comfort (Thermal Neutrality) for Sedentary and Active Human Subjects." ASHRAE Transactions 74 (part 2)(1968): 131-143.

27. Rohles, F. H.; Woods, J. E.; and Nevins, R. G. "The Influence of Clothing and Temperature on Sedentary Comfort." ASHRAE Transactions 79 (part 2)(1973): 71-80.

28. McNall, P. E.; Ryan, P. W.; Rohles, F. H.; Nevins, R. G.; and Springer, W. "Metabolic Rates at Four Activity Levels and their Relationship to Thermal Comfort." ASHRAE Transactions 74 (part 1)(1968): IV 3.2 - IV 3.13.

29. Klauss, A. K.; Tull, R. H.; Roots, L. M.; and Pfafflin, J. R. "History of the Changing Concepts in Ventilation Requirements." ASHRAE Journal 12 (June 1970): 51-55.

30. Tredgold, T. Principles of Warming and Ventilating Public Buildings. London: J. Taylor, 1824.

31. Billings, J. S. The Principles of Ventilation and Heating. New York: The Sanitary Engineer, 1884.

32. Proceedings of the Second Annual Meeting of the American Society of Heating and Ventilating Engineers. New York: ASHVE, 1896.

33. Report of the New York State Commission on Ventilation. New York: E. P. Dutton & Company, 1923.

34. Yaglou, C. P.; Riley, E. C.; and Coggins, D. I. "Ventilation Requirements." ASHVE Transactions 42 (1936): 133-162.

35. ASA Standard A53.1: American Standard Building Requirements for Light and Ventilation. Washington, D.C.: American Standards Association, 1943.

36. ASHRAE Standard 62-73: Standards for Natural and Mechanical Ventilation. New York: American Society of Heating, Refrigerating and Air Conditioning Engineers, 1973.

37. Wang, T. C. "A Study of Bioeffluents in a College Classroom." ASHRAE Transactions 81 (part 1)(1975): 32-44.

38. Cote, W. A.; Wade, W. A.; and Yocom, J. E. A Study of Indoor Air Quality. Final Report. U.S. Environmental Protection Agency Report No. EPA - 650/4-74-042. Washington, D.C.: U.S. EPA, 1974.

39. Traynor, G. W.; Anthon, D. W.; and Hollowell, C. D. Indoor Air Quality: Gas Stove Emissions. Berkeley, California: Lawrence Berkeley Laboratory, 1979.

40. Duncan, J. R.; Morkin, K. M.; and Schmierbach, M. P. "Air Quality Impact Potential from Residential Wood Burning Stoves." Paper 80 - 7.2, presented at the 73rd Annual Meeting of the Air Pollution Control Association, Montreal, Quebec, June 1980.

41. National Research Council. Indoor Pollutants. Report by the Committee on Indoor Pollutants. Washington, D.C.: National Academy Press, 1981.

42. Bruno, R. C. "Sources of Indoor Radon in Houses." Proceedings of the International Symposium on Indoor Air Pollution, Health and Energy Conservation, Amherst, Massachusetts, October 1981 (In Press).

43. Anderson, I.; Lundquist, G. R.; and Molhave, L. "Indoor Air Pollution due to Chipboard used as a Construction Material." Atmospheric Environment 9 (1975): 1121-1127.

44. Mokler, B. V.; Wong, B. A.; and Snow, M. J. "Respirable Particulates Generated by Pressurized Consumer Products. I. Experimental Method and General Characteristics." American Industrial Hygiene Association Journal 40 (1979): 330-338.

45. Molhave, L. "Indoor Air Pollution Due to Building Materials." In Indoor Climate, pp. 89-110. Edited by P. O. Fanger and O. Valbjorn. Horsholm, Denmark: Danish Building Research Institute, 1978.

46. National Research Council. Carbon Monoxide. Report by the Committee on Medical and Biologic Effects of Environmental Pollutants. Washington, D.C.: National Academy of Sciences, 1977.

47. National Research Council. Nitrogen Oxides. Report by the Committee on Medical and Biologic Effects of Environmental Pollutants. Washington, D.C.: National Academy of Sciences, 1977.

