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energy conservation in buildings and community systems programme

Technical Note AIVC 24

AIVC Measurement Techniques Workshop Proceedings and Bibliography

June 1988

Air Infiltration and Ventilation Centre

University of Warwick Science Park,
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Annex V Air Infiltration and Ventilation Centre

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PREFACE

International Energy Agency

In order to strengthen cooperation in the vital area of energy policy, an Agreement on an International Energy Programme was formulated among a number of industrialised countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organisation for Economic Cooperation and Development (OECD) to administer that agreement. Twenty-one countries are currently members of the IEA, with the Commission of the European Communities participating under a special arrangement.

As one element of the International Energy Programme, the Participants undertake cooperative activities in energy research, development, and demonstration. A number of new and improved energy technologies which have the potential of making significant contributions to our energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRO), assisted by a small Secretariat staff, coordinates the energy research, development, and demonstration programme.

Energy Conservation in Buildings and Community Systems

As one element of the Energy Programme, the IEA encourages research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is encouraging various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programmes, building monitoring, comparison of calculation methods, as well as air quality and inhabitant behaviour studies.

The Executive Committee

Overall control of the R&D programme "Energy Conservation in Buildings and Community Systems" is maintained by an Executive Committee, which not only monitors existing projects but identifies new areas where collaborative effort may be beneficial. The Executive Committee ensures all projects fit into a predetermined strategy without unnecessary overlap or duplication but with effective liaison and communication.

Annex V Air Infiltration and Ventilation Centre

The IEA Executive Committee (Building and Community Systems) has highlighted areas where the level of knowledge is unsatisfactory and there was unanimous agreement that infiltration was the area about which least was known. An infiltration group was formed drawing experts from most progressive countries, their long term aim to encourage joint international research and increase the world pool of knowledge on infiltration and ventilation. Much valuable but sporadic and uncoordinated research was already taking place and after some initial groundwork the experts group recommended to their executive the formation of an Air Infiltration and Ventilation Centre. This recommendation was accepted and proposals for its establishment were invited internationally.

The aims of the Centre are the standardisation of techniques, the validation of models, the catalogue and transfer of information, and the encouragement of research. It is intended to be a review body for current world research, to ensure full dissemination of this research and, based on a knowledge of work already done, to give direction and firm basis for future research in the Participating Countries.

The Participants in this task are Belgium, Canada, Denmark, Federal Republic of Germany, Finland, Italy, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the United States of America.

PROCEEDINGS

Workshop Report and Summary
Koge, Denmark, 1988

Peter S. Charlesworth
Senior Scientist AIVC

Representatives of 12 countries attended the Air Infiltration and Ventilation Centre's Measurement Techniques Workshop. The objective of the Workshop was to review current air infiltration and ventilation measurement techniques. The Workshop was hosted by Peter Collet (Technological Institute, Copenhagen, Denmark) and the week began with a visit to Genvex (Copenhagen), a company which has collaborated with the Technological Institute in the development of simplified mechanical ventilation systems.

Genvex representative B. Svendsen stated that many Danish dwellings are very airtight. In some homes this lack of infiltration and natural ventilation had led to poor indoor air quality. In turn this had created a number of problems, specifically; condensation on windows, mould, rot and fungus on window frames, damp patches on walls behind furniture and house mites in mattresses and carpets. In order to try and overcome these problems Genvex have designed a range of balanced mechanical ventilation systems. It was claimed that these systems significantly improve indoor air quality and, due to the incorporation of a cross flow heat exchanger, do not greatly increase the energy consumption of the building.

After a tour of the Genvex production facilities Workshop participants had an opportunity to view balanced mechanical ventilation systems in use in two kindergartens. These buildings had suffered from indoor climate problems and after research by the Technological Institute mechanical ventilation systems were installed. Indoor air quality problems had been reduced thus providing a better internal environment for pupils and teachers.

The measurement techniques workshop itself was introduced by David Harrje from Princeton University, USA. David's own experience of measurement techniques ranges from the development of a complex constant concentration tracer gas system to simple techniques which can be used to examine large numbers of buildings in a cost effective manner. He stated that dedication to the advancement of air flow measurement techniques had been central to the interests of the AIVC since its inception in 1979. The first AIVC conference (1980) was devoted to measurement techniques and since that time air flow measurement horizons have expanded to include, not only the evaluation of air change rate, but also measurements of the circulation of air between various internal spaces of a building. Similar advances have been made in the realm of pressure measurements, with the development of the AC Pressurization method and the introduction of multiple fan DC Pressurization techniques. The Workshop was seen as a forum for discussion and was an ideal opportunity for research workers to share ideas and experiences of infiltration and ventilation measurement techniques.

A number of technical papers were then presented under the Chairmanship of Willem de Gids (TNO, Netherlands). Peter Charlesworth (AIVC, UK) described the Air Infiltration and Ventilation Centre's Measurement Techniques Guide. Peter stated that measurement techniques were the fundamental means of acquiring a greater understanding of air infiltration and ventilation, in that they enable primary data to be obtained from existing structures. In recognition of this fact the Air Infiltration and Ventilation Centre has produced a document entitled "A Guide to Air Exchange Rates and Airtightness Measurement Techniques". The guide deals primarily with the measurement of air change rate, interzonal air flows and air leakage characteristics, the general aim being to increase awareness of measurement techniques and their application.

Peter Warren (Building Research Establishment, UK) brought workshop participants up to date on airtightness measurement standards by describing the International Standards Organisation (ISO) standard entitled "Measurement of Building Airtightness using Fan Pressurisation". Peter stated that this was an international standard and that ventilation demands and airtightness requirements varied from country to country. Hence the ISO standard would address only the practical aspects of the fan pressurisation technique itself, thus allowing national standards to dictate such matters as how the building should be prepared and what internal volume should be measured. The standard as described at the workshop was in its draft form.

Marianna Louma (Technical Research Centre, Finland) discussed testing the performance of outdoor air inlets designed for residences equipped with mechanical extract ventilation. New building regulations in Finland will promote the use of outdoor air inlets in buildings equipped with mechanical extract ventilation systems. The Technical Research Centre tested the performance, in terms of draught production, sound attenuation and condensation/frost formation, of several air inlets marketed in Finland. Based on these tests a proposal about the type of rules which should be applied when testing the suitability of air inlets was made. In general, it was concluded that controlled outdoor air intake by this method is only possible in airtight dwellings.

The theme of airtightness measurements was resumed by Peter Wouters (Building Research Institute, Belgium) who described the use of advanced single fan pressurisation techniques for determining leakage distribution in buildings. Peter stated that a single pressurization test of the entire building envelope does not provide enough information to meet the needs of certain applications. Without having to substantially increase equipment requirements, much more information can be obtained by using the advanced techniques developed at the Research Institute. Peter described some of these techniques and cited specific examples where they had been used to examine actual buildings

Attention was then turned to tracer gas techniques. John Shaw (National Research Council (NRC), Canada) described an automated Sulphur Hexafluoride tracer gas sampling system which is capable of taking (and analysing) air/tracer samples from up to 16 separate locations in a building in a time interval of about four minutes. The system has been used in a test room, to study the mixing of tracer gas and room air without the aid of internal mixing fans, and on site to examine the air distribution of a mechanically ventilated eight storey office building.

Peter Collet (Technological Institute, Denmark) described the history of the development of the constant concentration tracer gas (CCTG) method. He then described current CCTG equipment which is capable of the simultaneous evaluation of air flow rates in up to 15 different zones of a building. Peter then presented some case studies where the CCTG system had been used to solve practical problems in a variety of building types.

Several presentations were made on the subject of the perfluorocarbon tracer (PFT) technique. This method, often referred to as the "passive" technique, was developed at Brookhaven National Laboratory (BNL). Russell Dietz (BNL), who instigated the development of the technique, provided an overview of the use of PFT's in ventilation measurements. He discussed potential advantages and disadvantages of the PFT technique and compared the performance of the PFT method with other tracer technologies. The intercomparison of techniques was based on short-term (field collection of air samples of 15 min. or less duration, with subsequent laboratory determination of air flow rates) and real-time (field collection of multizone air samples of only a few minutes duration followed by in-the-field determination of flow rates) measurements. He concluded that PFT technology appeared to have the lowest field materials and man power requirement costs, and was the only technology capable of being applied in both short term and real-time modes.

Max Sherman (Lawrence Berkeley Laboratory (LBL) USA) discussed the analysis of errors associated with passive ventilation measurement techniques. The LBL study was based on mathematical models combined with typical weather data to calculate how an ideal passive ventilation measurement system would perform. It was found that the passive technique significantly under predicts the average ventilation rate and the use of multiple tracers accomplishes marginal improvement. He concluded that inadequate mixing was found to be a major impediment to the interpretation of the results and could completely invalidate the measurement.

Russell Dietz (BNL) then described work performed at Princeton University, USA, designed to assess the potential of the PFT method as used in a multi-family building. Measurements were made over a two week period using three types of tracer gas. The PFT measurements were compared with simultaneous measurements of air flow rates using a constant concentration tracer gas measurement system. At the time of the workshop the data from this study was being analysed and a full report will be published at a later date.

A similar intercomparison study was made in Ontario,Canada.This research work was described by John Shaw (NRC). The study evaluated the passive tracer technique for a period of 30 days. Ten tests were conducted in conjunction with a continuous sulphur hexafluoride injection tracer gas system in six experimental houses. When the air change rate was maintained at a constant value the two measurement methods showed good agreement. If the air change rate was varied throughout the test the two methods were not in as close agreement, with measured values differing by as much as 0.26 air changes per hour. It was concluded that in cases of constant ventilation rate the PFT method was suitable for evaluating the average air change rate.

The final formal presentation was by Max Sherman (LBL), who described a newly developed multi-gas constant concentration tracer gas instrument. This system uses a mass spectrometer as an analyser and is capable of sampling, analysing and controlling up to 5 separate tracer gases. This system is one of the most sophisticated in use and it can provide detailed information about air change rates and interzonal air flows

After each formal presentation a discussion about the current topic was held. At the end of the Workshop a general discussion was chaired by Max Sherman (LBL). The discussion centred mainly on the PFT technique and the intercomparison of measurement techniques.

These proceedings contain a selection of papers presented at the workshop. Also included are transcripts of discussions held on various topics. Any conclusions or opinions expressed in these papers and transcripts represent solely those of the author(s) and not necessarily those of the Air Infiltration and Ventilation Centre. Similarly the AIVC cannot be held responsible for technical inaccuracies or typographical errors in papers, or the inconsistent use of units throughout these proceedings

Introduction

David T Harrje

Center for Energy and Environmental Studies

Princeton University

March, 1988

The devotion to advancements in airflow measurement has been central to the interests of the AIVC from the very first AIC conference; and indeed from the Paris meeting where researchers exchanged measurement information in the formative stages of the Centre in 1978. Now ten years later, we are presented with another of the many opportunities the Centre has afforded to exchange ideas on the latest airflow measurement techniques.

Just as the Centre has expanded to include ventilation, together with air infiltration, so have our airflow measurement horizons expanded to search for not only an understanding of exterior air entering and leaving our buildings, but just how that air is circulated, through both natural and forced means, between rooms. Our concerns include indoor air quality and the movement of pollutants through a variety of building types. We recognize that unless these air movements are documented and ventilation rates to zones quantified we will have missed the first important step to understanding IAQ in a building -- knowing whether the appropriate amount of outside air is reaching the occupants in each zone of the building.

During this ten-year period, much has taken place in the development of airflow measurement systems and techniques. Automated air infiltration units had been functioning for years prior to that first meeting and our first formal conference. But through a cooperative spirit and similar goals in the various AIVC countries, major advancements have taken place in our airflow measurement capabilities. We are now able to simultaneously measure 10 or more building zones, we have linked the computer to many of our airflow measurement systems, allowing the information to be instantly available as well as allowing complex constant concentration systems (which rely on information feedback) to function successfully. Multi-tracers and innovations with single gas systems have allowed interzonal airflow measurements to be made. In contrast with our sophisticated systems our attention has also been directed toward simplicity. Collection of air samples during tracer decay or constant tracer injection has allowed the complex equipment to remain "back at the lab". Bags, plastic bottles, syringes, etc. have all been used with considerable success to collect samples and spread the tracer gases. The use of capillary adsorption tubes and bullet-sized multiple tracer sources represent an innovative advancement and will be a prime topic for discussion at this workshop.

Although we often think in terms of tracer techniques for quantitive airflow measurements, other techniques such as fan pressurization alone or together with infrared methods have allowed us to evaluate airflow paths and air leakage sites through the building envelope. Simplicity here may involve smoke tracers, acoustical methods and velocity measurement probes. Tracers and infrared scanning have been used to visualize air movements. These are just some of the methods that may be used.

Airflow measurement techniques have been applied to a variety of buildings from single-family to complex commercial buildings. Industrial and multifamily structures have been part of that variety. One of the points we will be considering are buildings that have been tested by more than one airflow measurement method. Through such tests we can better evaluate the capabilities of the various measurement approaches and these findings directly relate to the latest AIVC endeavor, the AIVC Measurement Techniques Guide.

This workshop is meant to provide the means for discussion of our findings, our measurement concerns, our measurement targets, what new developments are on the horizon, and our longer-term goals. This is not a time to hold back but rather an opportunity to share. No one has all the answers nor do we even know all the questions. Hopefully, more questions will arise as material is presented in the early portion of the workshop. These questions will be more deeply discussed in the final part of the workshop. Our aim is an AIVC Note which will summarize these discussions and it will include the presentations that are available. Again, as in the past, sharing our latest findings expressing our concerns, our goals and expectations we will all leave the workshop with enhanced understanding of the state-of-the-art in this rapidly changing field of airflow measurement techniques.

AIR INFILTRATION AND VENTILATION CENTRE
MEASUREMENT TECHNIQUES WORKSHOP 1988

Køge, Denmark
21-23 March 1988

PAPER 1

AIR INFILTRATION AND VENTILATION CENTRE MEASUREMENT TECHNIQUES GUIDE

PETER S CHARLESWORTH
Air Infiltration and Ventilation Centre
Bracknell, Berkshire

ABSTRACT

The provision of an adequate supply of uncontaminated air suitable for the needs of the occupants is an important aspect of building design and construction. Ventilation can be promoted by natural or artificial forces and it is necessary to understand this process since it affects both the energy consumption and internal environment of a building. Ventilation is a complex process which is influenced by a variety of constructional, behavioural and environmental parameters.

Measurement techniques provide the fundamental means of acquiring a greater understanding of air infiltration and ventilation, in that they enable primary data to be obtained from existing structures. In recognition of the importance of measurement techniques the Air Infiltration and Ventilation Centre has produced a document titled:

"A Guide to Air Exchange Rates and Airtightness Measurement Techniques".

The broad aims of this document are to identify the parameters which need to be evaluated, indicate the variety of techniques which are available, provide detailed information about several techniques and offer advice regarding the selection of techniques for particular applications. This paper briefly describes the scope, structure and content of this guide to air exchange rate and airtightness measurement techniques.

1 SCOPE AND STRUCTURE OF THE GUIDE

The guide is concerned with the measurement of those parameters which are important in gaining an understanding of air infiltration and ventilation.

The information in the guide is presented in seven chapters. These are:

Chapter 1: Selecting a Technique

Chapter 2: Measurement of Air Exchange Rates

Chapter 3: Measurement of Airtightness

Chapter 4: Measurement Equipment and Instrumentation

Chapter 5: Measurement Technique Standards

Chapter 6: Detailed description of Selected Measurement Techniques

Chapter 7: Description of Selected Instrumentation

The structure of the guide is illustrated in Figure 1. By examining this flow chart readers of the guide will be able to decide which sections of the guide will be of use to them.

The guide is produced in a loose leaf format thus enabling fresh developments in measurement technology to be readily accommodated.

1.1 CHAPTER 1: Selecting a Technique

Chapter 1 presents the parameters which are important to gaining a greater understanding of the ventilation behaviour of buildings. These are essentially:

Air Change Rate

Interzonal Air Flows

Air Leakage Characteristics

The means of measuring these parameters are indicated, the application of measurement techniques is discussed (see Figure 2) and summaries of the main techniques are presented (see Figure 3). This chapter is cross-referenced with the main body of the guide.

1.2 CHAPTER 2: Measurement of Air Exchange Rates

Chapter 2 presents the fundamental theory and practice of measuring air exchange rates. Air exchange between a building and the external environment (air change rate) is examined as is the air exchange between the various internal spaces of a building (interzonal air flows).

Air change rate is usually measured using single tracer gas techniques. Three main methods are examined:

Decay Rate Method

Constant Emission Rate Method

Constant Concentration Method

For interzonal air flow measurements multiple tracer gas methods are used. The multi-tracer gas versions of the three techniques listed above are examined.

1.3 CHAPTER 3: Measurement of Airtightness

Chapter 3 presents the fundamental theory and practice of measuring airtightness. Evaluation of the entire envelope is examined (DC Pressurization and AC Pressurization) as is the measurement of individual building components. This chapter also contains a section describing leakage location and other qualitative techniques.

1.4 CHAPTER 4: Equipment and Instrumentation

Chapter 4 describes in general terms some of the specialist equipment and instrumentation used to perform ventilation related topics. Four specific topics are addressed:

Tracer Gases

Tracer Gas Analysers

Commercial DC Pressurization Equipment

Measuring Climatic Parameters

This chapter is cross-referenced with Chapter 7 which contains detailed descriptions of several instruments.

1.5 CHAPTER 5: Measurement Technique Standards

Several standards have been developed which relate to ventilation measurements. This chapter discusses 10 selected standards from around the world. The criteria for selection being that they relate to site measurements of buildings or building components.

Two main groups of standards are examined:

Air Change Rate Measurement Technique Standards

Airtightness Measurement Technique Standards

Summaries of the standards are presented and comparisons made.

1.6 CHAPTER 6: Detailed Description of Selected Techniques

This chapter currently contains detailed descriptions of 9 selected measurement techniques. Because the guide is presented in a loose leaf format updates of current techniques or information about new techniques can be easily added. Information about each technique is presented in a standard format thus aiding comparison and selection. The information in the standard format is presented in the following sub-sections.

Type of Technique

Range of Application

Equipment and Instrumentation

Setting Up and Operating Details

Presentation of Results

Measurement Accuracy

Availability of Measurement System

1.7 CHAPTER 7: Description of Selected Instrumentation

Chapter 7 contains descriptions of several instruments which are used when making air exchange rates or airtightness measurements. Information is presented in a standard format to enable information to be easily located. Information about 3 instruments is currently presented in this chapter. However, due to the loose leaf nature of the guide other instruments may easily be added.

2 ROLE OF THE GUIDE

The role of this guide is to increase general awareness of air exchange rate measurement techniques and their application. By providing detailed information about several techniques ranging from the simple to the complex it is hoped to meet the needs of the following groups of people.

Research and Academic

The guide will act as a directory of current techniques and will promote discussion about measurements and research workers.

Specialist Consultants

The guide will encourage specialist consultants, operating in the field of building physics, to consider using air change rate and airtightness measurement techniques in their work.

Non-specialist Consultants

The guide will introduce measurement techniques to non-specialist consultants, indicate the variety of methods available and give advice regarding where further information may be obtained.

3 AVAILABILITY OF THE GUIDE

The guide to air exchange rates and airtightness measurement techniques is available from the Air Infiltration Ventilation Centre at:

Old Bracknell Lane West
Bracknell
Berkshire
United Kingdom
RG12 4AH

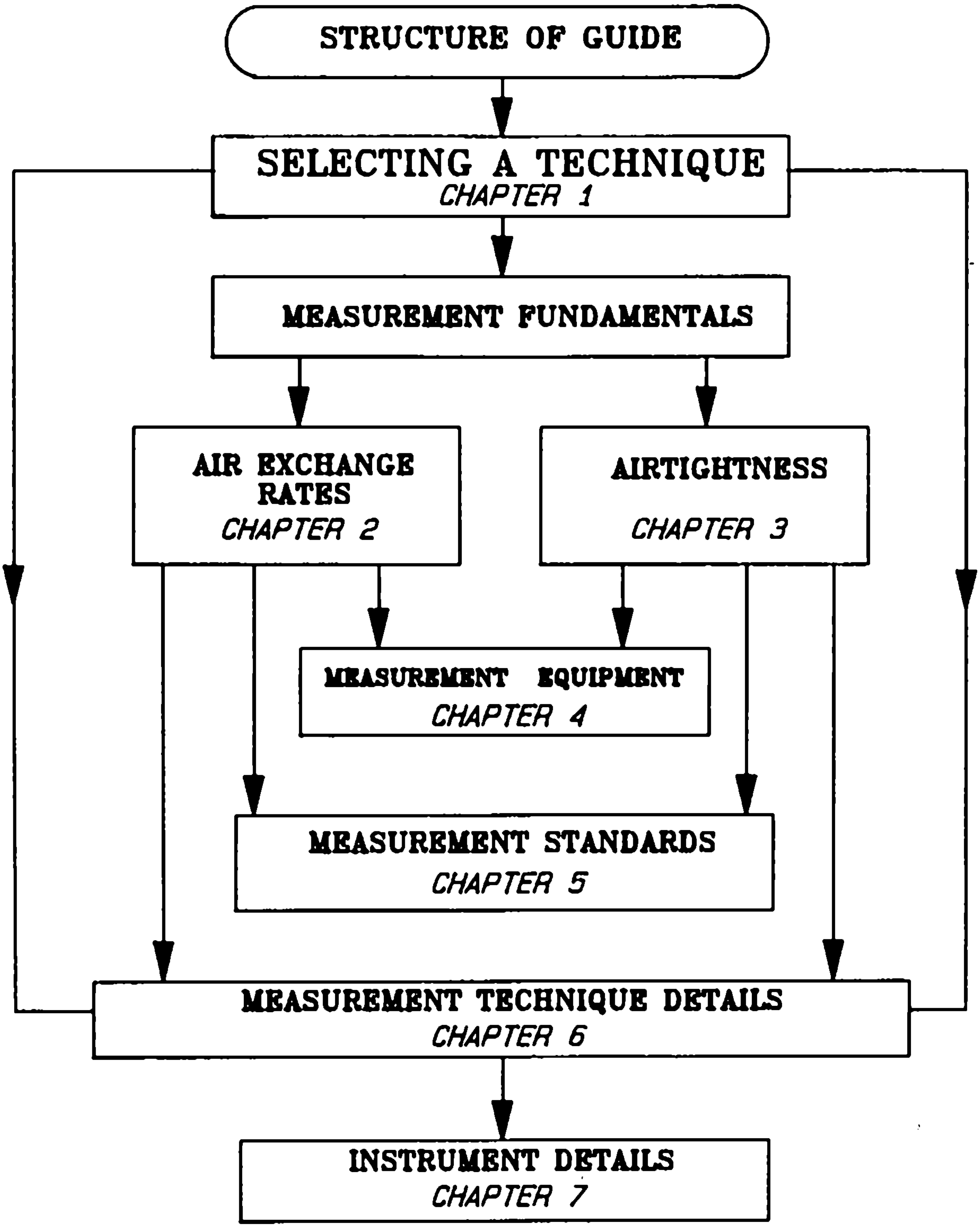


Figure 1 Scope and Structure of the Guide

TABLE 1.2.2. APPLICATION OF MEASUREMENT TECHNIQUES STANDARDS

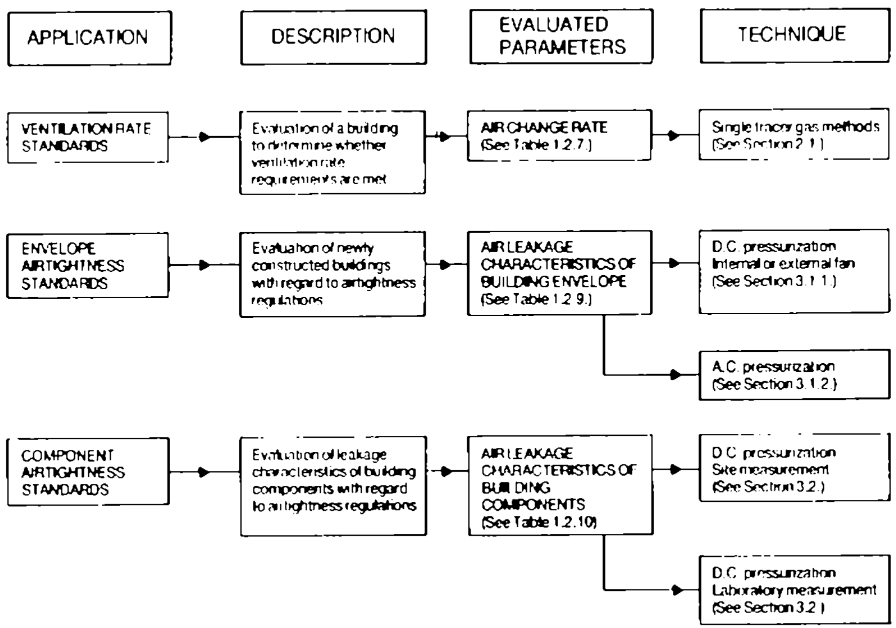


Figure 2 Example of Application and Selection Flow Chart

TABLE 1.2.8. SUMMARY OF MAIN MEASUREMENT TECHNIQUES INTERZONAL AIRFLOW METHODS

TECHNIQUE	EQUIPMENT	MEASURED QUANTITIES	FACTORS AFFECTING SELECTION
MULTIPLE TRACER GAS DECAY RATE (Further details in Section 2.2.)	*ESSENTIAL* Tracer gases Gas analyser Gas injection device Air sampling tubes and pump Zone selection device Mixing fans Chart recorder *OPTIONAL* Microcomputer	Concentration of each tracer gas in each zone Time (continuous) Zone volumes	Provides detailed information about instantaneous internal air flow patterns A knowledge of complex mathematics and a high degree of operator skills are required Equipment relatively inexpensive Usual use is in research work Practical with up to four gases Computer required for analysis
MULTIPLE TRACER GAS CONSTANT EMISSION RATE PASSIVE SAMPLING (Further details in Section 2.2.)	*SITE* Liquid tracer sources Tracer gas sampling devices Watch/calendar *LABORATORY* Thermal desorber (releases tracer gas from sampling device) Gas analyser	Emission rate of each tracer into measured zone Concentration of each tracer gas in each sample device Period of measurement Zone volumes	Site equipment costs are low Site equipment can be delivered and returned by mail No detailed information about variation of air flow Useful for pollution migration studies Laboratory equipment costs are high Practical with up to four gases Computer required for analysis
MULTIPLE TRACER GAS CONSTANT CONCENTRATION (Further details in Section 2.2.)	Tracer gases Gas analyser Gas injection and control devices Gas flow meters Zone selecting device Microcomputer Control software	Emission rate of each tracer into measured zone Concentration of each tracer in each zone Time (continuous) Zone volumes	Provides detailed continuous information about internal airflow patterns Highly sophisticated and expensive technique Practical with up to eight gases

Figure 3 Example of Measurement Techniques Summary Table

AIR INFILTRATION AND VENTILATION CENTRE
MEASUREMENT TECHNIQUES WORKSHOP 1988

Køge, Denmark
21-23 March 1988

PAPER 2

INTERNATIONAL STANDARDS ORGANISATION DRAFT PROPOSAL : DP 9972 MEASUREMENT OF BUILDING AIR TIGHTNESS USING FAN PRESSURIZATION

Presented by PETER WARREN
Building Research Establishment
Watford, UK

Contents

1 INTRODUCTION

The fan-pressurization method produces a result that characterizes the air tightness of the building envelope or parts there of. It can be used: (1) to compare the relative air tightness of several similar buildings or building components, (2) to identify the leakage sources and rates of leakage from different components of the same building envelope, and (3) to determine the air leakage reduction for individual retrofit measures applied incrementally to an existing building or building components. This method does not measure the air infiltration rate of a building. The results of the fan-pressurization test can be used to estimate the air infiltration by means of calculation. If a direct measurement of the air infiltration is desired, other methods must be used. It is better to use the fan-pressurization method for diagnostic purposes and measure the absolute infiltration rate with the tracer dilution method.