48. Cohen, B. L. "Health Effects of Radon from Insulation of Buildings." Health Physics 39 (1980): 937-941.

49. National Research Council. Formaldehyde and Other Aldehydes. Report by the Committee on Aldehydes. Washington, D.C., National Academy Press, 1981.

50. Schaefer, K. E. "Physiological Stresses Related to Hypercapnia During Patrols on Submarines." Undersea Biomedical Research, Submarine Supplement 1979: S15-S47.

51. Fanger, P. O. "Proposed Nordic Standard for Ventilation and Thermal Comfort." In Building Energy Management: Conventional and Solar Approaches, pp. 609-614. Edited by E. O. Fernandes, J. E. Woods, and A. P. Faist. New York: Pergamon Press, 1981.

52. Harrje, D. T.; Socolow, R. H.; and Sonderegger, R. C. "Residential Energy Conservation -- The Twin Rivers Project." ASHRAE Transactions 83 (part 1)(1977): 458-477.

53. Valbjørn, O.; Nielsen, P. A.; and Kjaer, J. "Indoor Climate Problems in Danish Dwellings. Complaints and Diseases Referred to the Type and Materials of Dwellings and the Use of Airings." Proceedings of the International Symposium on Indoor Air Pollution, Health and Energy Conservation, Amherst, Massachusetts, October 1981 (In Press).

54. Andersen, J. "Formaldehyde in the Indoor Environment -- Health Implications and the Setting of Standards." In Indoor Climate, pp. 65-87. Edited by P. O. Fanger and O. Valbjørn. Horsholm, Denmark: Danish Building Research Institute, 1978.

55. Lippmann, M.; and Schlesinger, R. B. Chemical Contamination in the Human Environment. New York: Oxford University Press, 1979.

56. Kuehner, R. L. "Humidity Effects on the Odor Problem." ASHRAE Transactions 62 (1956): 249-256.

57. Kerka, W. F.; and Humphreys, C. M. "Temperature and Humidity Effect on Odor Perception." ASHRAE Transactions 62 (1956): 531-552.

58. Woods, J. E. "Ventilation, Health and Energy Consumption: A Status Report." ASHRAE Journal 21 (July 1979): 23-27.

59. Long, K. R.; Pierson, D. A.; Brennan, S. T.; Frank, C. W.; and Hahne, R. A. Problems Associated with the Use of Urea-Formaldehyde Foam for Residential Insulation. Part I: The Effects of Temperature and Humidity on Formaldehyde Release from Urea-Formaldehyde Foam Insulation. Oak Ridge National Laboratory Report No. ORNL/SUB-7559/I. Washington, D.C.: U.S. Government Printing Office, 1979.

60. Colle, R.; Rubin, R. J.; Knab, L. I.; and Hutchinson, J. M. R. Radon Transport Through and Exhalation from Building Materials: A Review and Assessment. National Bureau of Standards Technical Note 1139. Washington, D.C.: U.S. Government Printing Office, 1981.

61. Brundrett, G. W. "Controlling Moisture in the Home." In Building Energy Management: Conventional and Solar Approaches, pp. 747-754. Edited by E. O. Fernandes, J. E. Woods, and A. P. Faist. New York: Pergamon Press, 1981.

62. Woods, J. E.; Winakor, G.; Maldonado, E. A. B.; and Kipp, S. "Subjective and Objective Evaluation of a CO_2-Controlled Variable Ventilation System." ASHRAE Transactions 88 (part 1) (1982). (In Press)

63. Brown, E. W. "The Value of High Oxygen in Preventing the Physiological Effects of Noxious Concentrations of Carbon Dioxide." U.S. Naval Medical Bulletin 28 (1930): 523-553.

64. Woods, J. E.; Maldonado, E. A. B.; and Reynolds, G. L. "How Ventilation Influences Energy Consumption and Indoor Air Quality." ASHRAE Journal 23 (September 1981): 40-43.

65. Tamura, G. T. "Measurement of Air Leakage Characteristics of House Enclosures." ASHRAE Transactions 81 (part 1)(1975): 202-211.

66. Harrje, D. T.; Dutt, G. S.; and Beyea, J. E. "Locating and Eliminating Obscure but Major Energy Losses in Residential Housing." ASHRAE Transactions 85 (part 2)(1979): 521-534.