2 SCOPE

This standard addresses the use of mechanical pressurization or depressurization of a building or building component. It describes techniques for measuring the resulting air flow rates at given indoor-outdoor static pressure differences. From the relationship between the air flow rates and pressure differences, the air leakage characteristics of a building envelope can be evaluated.

This standard is applicable to small temperature differentials and low-wind pressure conditions. For tests conducted in the field, it must be recognized that field conditions may be less than ideal. Nevertheless, strong winds and large indoor-outdoor temperature differentials should be avoided. The proper use of this standard requires a knowledge of the principles of air flow and pressure measurements.

This standard is intended for the measurement of the air tightness of building envelopes of single zone buildings. For the purpose of this standard, many multi-zone buildings can be treated as single zone buildings by opening interior doors or by inducing equal pressures in adjacent zones.

This standard is intended for the measurement of the air tightness of buildings and building components in the field. It does not address the laboratory evaluation of the air leakage through individual components. The results of the field measurements are not intended to characterize the air leakage of an isolated component but the air leakage of the component and its junction with the building envelope under given conditions of installation.

3 DEFINITIONS

The terms used in this standard are in accordance with ISO 7345. The following terms are specific to this standard:

<u>air-leakage rate</u> - the air flow rate across the building envelope or component. Note: This movement includes flow through joints, cracks, and porous surfaces, or combination thereof induced by the air moving equipment used in this standard (see Section 4) (usually expressed in m^3/s).

<u>building envelope</u> - the boundary or barrier separating the interior volume of a building from the outside environment. Note: For the purpose of this practice, the interior volume is the deliberately conditioned space within a building, generally not including the attic space, basement space, and attached structures, unless such spaces are connected to the heating and air conditioning system, such as a crawl space plenum.

4 APPARATUS

The following description of apparatus is general in nature. Any arrangement of equipment using the same principles and capable of performing the test procedure within the allowable tolerances is permitted.

Required Equipment (see Figure 1):

Air-Moving Equipment - A device that is capable of inducing a specific range of positive and negative pressure differences across the building envelope or component. The system shall provide constant air flow at each pressure difference for the period required to obtain readings of air flow rate. In large buildings, the HVAC systems can be used.

Pressure- Measuring Device - An instrument capable of measuring pressure differences with an accuracy of ± 5 percent of reading.

Air Flow Measuring System - A device to measure air flow within ± 5 percent of the reading.

Temperature-measuring Device - An instrument to measure temperature to an accuracy of ± 1 K.

Optional Equipment

Wind Measuring Device
Barometer
Humidity measuring device
Leakage detection equipment

5 MEASUREMENT PROCEDURE

5.1 Building Envelope

The following is the procedure for the whole building air tightness test:

All interconnecting doors (except for cupboards and closets -- which should be closed) in the conditioned space shall be opened such that a uniform pressure will be maintained within the conditioned space to within a range of less than 10 percent of the measured inside/outside pressure difference. This condition shall be verified by selected differential pressure measurements throughout the structure at the highest pressure contemplated.

Note: Good practice would require measuring pressures induced in adjoining spaces such as the attic and basement.

Note: The building should be prepared in accordance with the purpose of the test. Thus the opening, closing or sealing of specific openings such as vent dampers and fireplace openings should be done in accordance to whether it is the intention of the test to include these openings in the definition of the tightness of the building envelope.

HVAC balancing dampers and registers should not be adjusted. Fireplace and other operable dampers should be closed unless they are used to pass air to pressurize or depressurize the building.

Make general observations of the condition of the building. Take notes on the windows, doors, opaque walls, roof, and floor.

Measure outdoor temperatures at the beginning and the end of the test. Record the wind speed using either the Beauford scale or a nearby weather station.

Measure and record the indoor temperature at the beginning and the end of the test so that their average values can be estimated. If the product of the indoor/outdoor air temperature difference in degrees Kelvin and the building height in meters is greater than 200, do not perform the test since the pressure difference induced by the stack effect is too large to allow accurate interpretation of the results.

Connect the air moving equipment to the building envelope, using a window, door, or vent opening. Insure that any leakage at the joints of the equipment and the building are sealed.

Note: In an air tight building, it is possible that the door, window or vent used to pass air during the test is the most important leakage. One should be careful in such a case with regard to the selection of the position of the air moving equipment and/or the interpretation of the test results. Temporarily cover the opening used by the air moving equipment for moving air into or out of the building.

Zero the pressure measuring device by connecting the sample port to the reference port and adjust the zero so that the device indicates zero.

Install the pressure measuring device across the building envelope at any convenient representative location. Measure the zero flow pressure difference across the building envelope induced by natural conditions with the air moving equipment off and covered.

Note: Good practice dictates that the pressure difference be measured close to the neutral plane in the building. This is important only for tall buildings or large temperature differences.

Record the zero flow pressure reading. If the absolute value of the zero flow pressure reading is greater than 3 Pa, do not perform the test. Record induced flows only for induced pressure difference 10 times greater than the zero flow pressure difference.

Uncover and turn on the air moving equipment.

Note: When the building is depressurized air leakage sites can be located using infrared thermography in accordance with ISO Standard 6781, "Thermal Insulation - Qualitative detection of thermal irregularities in building envelopes - Infrared method".

Under no circumstances should unsafe, hazardous or uncomfortable conditions be created by the air moving equipment for the building, its contents or its occupants.

The range of the induced pressure difference shall be from 10 times the zero-flow pressure to 60 Pa depending on the capacity of the air-handling equipment. Increments of no more than 10 Pa shall be used for the full range of induced pressure differences.

Note: Since the capacity of the air handling equipment and the tightness of the building affect leakage measurements, the upper limit of 60 Pa may not be achievable. In such cases a partial range encompassing at least five data points shall be the substitute.

At each pressure difference, measure the air flow rate and the pressure difference across the envelope.

For each test, collect data for both pressurization and depressurization.

Repeat the zero-flow pressure difference measurement. If this reading differs from the last zero-flow pressure difference reading by more than 1 Pa, repeat the test.

5.2 Building Components

The component to be tested (for example a door, window, wall section, wall-to-wall or wall-to-floor joint) is covered with an air tight enclosure. This enclosure can be a plastic sheet carefully taped to the component's edges or a specially built box. The air moving equipment, including the air flow measuring device, and the pressure measuring device are connected to the air tight enclosure such that all the air delivered by the air moving equipment passes through the component when the enclosure is pressurized or depressurized.

Note: It is also possible to determine the leakage of a component without an air tight enclosure by performing the test once with the component sealed and again with the component not sealed. The flow at any pressure difference is then the difference between the flow with the component unsealed and the flow with the component sealed. If the flow difference can be determined within ± 5 %, this variant is acceptable.

The steps in this procedure are:

Cover the component to be tested with the air tight enclosure and seal the edges of the enclosures to the boundary of the component being tested.

Note the limits of the tested area and the characteristics of the tested component.

Pressurize the enclosure and component to 100 Pa and check for possible leaks using accepted methods such as smoke, an ultrasonic meter or tracer gas. Eliminate the observed leaks.

Turn off the air moving equipment and temporarily cover the opening used to pressurize the enclosure.

Zero the pressure measuring device by connecting the sample port to the reference port and adjust the device so that it indicates zero.

Install the pressure measuring device across the enclosure and measure the zero-flow pressured induced by natural conditions with the air moving equipment off. If the absolute value of the zero-flow pressure difference is greater than 3 Pa, do not perform the test.

The test is carried out by varying the applied pressure in increments of no more than 10 Pa from a differential pressure of 10 times the zero-flow pressure to 60 Pa. At each pressure record the pressure difference across the component in Pa and the air flow rate in m^3/s.

Note: Since many national laboratory pressure testing of building components is often done at higher pressure differences, it may be desirable to include such pressures in field pressurization tests if one wants to compare the results of the field testing with the laboratory results. However it should be noted that for any components the response of the component is nonlinear and care should exercise in including these data points in any subsequent data analysis.

Note: When the enclosure is transparent in the infrared (2-5 microns or 8-12 microns) and depressurized above 10 Pa, an infrared thermographic system with a window in the appropriate microns range can be used to locate the air leakage sites of the component.

Note: If possible, perform the test for both positive and negative pressures.

Record the indoor and outdoor air temperatures before and after the test.

Turn off the air moving equipment and measure the zero-flow pressure difference. If this reading differs from the last zero-flow pressure difference by more than 1 Pa, repeat the test.

6 DATA ANALYSIS

If the air flow is not measured directly from a flow meter, then additional calculations are needed to convert the readings to volumetric flow rate, for instance, pitot tube pressure to linear velocity and then volume flow rate. In the case of a calibrated motor fan, the flow rate can be obtained through the calibration curve of the motor fan. However the fan should be used in a manner consistent with the calibration method.

Convert the readings of the flow measuring system to volumetric air flows, Q, at the temperature and pressure of the outside air for depressurization tests or of the inside air for pressurization tests.

Subtract the average zero-flow pressure difference dP_o from the measured pressure difference dP_m to obtain the induced pressure difference dP:

$$dP = dP_m - dP_o$$

Plot the measured air leakage against the corresponding pressure differences on a log-log plot to complete the air leakage graph for both pressurization and depressurization (see Figure 3).

Derived Quantities:

The data shall be used to determine the coefficients *C* and *n* in the following equation:

(1) $$Q = C(dp)^n$$

using a least square technique, where *Q* is the flow rate in m^3/s and *dP* is the differential pressure in Pascals. In determining the fit of the above equation, the confidence intervals of the two derived coefficients *C* and *n* should be calculated.

Correct the coefficient *C* to standard conditions (20°C and 1.013×10^5 Pa)

(2) $$C_o = C\left(\frac{\mu}{\mu_o}\right)^{2n-1} \cdot \left(\frac{\rho}{\rho_o}\right)^{1-n}$$

where μ is the dynamic viscosity of air and ρ is the air density. The unsubscripted quantities refer to the values at the conditions of the test, the subscripted quantities at the standard reference conditions.

The effective leakage area in m², A_L, can be calculated from the leakage coefficient, C, the exponent n, a reference pressure, dP_r from the equation:

$$A_L = C_o \left(\frac{\rho_o}{2} \right)^{\frac{1}{2}} (dP_r)^{\left(n - \frac{1}{2}\right)} \quad (3)$$

The conventional reference pressure is 4 Pa, but other values may be used if the value is included in the report section.

Note: The leakage area derived by equation 3 corresponds to a physical area if the discharge coefficient of the leakage is 1.

If the flow at a specified pressure difference is desired (such as 50 Pa) then it should be determined form equation (1) using the derived C and n and the specified pressure difference. The error in the calculated flow should also be determined statistically from the data used to determine equation (1).

7 REPORT FORMAT

The report shall contain at least the following information:

A. Description of the Test Specimen:

Building

1 Location

2 Date built (estimate if unknown)

Building Envelope Tightness Test

3 Floor area of conditioned space

4 Volume of conditioned space

5 Other building data required to obtain derived results (such as the envelope area if envelope tightness per unit area is required)

6 Condition of openings in exterior shell:

(a) Doors(including storm doors) -- locked or unlocked

(b) Windows (including storm windows) -- latched or unlatched,

(c) Ventilation openings -- dampers closed opened or sealed,

(d) Chimneys -- dampers closed, opened or sealed,

(e) Condition of other openings during test (for example, broken windows, HVAC damper and louver settings, etc.).

7 HVAC System:

(a) Furnace

(b) Blower capacity, and

(c) Duct location.

Component Test

8 Component Description with diagram

9 Area of measured surface

10 List of materials

11 Component Location in building envelope

12 Component age

13 Other pertinent information

B. Test Equipment
1 Technique employed
2 Equipment used,

C. Test Data
1 Date of test
2 Times of beginning and end of test
3 Table of induced pressure differences and corresponding air flows
4 Inside and outside temperatures
5 Atmospheric pressure (can be determined from altitude)
6 Wind speed (weather station or estimate from Beauford scale

D. Plot of air leakage graph(s) (see Figure 3).

E. The leakage coefficients C and C_o and exponent for both pressurization and depressurization determined by the method given in Section 6 along with their confidence limits. The leakage coefficient and exponent can be used to calculate the flows at the other pressures.

F. Other derived quantities such a leakage area and building air tightness at a given pressure should be reported if required.

For any derived quantity, an estimate of the confidence interval shall be included in the data analysis.

8 ACCURACY

The accuracy of this procedure largely dependent on the instrumentations and apparatus used and on the ambient conditions under which the data are taken.

It is more precise to take data at higher pressure differences than at lower differences. Therefore, special care should be exercised when measurements are taken at low pressure differences.

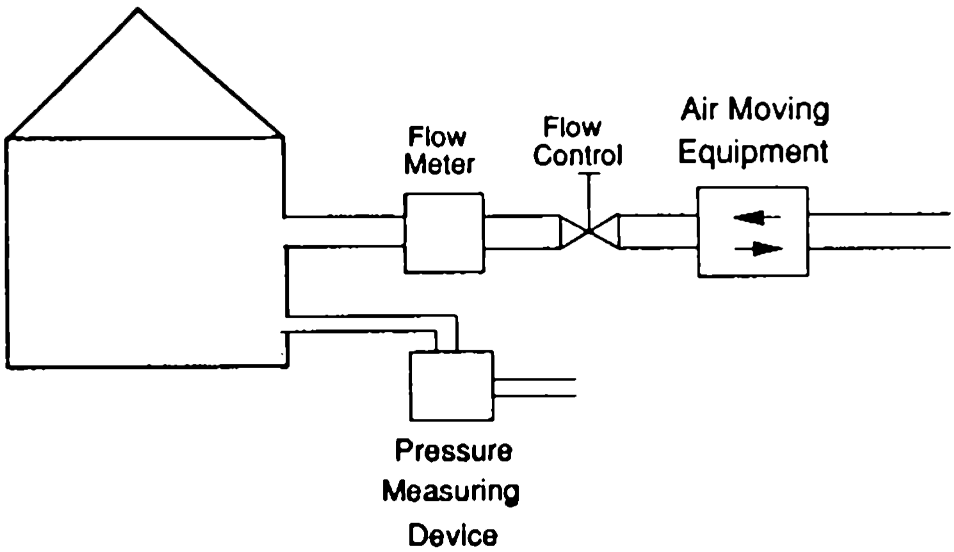


Figure 1. Schematic Layout of Equipment for Whole Building Test

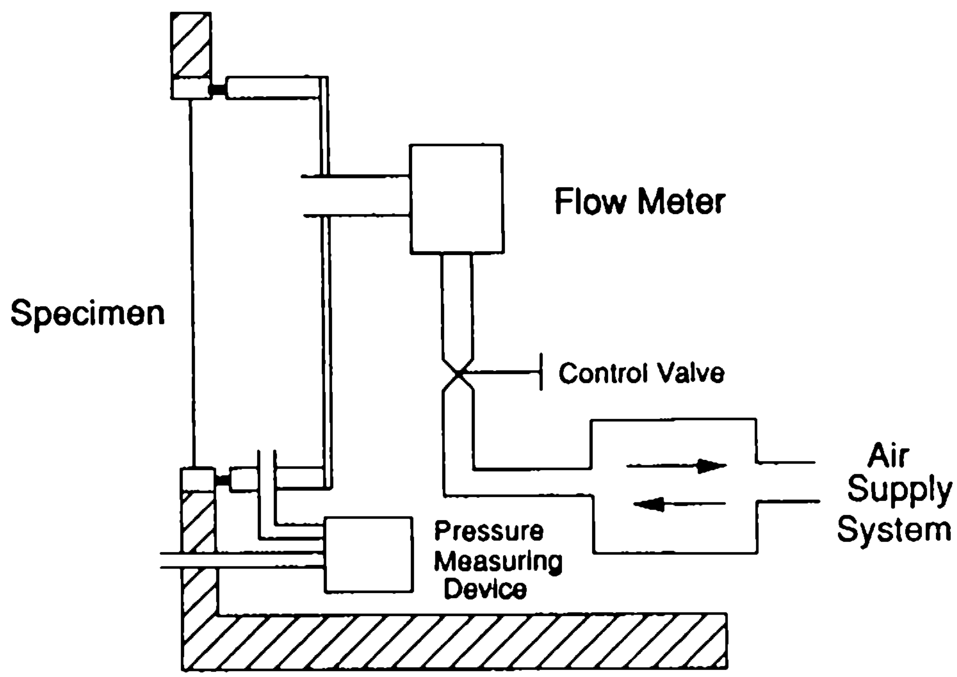


Figure 2. Schematic Layout of Equipment of Component Air Tightness Test Using a Pressurized Enclosure

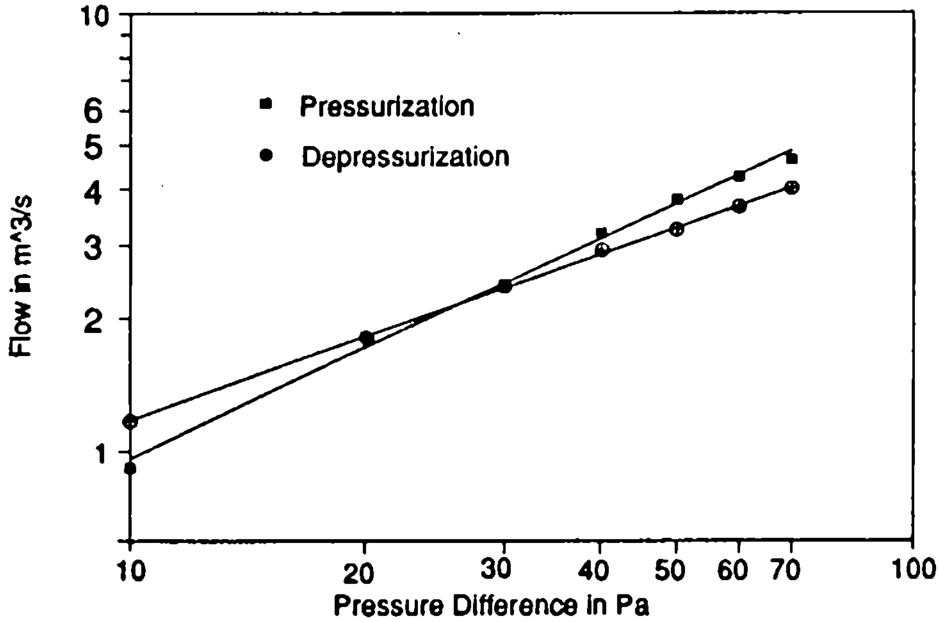


Figure 3. Sample of Air Leakage Graph

Annex 1

Description of Equipment Used to Pressurize Buildings

There are several ways to pressurize the building envelope. The three most common are:

Fan and Duct System

The size of the air duct and the capacity of the fan or blower shall be matched so that the linear flow velocity within the air duct falls within the range of measurement of the air flow meter.

Blower Door

A blower door assembly is an accepted method in many countries for performing envelope tightness measurements. Components peculiar to this assembly are:

Blower Door - A door mount for fan or blower. It must be adjustable to fit common door openings

The fan or blower should possess a variable-speed motor to accommodate the range of required flow rates. In order to conform to this standard, a blower door assembly must be calibrated to produce flow measurements to the accuracy specified in section 4 for air flow measuring systems.

Building HVAC System Fans

For determining the air tightness of large buildings, it is possible to use the building ventilation system fans for pressurization and depressurization of the building. Since it is often difficult to satisfy accepted criteria for air flow measurements in ducts in an actual building HVAC system, the air flow can be determined by using a constant injection of tracer into the airstream entering or leaving the building. The air flow is determined by

$$Q = \frac{q}{c}$$

where Q is the air flow rate, q is the tracer gas injection rate and c is the tracer gas concentration.

Annex 2

Dependence of Air Density and Viscosity on Temperature, Dew Point and Barometric Pressure

The air density ρ in kg/m³ at temperature T in degrees C, barometric pressure P_{bar} in Pascals. and dew point θ in degrees C can be obtained by the equation:

$$\rho = \frac{334.4}{273.13 + T}\left(\frac{P_{bar} - P_w}{101332}\right)$$

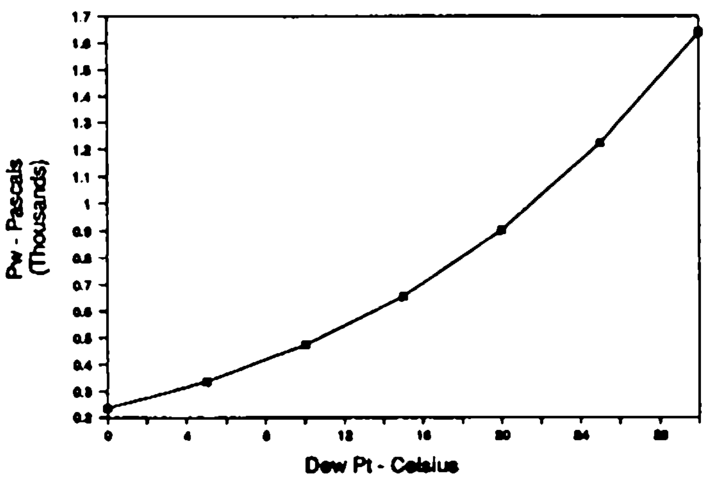
where P_w is a function of the dew point temperature θ.

θ	P_w
0 °C	235.1 Pa
5 °C	335.7 Pa
10 °C	473.0 Pa
15 °C	657.8 Pa
20 °C	902.5 Pa
25 °C	1223.3 Pa
30 °C	1637.8 Pa

Table A2.1 P_w in Pa versus Dew Point Temperature θ in °C

The dynamic viscosity μ in kg/(s•m) at a temperature T in °C can be obtained from the equation

$$\mu = 17.2 + 0.0519T \qquad \text{(A2.2)}$$



P_w versus Dew Point Temperature

Annex 3

An Acceptable Method for Estimating Errors in Derived Quantity

This standard contains several derived quantities which are often use to summarize the tightness of the building or component tested. It is important to report an estimate of the error in such quantities. There is no one method to do this and the problem is more complicate that it appears. The following is an acceptable method: all derived quantities depend on the estimation of the coefficients *C* and *n* of eq. 3. To determine *C* and *n*, make a log transformation of the variables *Q* and *dP* for each reading.

$$x_i = \ln(dP_i)$$

$$y_i = \ln(Q_i) \qquad \text{for i = 1 .. N}$$

where *N* is the total number of test readings. Eq. 3 then transforms into

$$y = \ln(C) + n \cdot x \qquad \text{(A3.1)}$$

Compute the following quantities

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad \text{(A3.2)}$$

$$\bar{y} = \frac{1}{N}\sum_{i=1}^{N} y_i \qquad \text{(A3.3)}$$

$$S_x^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2 \qquad \text{(A3.4)}$$

$$S_y^2 = \frac{1}{N-1}\sum_{i=1}^{N}(y_i - \bar{y})^2 \qquad \text{(A3.5)}$$

$$S_{xy} = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y}) \qquad \text{(A3.6)}$$

Then the best estimate of *n* and *ln(C)* are given by:

$$n = \frac{S_{xy}}{S_x^2} \qquad \text{(A3.7)}$$

$$\ln(C) = \bar{y} - n \cdot \bar{x} \qquad \text{(A3.8)}$$

$$C = \exp^{(\bar{y} - n \cdot \bar{x})} \qquad \text{(A3.9)}$$

An estimate of the confidence intervals of *C* and *n* can be determined as follows:

The variance of *n* is given by the estimate

$$S_n = \frac{1}{S_x}\left(\frac{S_y^2 - n \cdot S_{xy}}{N-2}\right)^{\frac{1}{2}} \qquad \text{(A3.10)}$$

and the estimate of the variance of *ln(C)* is given by

$$S_{ln(C)} = S_n \left(\frac{\sum_{i=1}^{N} x_i^2}{N}\right)^{\frac{1}{2}} \qquad \text{(A3.11)}$$

If *T(p,N)* is the significance limit of the two-sided Student distribution for a probability *p* on *N* events, then the confidence interval at that probability for *ln(C)* and *n* are respectively:

$$I_{ln(C)} = S_{ln(C)} T(p,N-2) \qquad \text{(A3.12)}$$

$$I_n = S_n T(p,N-2) \qquad \text{(A3.13)}$$

The values of the two-sided student distribution are given in Table A3.1.

This means that with a probability *p* the coefficient *n* lies in the interval $(n-I_n, n+I_n)$ and the coefficient *C* lies in the interval

$$\left(C \cdot \exp^{-I_{ln(C)}}, C \cdot \exp^{I_{ln(C)}}\right)$$

The estimate of the variance around the regression line (A3.1) at the value x is

$$S_y(x) = S_n \left\{\frac{N-1}{N} S_X^2 + (x - \bar{x})^2\right\}^{\frac{1}{2}} \qquad \text{(A3.14)}$$

and the confidence interval in the estimate of *y* using A3.1 at any *x* is

$$I_{y(x)} = S_y(x) T(p,N-2) \qquad \text{(A3.15)}$$

Therefore the flow *Q* predicted by eq. (1) at any pressure difference *dP* lies in the interval

$$\left(Q \cdot \exp^{-I_{y(ln(dP))}}, Q \cdot \exp^{I_{y(ln(dP))}}\right)$$

with a probability *p*.

It is this interval that should be used to estimate the error in the equivalent leakage area or the the flow across the building or component at a reference pressure (for example 50 Pa). For example the confidence interval of the estimate of the leakage area A_L using eq. 3 is

$$\left(A_L \cdot \exp^{-I_{y(ln(dP_r))}}, A_L \cdot \exp^{I_{y(ln(dP_r))}}\right)$$

with a probability *p*.

p	0.8	0.9	0.95	0.99	0.995	0.999
N						
1	3.078	6.3138	12.706	63.657	127.32	636.619
2	1.886	2.9200	4.3027	9.9248	14.089	31.598
3	1.638	2.3534	3.1825	5.8409	7.4533	12.924
4	1.533	2.1318	2.7764	4.6041	5.5976	8.610
5	1.476	2.0150	2.5706	4.0321	4.7733	6.869
6	1.440	2.0150	2.5706	4.0321	4.7733	6.869
7	1.415	1.8946	2.3646	3.4995	4.0293	5.408
8	1.397	1.8595	2.3060	3.2498	3.6897	4.781
9	1.383	1.8331	2.2622	3.2498	3.6897	4.781
10	1.372	1.8125	2.2281	3.1693	3.5814	4.587

Table A3.1 Two-Sided Confidence Limits T(p,N) for a Student Distribution

Discussion

W de Gids (Netherlands)
: In the standard is the measured zone precisely defined?

P Warren (UK)
: No. The standard addresses how to measure, but leaves National standards to define what to measure.