67. Lints, M. C.; Rizzuto, J. E.; and Desmond, R. M. "A Study of Air Infiltration in Tight Homes." In Proceedings of the 5th National Passive Solar Conference, pp. 441-445. Edited by J. Hayes and W. Kolar. Kileen, Texas: American Section of the International Solar Energy Society, 1981.

68. Shaw, C. "A Correlation between Air Infiltration and Air Tightness for Houses in a Developed Residential Area." ASHRAE Transactions 87 (part 2)(1981): 333-341.

69. Grimsrud, D. T.; Modera, M. P.; and Sherman, M. H. "A Predictive Air Infiltration Model -- Long-Term Field Test Validation." ASHRAE Transactions 88 (part 1)(1982). (In Press)

70. Renbourn, E. T.; Angus, T. C.; Ellison, J. M.; Croton, L. M.; and Jones, M. S. "The Measurement of Domestic Ventilation: An Experimental and Theoretical Investigation with Particular Reference to the Use of Carbon Dioxide as a Tracer Substance." Journal of Hygiene 47 (1949): 1-38.

71. Houghten, F. C.; and Blackshaw, J. L. "Indices of Air Change and Air Distribution." ASHVE Transactions 39 (1933): 261-276.

72. Marley, W. G. "The Measurement of the Rate of Air Change." Journal of the Institution of Heating and Ventilating Engineers 2 (1935): 499-503.

73. Hitchin, E. R.; and Wilson, C. B. "A Review of Experimental Techniques for the Investigation of Natural Ventilation in Buildings." Building Science 2 (1967): 59-82.

74. Grimsrud, D. T.; Sherman, M. H.; Janssen, J. E.; Pearman, A. N.; and Harrje, D. T. "An Intercomparison of Tracer Gases Used for Air Infiltration Measurements." ASHRAE Transactions 86 (part I)(1980): 258-267.

75. Dick, J. B. "Measurement of Ventilation Using Tracer Gas Techniques." Heating, Piping and Air Conditioning 22 (1950): 131-137.

76. Coblentz, C. W.; and Achenbach, P. R. "Design and Performance of a Portable Infiltration Meter." ASHRAE Transactions 63 (1977): 477-482.

77. Bahnfleth, D. R.; Moseley, T. D.; and Harris, W. S. "Measurement of Infiltration in Two Residences." ASHRAE Transactions 63 (1957): 439-476.

78. Jordan, R. C.; Erickson, G. A.; and Leonard, R. R. "Infiltration Measurements in Two Research Houses." ASHRAE Transactions 70 (1964): 344-350.

79. Laschober, R. R.; and Healy, J. H. "Statistical Analyses of Air Leakage in Split-Level Residences." ASHRAE Transactions 70 (1964): 364-374.

80. Hunt, C. M.; and Burch, D. M. "Air Infiltration Measurements in a Four-Bedroom Townhouse Using Sulfur Hexafluoride as a Tracer Gas." ASHRAE Transactions 81 (part 1)(1975): 186-201.

81. Prado, F.; Leonard, R. G.; and Goldschmidt, V. W. "Measurement of Infiltration in a Mobile Home." ASHRAE Transactions 82 (part 2)(1976): 151-166.

82. ASTM Standard E 741-80. Standard Practice for Measuring Air Leakage Rate by the Tracer Dilution Method. Philadelphia, Pennsylvania: ASTM, 1980.

83. Malmström, T.; and Ahlgren, A. "Aspects of Efficient Ventilation in Office Rooms." Proceedings of the International Symposium on Indoor Air Pollution, Health and Energy Conservation, Amherst, Massachusetts, October 1981. (In Press)

84. Skåret, E.; and Mathisen, H. M. "Ventilation Efficiency." Proceedings of the International Symposium on Indoor Air Pollution, Health and Energy Conservation, Amherst, Massachusetts, October 1981. (In Press)

85. Janssen, J. E.; Hill, T. J.; Woods, J. E.; and Maldonado, E. A. B. "Ventilation for Control of Indoor Air Quality." Proceedings of the International Symposium on Indoor Air Pollution, Health and Energy Conservation, Amherst, Massachusetts, October 1981. (In Press)

86. Drivas, P. J.; Simmonds, P. G.; and Shair, F. H. "Experimental Characterization of Ventilation Systems in Buildings." Environmental Science and Technology 6 (1972): 609-614.