AIR INFILTRATION AND VENTILATION CENTRE
MEASUREMENT TECHNIQUES WORKSHOP 1988

Køge, Denmark
21-23 March 1988

PAPER 3

AIR INLET PERFORMANCE

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SYNOPSIS

This paper discusses the performance of air inlets in residencies equipped with mechanical extract ventilation. The discussion is based around a proposal for the approval rules for the flow and sound technical characteristics of the air inlets and tests made for some air inlets marketed in Finland. The paper concludes that controlled outdoor air intake is possible only in a tight house.

1. INTRODUCTION

Controlled outdoor air intake in residencies is required in the revised National Building Code of Finland, Part D2, The Indoor Climate and Ventilation /2/. As the requirement will increase the use of outdoor air inlets in mechanical extract ventilation systems, The Laboratory of Heating and Ventilation tested some air inlets marketed in Finland. On the basis the tests also a proposal was made for the approval rules of the flow and sound insulation characteristics /3/ of the air inlets.

The approval of air inlets will be taken into use probably in 1988, and it includes the measurement of the air flow, draughtlessness, sound insulation and sensitivity to condensation and frost formation. Applications for the approval will be sent to the Ministry of Environment and the Laboratory of Heating and Ventilation makes the required measurements.

This contribution will treat the measurements required for the type approval and laboratory tests which were made on some air inlets marketed in Finland in 1986. The planning of the outdoor air intake of a detached house will be also treated as an example.

2. THE CHARACTERICTICS OF AIR INLETS INCLUDED IN APPROVAL

2.1 Air flow

The approval includes measurement of the air flow-pressure difference curve within the pressure difference range 3 - 30 Pa. The air flow of the air inlet is measured by using different openings of the air inlet with a test arrangement shown in figure 1.

2.2 Draughtlessness

The approval decision of an air inlet presents the biggest draughtless air flow obtained at the outdoor air temperature of 0 and -20 °C. The draught at the occupied zone is judged according to figure 2.

Outside temperatures of 0 ja -20 °C are relatively common in Finland. For example, in southern Finland (Helsinki) the frequency of the outside temperature interval -5.9 °C to +5.9 °C is about 42 % in a year, and the frequency of outside temperatures below -18 °C is about 2 %.

The pressure difference between outside and inside air in the draughtlessness tests is 5 - 20 Pa corresponding to the usual pressure differences in residencies equipped with a mechanical extract ventilation system. The tests for adjustable air inlets are made with fixed pressure differences, primarily 5 and 10 Pa. Besides, the biggest draughtless air flow can be measured at the pressure difference of 20 Pa.

In the test room (figure 3) there is an outdoor air simulating cooling chamber behind the window. The temperature of the cooling chamber and the pressure difference between the room and the cooling chamber are adjustable as well as the volume and the temperature of the air led to the air inlet. When the temperature of the outdoor air is -20 °C, the heating efficiency needed to warm up the outdoor air to the room temperature is set on the radiator. When the temperature of the outside air is 0 °C, the radiator is closed, because that kind of situation can appear in practice when a radiator controlled by a thermostat is used.

2.3 Sensitivity to condensation

The approval decision will present the observations of condensation, frost formation and dripping water corresponding to the outside air flow used in the condensation test. An estimation of which constructions are exposed to moisture will be made.

During the test the relative humidity of the test room is regulated to 30 %. The outdoor temperature is -20 °C and the outdoor air flow is the biggest draughtless air flow obtained at the outside temperature of -20 °C. During the test condensation or frost formation on the air inlet and dripping water will be observed. The duration of the test is at least five hours.

2.4 Sound insulation

The approval decision will present the sound insulation values of the air inlet measured according to the method Nordtest ACOU 037. The sound insulation describes how much outdoor noise comes inside through the air inlet.

3 TESTS MADE FOR THE AIR INLETS

3.1 Tested air inlets

Some air inlets of different kind marketed in Finland in 1986 were gathered to the tests /1/. Ten tested air inlets were:

- a ventilation window equipped with a filter 1
- ordinary air inlet 6

- air inlet connected to the radiator 1
- air inlet connected to the window frame 2

According to the brochures some of the air inlets tested can be mounted e.g both behind the radiator and above the window.

The air flow and draughtlessness of the air inlets were defined approximately according to the foregoing proposed approval rules. The observations of condensation were made only during the draughtlessness tests without regulating the relative humidity of the test room. The sound insulation was not measured.

3.2 Air flow rate

Table 1 shows the air flow rate obtained through some in Finland marketed air inlets at the pressure difference of 10 Pa.

One half of the tested air inlets were such that not even the fresh air flow of 4 dm^3/s needed for one person was obtained at the pressure difference of 10 Pa. The air inlets are too tight for the usual pressure differences in residencies. Air inlets, which did not give even 4 dm^3/s, were left out of the rest of the tests.

3.3 Draughtlessness

The draughtless air flows for different air inlets were 1.4 - 5.9 dm^3/s at the outdoor air temperature of -20 °C and 2.6 - 5.9 dm^3/s at the outside temperature of 0 °C. The biggest obtained draughtless air flow can supply the need of fresh air for 1.5 persons.

3.4 Sensitivity to condensation

On the all tested air inlets appeared water drops at the outside temperature of -20 °C. The relative humidity of the test room changed from 27 to 43 %; that is why the tests made for different air inlets can not be compared.

4 AN EXAMPLE OF PLANNING THE OUTDOOR AIR INTAKE OF A DETACHED HOUSE

In planning the outdoor air intake we must take into account that all the outdoor air flow of the house can not be obtained through air inlets. The tightness of the house and the pressure difference between outside and inside air determine the air flow obtained through the air inlets according to the next formula

$$n_a = n - n_i \quad , \text{ also}$$

$$n_a = n - n_{50} \quad \left(\frac{\Delta p_v}{50 \text{ Pa}}\right) \quad , \text{ in which}$$

n_a = air flow rate obtained through the air inlets, 1/h
n = planned air change rate, 1/h
n_i = infiltration rate, 1/h
n_{50} = air leakage at the pressure difference of 50 Pa, 1/h
Δp_v = pressure difference over the building envelope, Pa
N = leakage exponent, which varies from 0.5 to 1.0.

In the next examples to the leakage exponent has been given the value n = 0.7, which is common in practice.

The pressure difference over the building envelope can not hardly be lower than 5 Pa, because wind and temperature differences change the air flow according to the room. The infiltration rate of a usual detached house (air leakage n_{50} = 3 1/h) at the pressure difference of 5 Pa is 0.6 1/h, and the air infiltration rate of a tight house (air leakage n_{50} = 1 1/h) is 0.2 1/h. If the total planned air change rate is 0.5 1/h, it will be exeeded in a usual house already by the air infiltration rate. In a tight house the difference between the planned air change rate and infiltration rate 0.3 1/h, which is 60 % of the total air flow rate, can be obtained through the air inlets. If the pressure difference is bigger than 5 Pa, the air flow share obtained through the air inlets will be even smaller.

The floor area of the example building is 100 m^2 and the volume is 250 m^3. The planned air change rate is 0.5 1/h. When the pressure difference over the building envelope is 5 Pa, the air flow rate obtained through the air inlets is 20 dm^3/s. It can be divided into bedrooms, e.g 8 dm^3/s, 6 dm^3/s and 6 dm^3/s.

5 SUMMARY

The approval of the air inlets used in mechanical extract ventilation systems will include the measurement of the air flow, draughtlessness, sensitivity to condensation and sound insulation of the air inlets. The measurements of draughtlessness and sensitivity to condensation are made in a test room, which is aimed at simulating the use conditions of the air inlets.

No performance requirements are required for the approval of the air inlets, e.g concerning air flow rate or draughtless operation. The approval decision will present the air flow-pressure difference curve, the biggest obtained draughtless air flows at the outside temperature of 0 and -20 °C valued according to the draught curves in the National Building Code of Finland /2/, the observations made in condensation tests of the possible water dropping and the sound insulation values of the air inlet.

Ten different air inlets marketed in 1986 in Finland were tested in nearly the same test conditions as required by the approval proposal. The biggest draughtless air flow obtained in draughtlessness tests was 5.9 dm^3/s ($t = -20$ °C, $\Delta p = 10$ Pa).

The air flow rate obtained through the air inlets depends on the planned air change rate, tightness of the building envelope and the pressure difference over the building envelope. In an untight house the air infiltration rate often exeeds the planned air change rate. Only in a tight house can the air inlets be dimensioned and chosen for instance according to the draughtlessness tests.

The approval of air inlets is also used in Sweden /4/ and also there the above mentioned characteristics of the air inlets are tested. The methods are not exactly similar in Sweden and Finland. Besides, in Sweden requirements are set for the outer characteristics of the air inlets, which in Finland are not touched.

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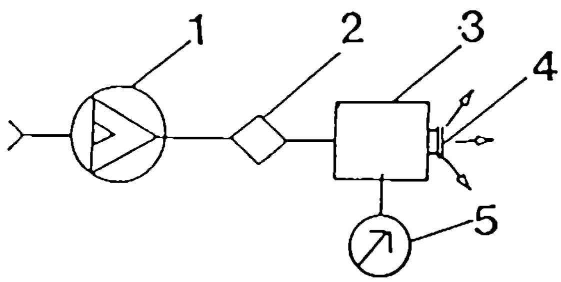

Figure 1. Test arrangement of the air flow rate measurements. /3/

1	adjustable fan
2	air flow rate meter
3	balancing box of air flow
4	test air inlet
5	pressure difference meter

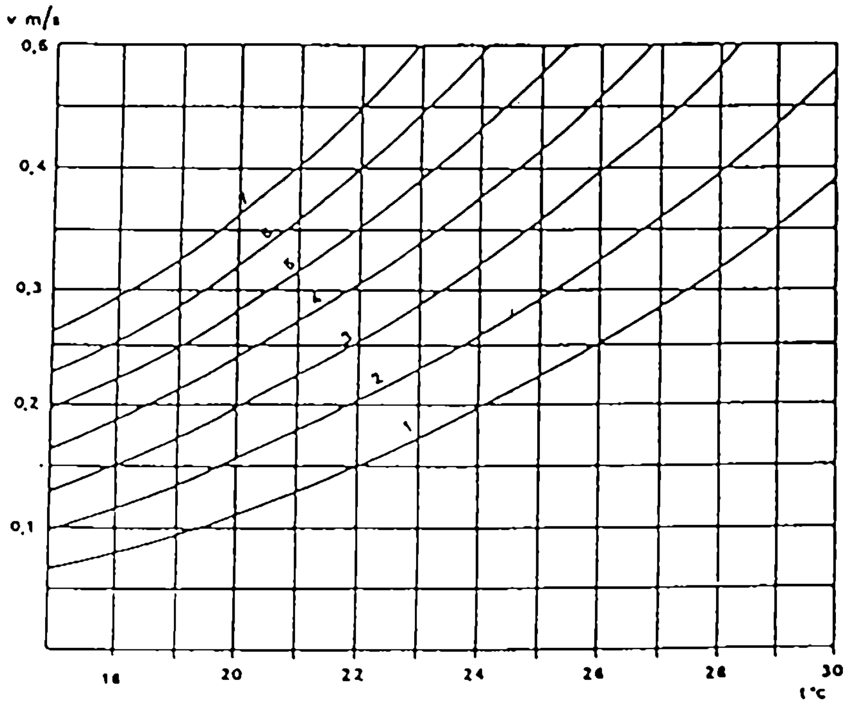

Figure 2. Draught curves for maximum air velocity /2/. Curve 2 is applied for dwelling rooms.

v = maximum velocity of the air
t = air temperature

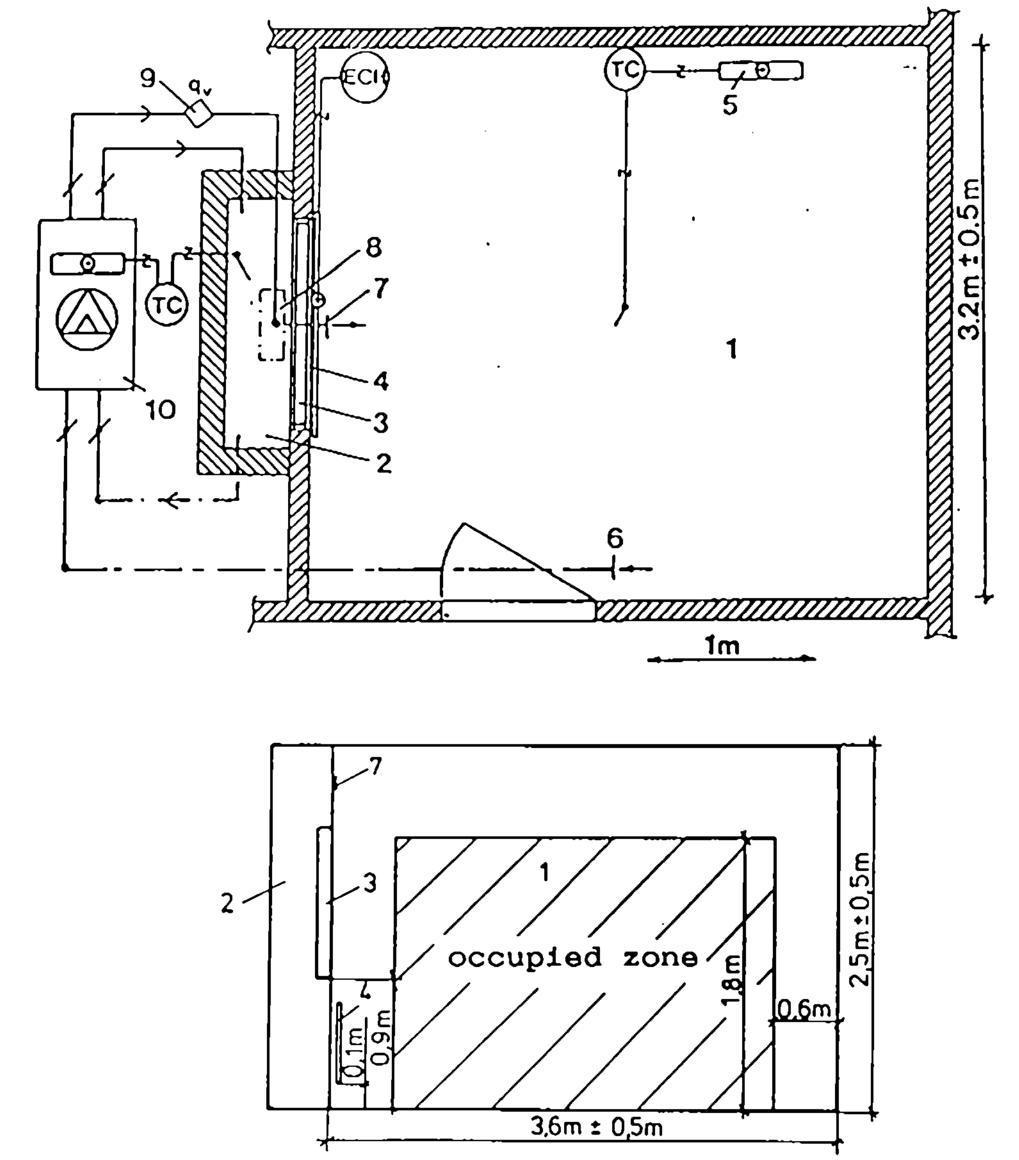

Figure 3. The test room for the draughtlessness tests for the air inlets. /3/

1	test room
2	cooling chamber
3	window 1.2 m x 1.2 m
4	radiator 0.6 m x 1.3 m
5	heater
6	air outlet
7	test air inlet
8	balancing box of air flow
9	air flow rate meter
10	refigerating machine
TC	air temperature controller
ECH	adjustable transformer

Table 1. The air flow rate of air inlets when the pressure difference Δp=10 Pa and the flow function $q=k\Delta p^n$. /1/

Air inlet	Opening	Filter	q_v dm^3/s (Δp=10 Pa)	k $\frac{dm^3}{s\ Pa^n}$	n
VENTILATION WINDOW					
ALLERCO-VENTILATION WINDOW 1)	opening 1/1	F	9,8	1,10	0,95
	opening 2/3	F	7,6	0,85	0,95
	opening 1/3	F	4,8	0,54	0,95
ALLERCO-VENLTILATION WINDOW 1)	opening 1/1	G	36,7	4,7	0,88
	opening 2/3	G	26,6	3,5	0,88
	opening 1/3	G	14,8	2,0	0,87
ALLERCO-VENTILATION WINDOW 1)	opening 1/1	E+g	7,8	1,15	0,83
	opening 2/3	E+g	6,2	0,91	0,83
	opening 1/3	E+g	3,7	0,54	0,83
ORDINARY AIR INLETS					
FRESH 30	fully opened	no	7,3	2,0	0,56
FRESH 80	fully opened	yes	5,5	1,5	0,56
SPV-10	fully opened	yes	3,5	0,85	0,61
RIV	fully opened	yes	2,2	0,81	0,59
VM-100	fully opened	yes	3,2	0,57	0,59
ALLERCO-BOX	fully opened	yes	4,9	1,4	0,55
AIR INLETS CONNECTED TO THE RADIATOR					
PAM-V,"STRAIGHT"	fully opened	yes	3,0	0,78	0,57
PAM-V,"CURVE"	fully opened	yes	2,6	0,68	0,58
AIR INLETS CONNECTED TO THE WINDOW FRAME					
BIOBE 40	opening 1/1	no	6,0	1,45	0,62
	opening 1/2	no	5,4	1,30	0,62
VM-30		yes	0,61	0,14	0,64

1) 1,18 m x 1,02 m

Table 2. The draughtlessness test of air inlets. /1/

Air inlet	Blowing direction	Installation place	Opening position	t_u = 0 °C, P = 0 W: A dm^2	Δp Pa	q_v dm^3/s	$\bar{v}$ m/s	n	Opening position	t_u = -20 °C: A dm^2	Δp Pa	q_v dm^3/s	$\bar{v}$ m/s	n	P W
ALLERCO-BOX		SE SE	10 mm 10 mm	0,25 0,25	5 10	2,6 4,0	1,0 1,6	0,36 0,39	10 mm 5 mm	0,25 0,12	5 10	2,6 2,9	1,0 2,3	0,36 0,59	125 140
FRESH 30		SE SE	10 mm 7 mm	0,73 0,51	5 10	5,0 5,9	0,69 1,2	0,23 0,28	2,5 mm 4 mm	0,18 0,29	5 10	2,2 3,1	1,2 1,1	0,42 0,26	106 152
FRESH 80		SE SE	11 mm 1) 11 mm 1)	0,45 0,45	5 10	3,5 5,9	0,78 1,3	0,27 0,32	11 mm 1) 11 mm 1)	0,45 0,45	5 10	4,3 5,9	0,80 1,3	0,35 0,32	210 283
BIOBE 40		IP IP	1/1 1/2	0,40 0,19	5,5 9,4	4,7 5,1	1,2 2,7	0,39 0,68	1/1 1/2	0,40 0,19	3,5 4,7	3,4 3,2	0,85 1,7	0,35 0,60	160 150
ALKERCO VENTILATION WINDOW F		TI TI	1/1 1/3	19,2 7,3	3,5 6,3	3,6 3,0	0,02 0,04	0,008 0,013	1/1 1/3	19,2 7,3	1,3 3,1	1,4 1,6	0,007 0,022	0,005 0,010	68 78
ALLERCO VENTILATION WINDOW E+g		TI							1/1	19,2	1,3	1,4	0,007	0,005	69

t_u outdoor air temperature
q_v maximum draughtless air flow rate
A area of blowing opening
$\bar{v}$ velocity of air in the blowing opening
Δp pressure difference between outdoor and indoor air
P efficiency of electric heater
SE in the wall above the window
IP in the window frame
TI in the opening of ventilation window
1) maximum opening
n disharging factor $\frac{q_v/A}{\sqrt{\frac{2\Delta p}{\rho}}}$, where
ρ density of supply air

Discussion

C A Roulet (Switzerland)
What criteria are used to define a draught?

M Louma (Finland)
The draught in the occupied zone is judged according to the draught curves presented in the Finnish Building Code (see Page 14 and Figure 2, Page 20).

J Kronvall (Sweden)
Where was the air extracted from the test chamber?

M Louma (Finland)
The air from the test chamber was extracted through a narrow opening below the door. The air in the cooling chamber was circulated through a refrigeration machine (see Figure 3, Page 21).

P Levin (Sweden)
Recently, many air inlet devices for use behind radiators have appeared on the market, please comment on the results you have obtained for this type of inlet.

M Louma (Finland)
One of the air inlets was tested when connected to a radiator. The air flow through the inlet was 2.6 dm^3/s at a pressure difference of 10 Pa. The flow function was:

$$q = 0.68\ (\Delta p)^{0.58}$$

This air inlet was not used in the draught tests because the air flow at 10 Pa. was less than 4 dm^3/s.

AIR INFILTRATION AND VENTILATION CENTRE
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PAPER 4

ADVANCED SINGLE FAN PRESSURIZATION

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1. INTRODUCTION

Pressurisation measurements (fig. 1) have become in many countries a common measurement.

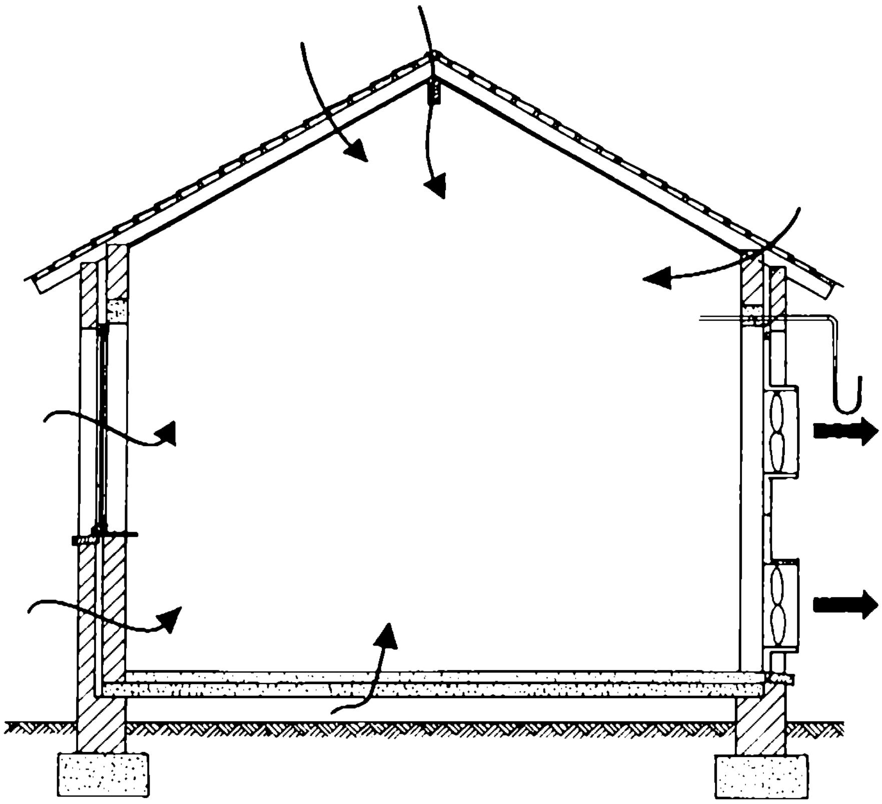


Figure 1 - Pressurisation measurement.

This is reflected by the standardisation of the measurement procedure in several countries [1].

The results of these measurements are used for several applications :

- determination of building performance.
  Several countries have requirements and/or guidelines on airtightness,

e.g. - Sweden, Norway : based on n_{50}-value
- USA : based on effective leakage area (ELA) for $\Delta P = 4$ Pa
- The Netherlands: based on air flow at 10 Pa.

- estimation of ventilation rates.
  e.g. : - simple rule of thumb : n_{50}/K where the average for $K = 20$ [2]
  - LBL-model [3].

An important limitation of a global pressurisation measurement is the lack of information concerning the leakage distribution. Special techniques are available to estimate the leakage distribution and/or the airtightness of components.
They are briefly summarised in 2. One of them - advanced single fan pressurisation - is analysed in detail in 3.

2. ADVANCED PRESSURISATION MEASUREMENTS

Several techniques are available to obtain information on the leakage characteristics of certain parts of a building. The following summing-up gives an idea of these techniques without the intension of being complete.

2.1. Component pressurisation system (fig. 2.1).

The approach is very common in the laboratory.
It exists of an halfone airtight box in which a fan is built in.
This box is pressed against the component.
This technique can also be used on the field for windows and other components. Important measurement errors can occur when the air flow is not one-dimensional. This is illustrated in fig. 2.2.

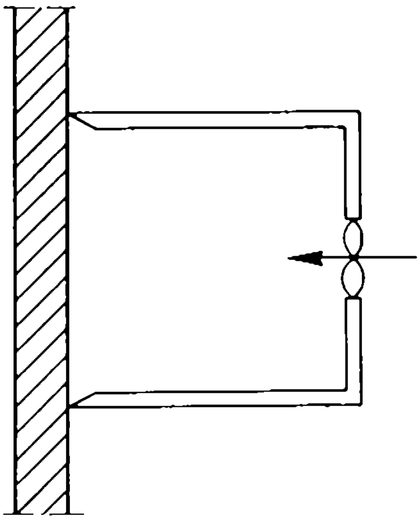


Figure 2.1

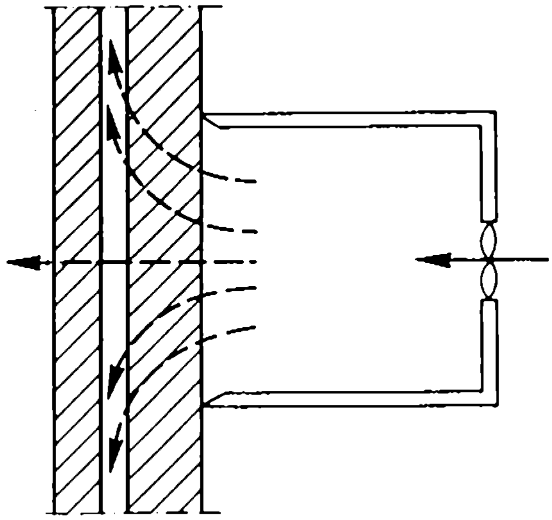


Figure 2.2

2.2. Direct determination by difference between pressurisation results

This approach requires 2 measurements :

- a reference measurement for the original situation
- a second measurement with the window sealed up by using a PVC-foil or another technique.

The advantage is the absolute character of this approach. The disadvantages are the required manpower to make the component airtight and the limitation in most cases to pressurisation only and not depressurisation.

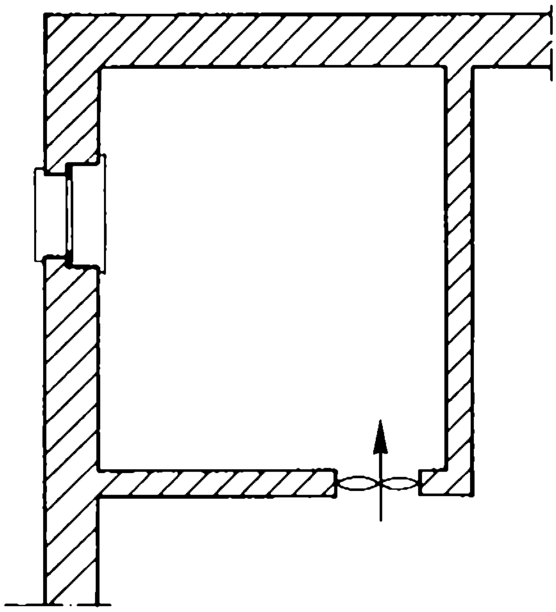


Figure 3.1 - Reference measurement.