87. Lidwell, O. M. "The Evaluation of Ventilation." Journal of Hygiene 58 (1960): 297-305.

88. Sandberg, M. "What is Ventilation Efficiency?" Building and Environment 16 (1981): 123-135.

89. Woods, J. E. "Ventilation, Health and Energy Consumption: A Status Report." ASHRAE Journal 21 (July 1979): 23-27.

90. Moschandreas, D. J.; and Zabransky, J. "Spatial Variation of Carbon Monoxide and Oxides of Nitrogen Concentrations Inside Residences." Proceedings of the International Symposium on Indoor Air Pollution, Health and Energy Conservation, Amherst, Massachusetts, October 1981. (In Press)

91. Hollowell, C. D.; Berk, J. V.; Brown, S. R.; Dillworth, J.; Koonce, J. F.; and Young, R. A. "Indoor Air Quality in New Energy-Efficiency Houses and Retrofitted Houses." Proceedings of the International Symposium on Indoor Air Pollution, Health and Energy Conservation, Amherst, Massachusetts, October 1981. (In Press)

92. GEOMET. Indoor Air Monitoring Protocol Guidelines for Residential Weatherization Programs. GTI Report ES-923 for the U.S. Environmental Protection Agency. Rockville, Maryland: GEOMET, 1981.

93. Moschandreas, D., gen. ed. Indoor Air Pollution in the Residential Environment. 2 vols. U.S. Environmental Protection Agency Report EPA-600/7-78-229a and -299b. Washington, D.C.: U.S. Government Printing Office, 1978.

94. Hollowell, C. D.; Berk, J. V.; and Traynor, G. W. Indoor Air Quality Measurements in Energy Efficient Buildings. Lawrence Berkeley Laboratory Report LBL-7831, presented at the 71st Air Pollution Control Association Meeting, Houston, Texas, June 1978.

95. Nevins, R. G. Air Diffusion Dynamics: Theory, Design and Application. Birmingham, Michigan: Business News Publishing Company, 1976.

96. Int-Hout, D. III "A Measurement System for Determination of Air Diffusion Performance in Interior Spaces." ASHRAE Transactions 88 (part 1)(1982). (In Press)

97. Maldonado, E. A. B.; Junkhan, G. H.; and Woods, J. E. "Use of a Gas Mixture for Experimental Modeling of Mixed Free and Forced Convection in Enclosures." Proceedings of the Seventh International Heat Transfer Conference, Munich, Germany, September 1982. (In Press)

98. Nishi, Y. "Field Assessment of Thermal Characteristics of Man and His Environment by Using a Programmable Pocket Calculator." ASHRAE Transactions 83 (part 1)(1977): 103-124.

99. Woods, J. E.; and Peterson, P. W. "Impact of Environmental Control on Residential Energy Use Management." In Proceedings of the International Conference on Energy Use Management, Vol. III/IV, pp. 305-312. Edited by R. Fazzolare and C. B. Smith. Oxford: Pergamon Press, 1977.

100. Thermodynamic Properties of Refrigerants. New York: American Society of Heating, Refrigerating and Air Conditioning Engineers, 1969.

101. Grimsrud, D. T.; Sherman, M. H.; Blomsterberg, A. J.; and Rosenfeld, A. H. "Infiltration and Air Leakage Comparisons: Conventional and Energy-Efficient Housing Designs." In Changing Energy Use Futures, Vol. III, pp. 1351-1358. Edited by R. Fazzolare and C. B. Smith. Oxford: Pergamon Press, 1979.

102. Janssen, J. E.; Glatzel, J. J.; Torborg, R. H.; and Bonne, V. "Infiltration in Residential Structures." In ASME Symposium Bulletin: Heat Transfer in Energy Conservation, pp. 33-38. New York: ASME, 1977.

103. "The Low Velocity Anemometer." DISA Information, No. 7, January 1969: 32-35.