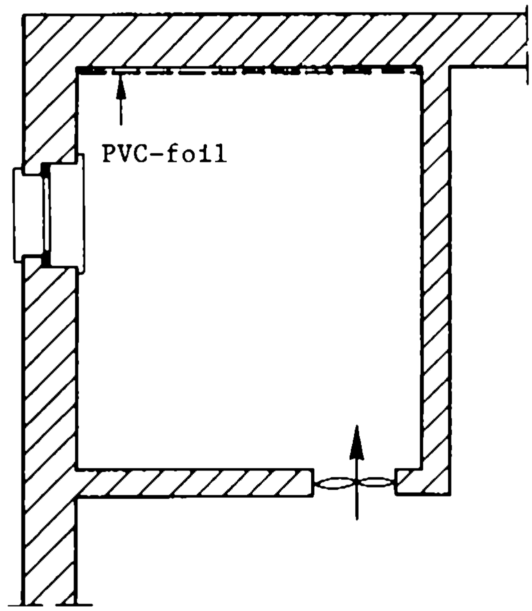


Figure 3.2 - PVC-foil to make wall airtight.

2.3. Multifan pressurisation

The main idea of this approach is to use 2 or more fans to control in a active way the pressure difference across a certain component or a group of components.
In most cases is the aim of this active control to make the pressure difference across the component(s) equal to zero.
Figure 4 gives an example of a common application. The result of such a single measurement (= Q_2) is an estimation of the airtightness of the outside walls in room A.
Figure 5 gives an example of an approach where 2 measurements are necessary.
In this case is the result (Q_4 - Q_2) an estimation of the air-tightness of the internal wall between rooms A and B.
A distinction between 2 analysis procedures can be made.

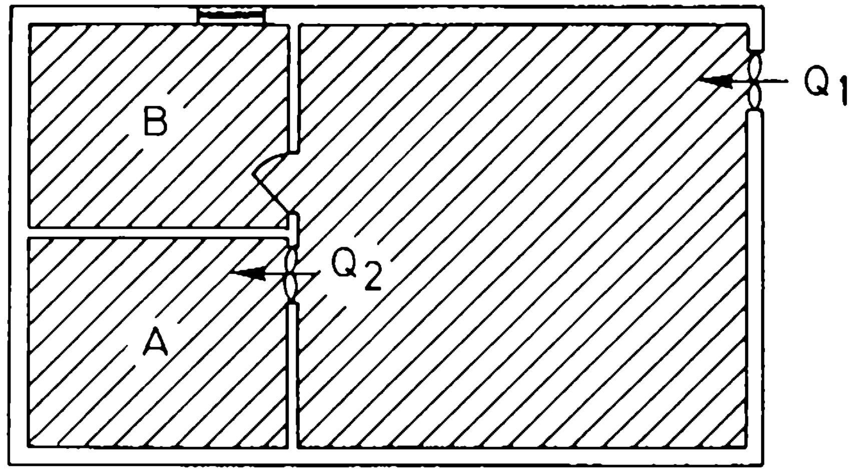


Figure 4

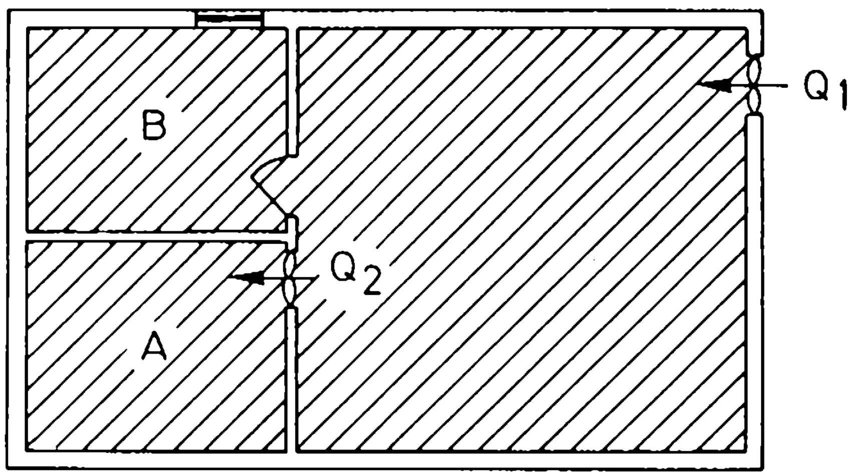


Figure 5.1

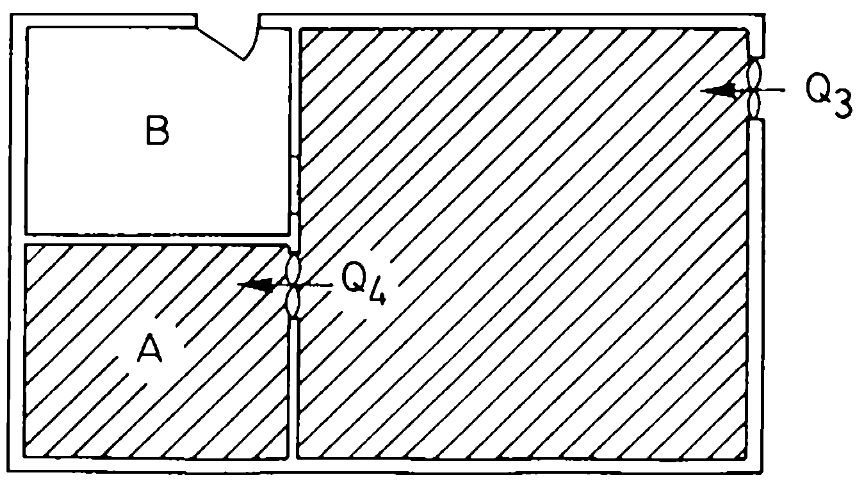


Figure 5.2.

a) One assumes N to be known

A single measurement (e.g. at 50 Pa) as given in figures 4 and 5, allows to determine C.

b) One wants to estimate C and N

In this case it is necessary to repeat the measurements for several pressure differences between inside and outside. One can also increase the number of points by creating several pressure differences across the components for a given pressure difference between inside and outside. Figure 6 gives a third possible measurement in the addition to the 2 measurements shown in figure 5.

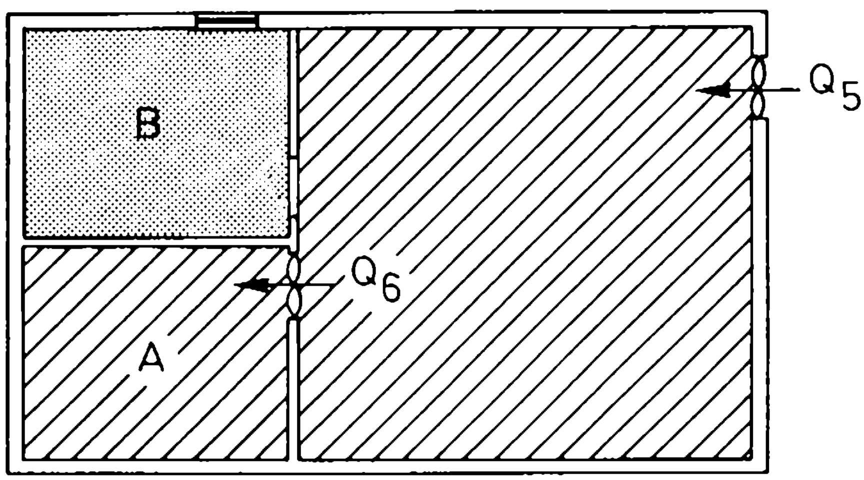


Figure 6

2.4. Advanced single fan pressurisation

This is based on a passive control of the pressure difference across a component. The example of figures 7.1 and 7.2 clarifies what is meant with 'PASSIVE' control.

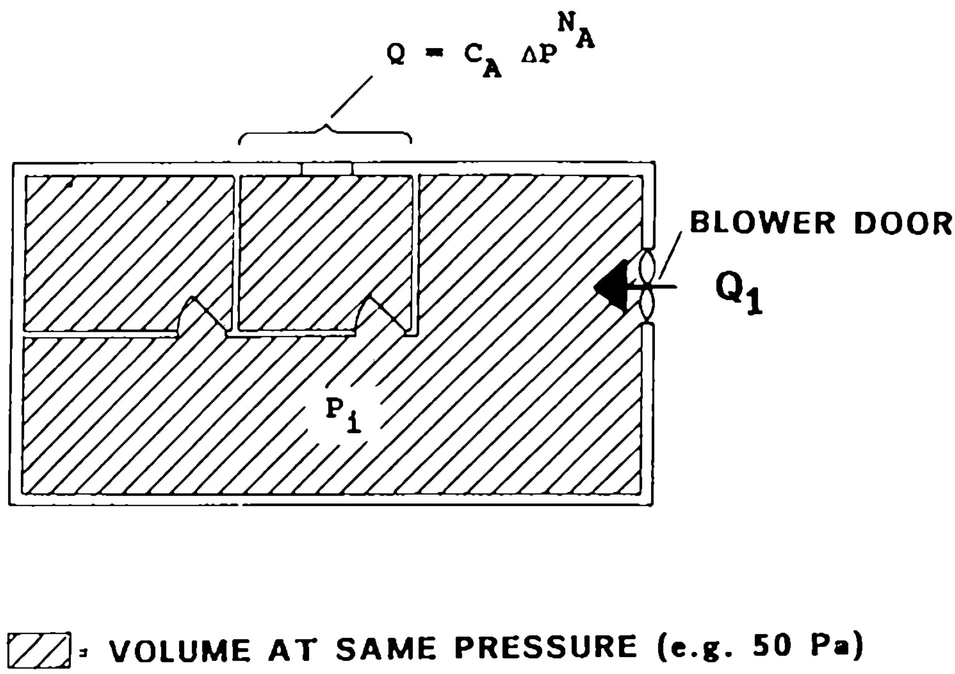


Figure 7.1

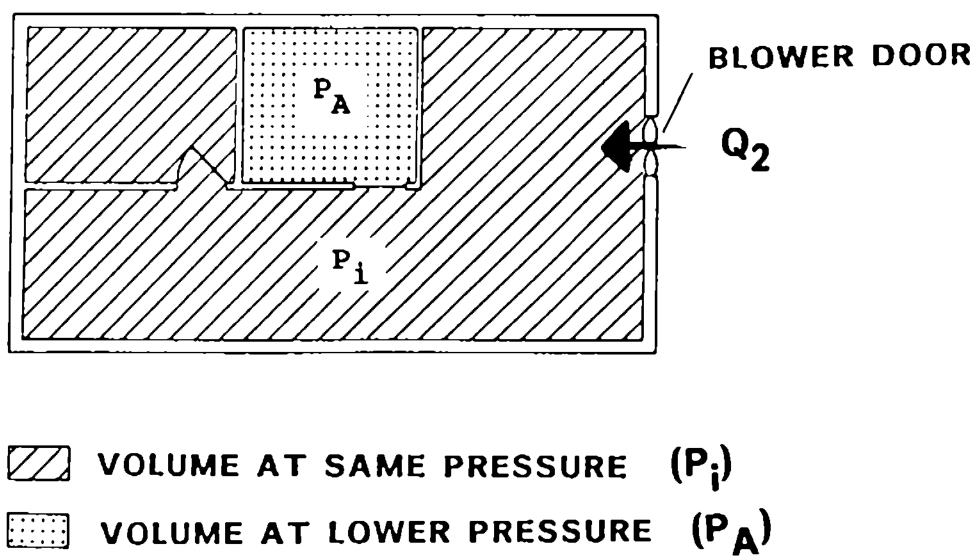


Figure 7.2

One has :

Measurement 1 :

$$Q_1 = C_o (P_i - P_e)^{N_o} + C_A (P_i - P_e)^{N_A}$$

Measurement 2 :

$$Q_2 = C_o (P_i - P_e)^{N_o} + C_A (P_A - P_e)^{N_A}$$

or

$$Q_1 - Q_2 = C_A [(P_i - P_e)^{N_A} + (P_A - P_e)^{N_A}] \quad (1)$$

This is one equation with 2 unknown variables : C_A and N_A.

One can only solve this equation by :

- or estimating N_A (e.g. $N_A = N_o$)
- or repeating the measurements for different $(P_i - P_e)$ and/or $(P_A - P_e)$ and estimating C_A and N_A on a statistical basis.

Advanced single fan pressurisation is treated in more detail in 3.

2.5. Combination of pressurisation and tracergas-measurements

There are situations where accuracy requirements and/or special boundary conditions require a combination of a pressurisation measurement and a tracergas measurement at the same time. The principle of this approach is described in an article in the Air Infiltration vol. 8, n° 1, Nov. 1986 [5].

3. ADVANCED SINGLE FAN PRESSURISATION

3.1. Introduction

The basis idea of 'Passive' control was already described in 2.4.

The applications can be classified in 2 groups :

a) Qualitative approach

The aim is to have a rather rough idea of the situation. Detailed calculations are not needed.

b) Quantitative approach

The aim is to determine in a more or less accurate way the leakage of one or more components. Detailed calculations are needed and a statistical analysis is useful.

Both approaches can be complementary : the qualitative approach can serve as a first orientation concerning the leakage distribution.

It can also allow to select an appropriate measurement procedure to be used for the quantitative approach.

3.2. Qualitative approach

The information needed is mostly limited to pressure differences.