104. Alter, H. W. "Indoor Radon Levels. Field Experience Using the TRACH ETCH Method." Proceedings of the International Symposium on Indoor Air Pollution, Health and Energy Conservation, Amherst, Massachusetts, October 1981. (In Press)

APPENDIX A

Method of Calculation of Zonal Air Exchange Rates

The values of the slopes of the concentration decays (semilog representation) were calculated using a least-squares procedure. In each case, the first two hours of the decay were not used in the calculation. Mathematically, the slope was given by:

$$R = -\frac{\sum_{i=1}^{n} \log(C_i)\, t_i - n\,\overline{(\log C)}\,\bar{t}}{\sum_{i=1}^{n} t_i^2 - n\,\bar{t}^2} \tag{26}$$

The goodness of fit was judged in terms of r^2:

$$r^2 = \frac{I\sum_{i=1}^{n} \log(C_i) - R\sum_{i=1}^{n} \log(C_i)\, t_i - \frac{1}{n}\left(\sum_{i=1}^{n} \log C_i\right)^2}{\sum_{i=1}^{n} (\log C_i)^2 - \frac{1}{n}\left(\sum_{i=1}^{n} \log C_i\right)^2} \tag{27}$$

Confidence intervals were obtained to assess the meaningfulness of the values:

$$R \pm t_{n-2,\alpha/2}\sqrt{\frac{\sum_{i=1}^{n} (C_i - \hat{C}_i)^2 \Big/ (n-2)}{\sum_{i=1}^{n} t_i^2 - n\,\bar{t}^2}} \tag{28}$$

As an example, values for the decays obtained in uniform mixing test #1 are listed in Table 31. The values of the confidence intervals show that the uncertainty ranged from 3% to 12% of the value of the slopes. Thus, the uncertainty of the measurements was reasonably small, especially for the larger values of the air exchange rates. Furthermore, the uncertainty of the results was similar to the reported accuracy of the gas analyzer that was used (5%).

Table 31. Statistics for uniform mixing test #1

Zone	n	R	r^2	5% confidence interval range
Southwest bedroom	25	0.17	0.995	0.02
North bedroom	24	0.22	0.996	0.01
Upper hallway	25	0.27	0.997	0.01
Basement	25	0.33	0.998	0.01
Upper greenhouse	25	0.29	0.990	0.01
Lower greenhouse	25	0.29	0.985	0.01
Living room[a]	25	0.30	0.997	0.01

[a]Single location only.

APPENDIX B

Detailed Description of the Proposed Procedure for Indoor Air Quality Surveys

Step 1 -- Conduct tracer-gas study

One probe should be placed in each uniformly mixed space. Regular rectangular shaped rooms can usually be considered uniformly mixed unless they have high ceilings (i.e., more than 2.4 m high) but, if extra sampling ports are available, more than one sample can be collected in large rooms to better assess uniformity. Conversely, if not enough channels are available, rooms which communicate through large openings can be treated as a single zone with little error. For buildings with continuous forced air supply, uniformly mixed zones can only be determined by direct measurement of the properties of the air. Use of an appropriate grid of measurement locations will be required for each room as described by Nevins [95] and Int-Hout [96].

A tracer-gas (e.g., SF_6) should be thoroughly mixed in the house to obtain as similar as possible concentrations at all sampling locations. The mixing should be done by running the central air system, if available. In this way, zones which do not have adequate air supply from the central air system can also be identified. When no central air system exists, portable fans should be used.

Once uniformity is attained, the central air system or portable fans should be turned off and doors separating rooms where samples are being collected should be shut. However, if a particular door is seldom closed in normal house operation, that door may be left open during the study. The decay of the concentration of the tracer gas should then be monitored for a minimum of four hours, but six hours are recommended. Analysis of the results should include the rate of decay of the linear portion of decay in a semilog plot for each channel. A relative order of magnitude of the value of the integral of the concentration for each space should be obtained by either visual observation or numerical calcuation so that ventilation efficiencies (see chapter "Proposed Procedure for Indoor Air Quality Evaluation") for each zone can be established.

Step 2 -- Conduct house survey

Locate sources of contaminants throughout the house. This should be done by visual observation by trained personnel and by asking for appropriate information from the house occupants. This information should be obtained through the use of a standard questionnaire such as that given in the annex.

Step 3 -- Conduct monitoring of indoor air quality factors

Thermal factors should be measured in each group of uniformly mixed zones with similar air exchange rates and ventilation efficiencies.

Contaminant monitoring should take place in the zone where it is released and in the zone of the house which has the lowest ventilation efficiency. As different contaminants can be released in different zones, monitoring may have to be done at several distinct zones in the house.

Monitoring can be accomplished in a single day, but if radon is monitored with TERRADEX sensors, these should be left in place for a minimum of 30 days or for a recommended 3 months. However, as TERRADEX sensors come with appropriate mailing equipment and instructions, the occupants themselves can be asked to mail the sensors directly for analysis.

ANNEX TO APPENDIX B

Questionnaire Used in the Field Tests

House ______________________________ Date ____________

A. List of occupants: please indicate sex (M-F) and age group (< 10, 10-20, 20-60, > 60).

1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________
5. ______________________________

B. For each occupant, please indicate typical hourly location within the house for a weekday:

← a.m. → ← p.m. →

0 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12

Ex.: SE bedroom | kitchen | ... | kitchen | living room | SE bedroom

1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________
5. ______________________________

C. For each occupant, please indicate typical hourly location within the house during weekends:

← a.m. → ← p.m. →

0 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12

1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________
5. ______________________________

D. List any UNVENTED appliances:

Gas range ________

Portable gas heater ____________ Type of fuel _________________

Clothes dryer ___________ Type of fuel _________________

Other (specify) ____________________ Type of fuel _________________

E. For each UNVENTED appliance listed in "D", indicate typical operating times.

Gas range __________________

Portable gas heater ___________________

Clothes dryer _______________________

Other (specify) _____________________________

F. Does the house have special exhaust hoods or fans for the kitchen or bathrooms? Please specify.

G. For cooking, please indicate approximate total weekly number of hours the following methods are used:

Range top (electric) with lid on ____________

Range top (electric) without lid ____________

Range top (gas) with lid on ____________

Range top (gas) without lid _____________

Oven (gas) _____________

Oven (electric) _____________

Microwave _______________

Other (specify) ________________________________

H. Does the house have a fireplace? If yes, please indicate typical operating schedule.

I. Does the house have an air cleaner? If yes, is it connected to forced air system? ________; is it a portable unit? __________

J. Specify the type(s) of heating/cooling system(s) present in the house.

Gas-fired forced air system ____________

Oil-fired forced air system ____________

Electric forced air system _____________

Perimeter hot-water or steam radiating/convecting system _____________
(Specify fuel for water heater ___________________)

Wood furnace ______________

Heat-pump _______________

Central air conditioning system ____________________

Window air conditioning units __________________
(Specify number and location _______________________________________)

Humidifier ____________

Dehumidifier ________________

Gas-fired domestic water heater ________________

Electric domestic water heater _________________

Other (please specify) ____

K. Specify the typical temperature and humidity set points for the heating and cooling systems. Please include night or day setbacks, if used.

L. From the following list, indicate which products are used in the house on a regular basis.

Powdered detergents ________

Liquid detergents __________

Floor cleaners (wax, polish) _____________

Solid air freshners __________

Aerosol air freshners ________

Personal hygiene sprays (hair, deodorizers, perfumes, etc.) ______

Furniture cleaners __________ (wax, polish)

Pesticides ____________ (solid or spray)

Oven cleaner ____________

Other (specify) ______________

M. In the last five years, has any special window weatherstripping or wall caulking been done? Please specify.

N. In the last two years, has any part of the house or furniture been insulated, painted or varnished? Please specify.

O. Does any occupant smoke? If yes, please indicate occupant number (as per items A, B, and C) and average frequency and type (cigarette, cigar, or pipe) of smoking (e.g., 1 cigarette per hour).

P. Has any particular persistent smell been noticed inside the house? If yes, provide as many details as possible including smell description, where and when it is stronger, etc.

Q. Please list total fuel consumption for your house for the previous year. Include gas, oil, electricity, wood, and others as appropriate. If possible, break down consumption by month.