Two examples to illustrate this :

Example 1 :

Indication if the building can be treated as a single zone. The following procedure allows to give a rough answer to this question :

- the pressurisation door is used to create a more or less constant pressure difference (e.g. 50 Pa).
- the internal door of one room is closed and the pressure difference across this door is measured.
- this procedure is repeated for all the rooms.

Table 1 gives an overview of the results obtained on three occupied social houses in Belgium [6].

	House 1	House 2	House 3
Dwelling			
- room 1	15	32	7
- room 2	16	20	22
- room 3	26	23	6
- bathroom	21	22	3
n_{50}-value (h^{-1})	9,7	18	4

Table 1 - Pressure difference across internal doors (Pa). ΔP (dwelling - outside) = 50 Pa.

Possible criteria for deciding if a building can be treated as a single zone or not, don't form part of this paper, but it is clear that house n° 3 approaches much more a single zone than house n° 2.

Example 2 :
Indication of the leakage paths within a room.

In some cases it can be useful to have an idea if significant leakages exist between different zones.
A single fan in combination with pressure difference measurements can give a first indication.
Fig. 8 shows a house of which we wanted to know if there are leakages between the zones [7].
Table 2 summarises some of the measured pressure differences.

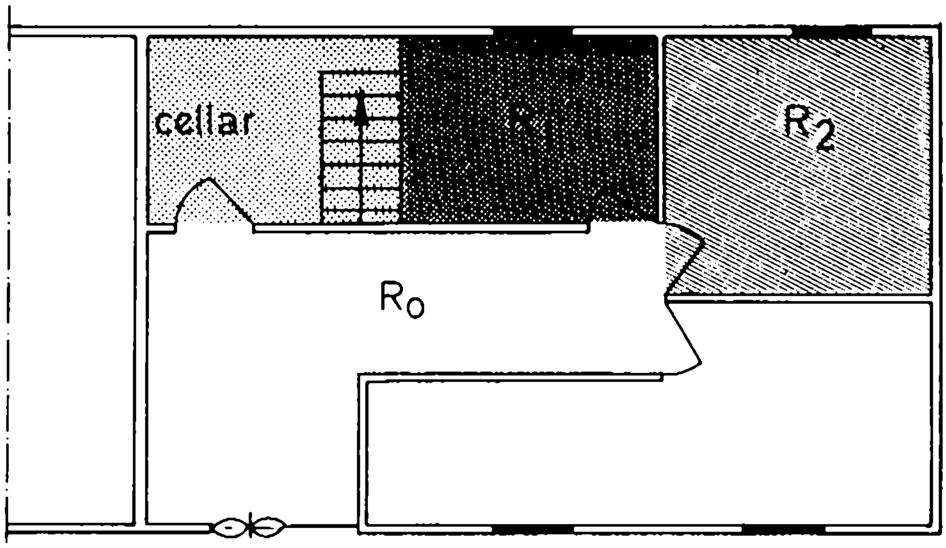


Figure 8 - The cellar is also under the whole house.

	Cellar door			
	Open		Closed	
	ΔP (R_1-R_o) (Pa)	ΔP (R_2-R_o) (Pa)	ΔP (R_1-R_o) (Pa)	ΔP (R_2-R_o) (Pa)
door R_1 closed	3,8	0	7,8	0
doors R_1 + R_2 closed	5,3	21,5	11	22

Table 2 - Pressure differences across internal doors for ΔP (dwelling - outside) = 50 Pa (Pa).

The following conclusions can be drawn from this table :

- the leakages between the building and room 1 are much larger than the leakages between room 1 and the outside (ΔP (R_1 - R_o) = 3,8 Pa).

- there are leakages between room 1 and room 2 because the pressure difference P_o-P_1 increases to 5,3 Pa when closing the door of room 2 and maintaining P_i - P_e at 50 Pa.
- There are important leakages between room 1 and the (basement + basement entry) because the pressure difference increases from 3,8 Pa to 7,8 Pa when closing the cellar door.
- The leakages between room 2 and the cellar door are very small : closing the cellar door gives an increase from 21,5 Pa to 22 Pa.

More conclusions are possible. It clearly illustrates that this approach gives useful information. A big advantage is the required effort to have the information : no more than 15 minutes of additional measurements.

Other applications of the qualitative approach are possible. The 2 examples in this paper only trie to show some of this applications.

3.3. Quantitative approach

The principle is already described in 2.4.
The following 2 examples give an idea of practical applications.

3.3.1. Examples to illustrate the quantitative advanced single fan approach

3.3.1.1. **Example 1 : Determination of the leakage between the heated volume and the basement of a social house**

These measurements were carried out in the framework of IEA annex 14 on 'Energy and Condensation'.
A fully description is given in [7].
Figure 9 gives a simplified cross section of the dwelling.

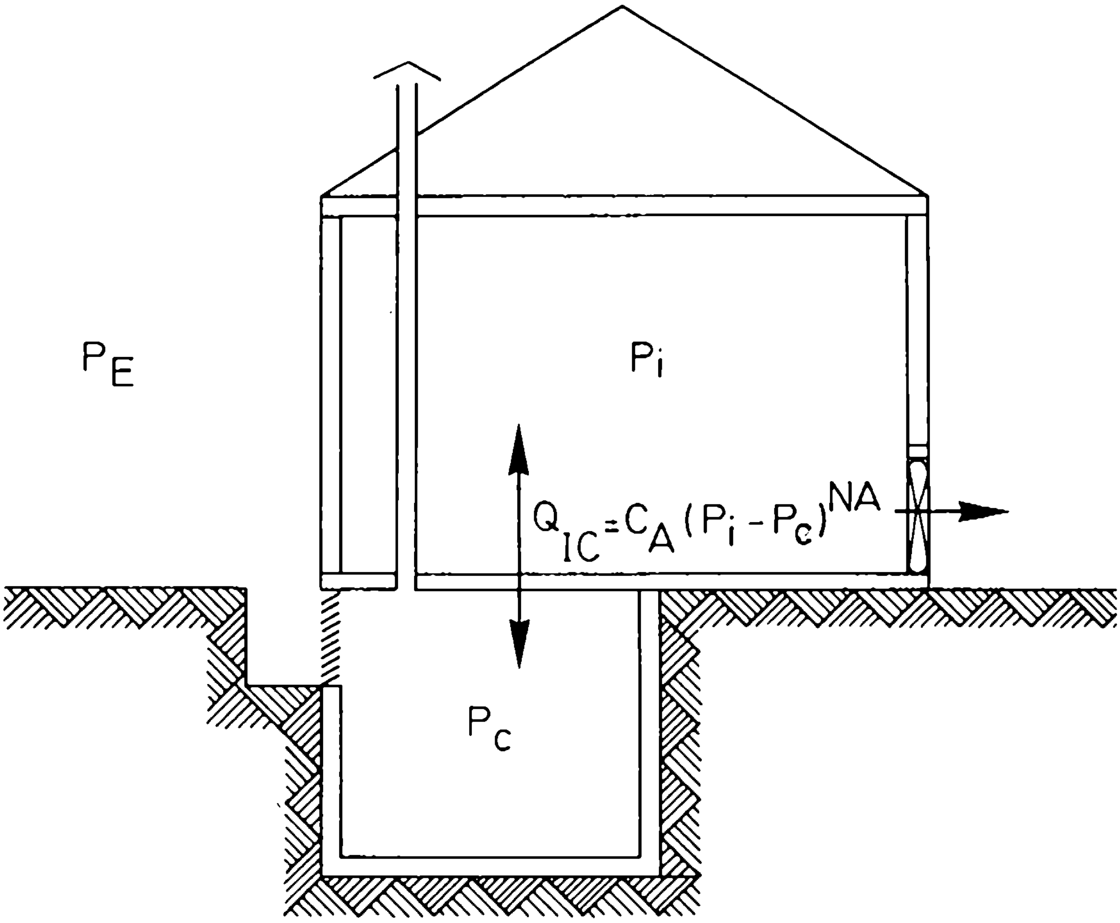


Figure 9

A description of the pressurisation measurements is given in table 3. The results are summarised in table 4, while table 5 gives the measured pressure difference across the cellar door as a function of the pressure difference between inside and outside.

Measurement	Description
1	This dwelling at present (normal use)
2	The extractor fan in the kitchen is made airtight
3	The entry panel to the attic is also made airtight
4	The ventilation bricks in the cellar are also made airtight
5	The chimney of the boiler in the cellar is also made airtight

Table 3

		Measured results					
	Measurement	C	N	Q_{50}	n_{50}	ELA(4)	ELA(10)
		m^3/hPa^N	-	m^3/h	h^{-1}	cm^2	cm^2
1	Reference	104	0,66	1380	5,3	280	530
2	Kitchen extractor	86	0,69	1260	4,8	240	465
3	Attic entry	82	0,68	1170	4,5	225	435
4	Airing cellar	84	0,63	1000	3,9	215	400
5	Chimney boiler	67	0,65	840	3,2	180	330

Table 4

ΔP_{ie} (Pa)	Measurement				
	3.1	3.2	3.3	3.4	3.5
20	8,6	8,8	8,6	5,7	2,4
40	21,7	22,1	22,3	11,8	4,6
50	27,2	27,4	27,4	14,5	5,7
60	32,8	32,8	32,5	16,8	6,7
80	-	43,0	43,0	22,6	9,0
100	-	-	-	-	11,3
120	-	-	-	-	13,2

Table 5 - Dwelling n° 3 - Pressure difference between dwellings and cellar.

These results allow to estimate the leakage between the heated volume and the basement.

a) Simplified approach : single measurements.

The results for 1 pressure difference between inside and outside (e.g. 50 Pa) are used and N_A is estimated e.g. $N_A = 0,6$.

Table 6 resumes the useful data.

Meas.	Description	C $m^3/h\ Pa^N$	N	Q_{50} (m^3/h)	n_{50}	$P_i - P_c$ for 50 Pa
3	normal cellar	82	0,68	1170	4,5	27,4
4	airing cellar closed	84	0,63	1000	3,9	14,5
5	chimney closed	67	0,65	840	3,2	5,7

Table 6

Any of the 3 measurements allow to estimate C_A :

meas. 3 - 4 : $C_A\ (27{,}4)^{0,6} - C_A\ (14{,}5)^{0,6} = (1170-1000)\ m^3/h$

$C_A = 74\ m^3/h\ Pa^N$

meas. 3 - 5 : $C_A\ (27{,}4)^{0,6} - C_A\ (5{,}7)^{0,6} = (1170-840)\ m^3/h$

$C_A = 74\ m^3/h\ Pa^N$

meas. 4 - 5 : $C_A\ (14{,}5)^{0,6} - C_A\ (5{,}7)^{0,6} = (1000-840)\ m^3/h$

$C_A = 74\ m^3/h\ Pa^N$

Interpretation :

This approach seems to give a stable estimation for C_A which indicates that the choice $N_A = 0{,}6$ was probably rather good for this case where there were important leakages around the basement door.

b) Estimation of the optimal combination of C and N

Equation 1 in 2.4. is not appropriate for ordinary least square calculations because the equation cannot be written as a linear function of C_A and N_A.
C_A and N_A has to be determined in an other way.
Table 7 gives an indication of the importance of the choice of N_A.
Table 7 gives the results for 4 values of N and for 3 values of $P_i - P_e$: 20,50 and 80 Pa.

	N = 0,55		N = 0,60		N = 0,65		N = 0,70	
	C	Q_{50}	C	Q_{50}	C	Q_{50}	C	Q_{50}
$P_i - P_e = 20Pa$								
meas.3 and 4	113	970	94	980	79	1000	67	1040
meas.3 and 5	97	830	82	860	70	890	60	928
meas.4 and 5	86	740	74	770	64	810	55	850
$P_i - P_e = 50Pa$								
meas.3 and 4	93	800	74	770	58	740	47	730
meas.3 and 5	92	800	74	770	60	760	49	760
meas.4 and 5	92	800	74	770	62	790	51	790
$P_i - P_e = 80Pa$								
meas.3 and 4	121	1040	94	980	73	930	57	880
meas.3 and 5	100	860	79	830	62	790	50	770
meas.4 and 5	78	670	62	650	50	640	41	630
Average	**97**	**830**	**79**	**830**	**64**	**810**	**53**	**820**
Minimum	78	670	62	650	50	640	41	630
Maximum	121	1040	94	980	79	1000	67	1040
$\frac{\text{Max. - Min}}{\text{Average}}$	0,44		0,41		0,45		0,49	
Average Q_4	210		180		160		140	
Average Q_{10}	340		320		290		270	

Table 7 - C- ($m^3/h\ Pa^N$) and Q_{50}-values (m^3/h) as a function of the N-value, $P_i - P_e$ and choosen combination of measurements.

Interpretation :

- The choice of N in the range 0,55 - 0,70 has a small effect on the estimated airflow Q_{50} : a variation of less than 15 %.

- The estimated values for Q_{50} are by far the most stable for $P_i - P_e = 50$ Pa.
  This seems logical because the accuracy on the airflow is the highest in the central zone of the measurement range which is around 50 Pa.

- The C-values (which are the air flows for $\Delta P = 1$ Pa) are a strong function of the assumption on N : the highest value (for N = 0,55) is more or less the double of the lowest value (for N = 0,70). Therefore it is logical that also Q_4 ($\Delta P = 4$ Pa) and Q_{10} ($\Delta P = 10$ Pa) are a more or less strong function of the value assumed for N.

- The range in C-value for the 9 calculations is the smallest for N = 0,60. This indicates that the assumption N = 0,60 was probably a reasonable choice.

Some more general indications of these results seems to be that :

1. the corresponding Q_{50}-value can be estimated with a reasonable accuracy in a more or less independant way of the choice of N

2. a good choice of N is nevertheless important if the results are to be used as input data in calculation models in which pressure difference of less than 5 Pa are very common.

3.3.1.2. **Example 2 : Estimation of the airtightness of leaky roofs with a false ceiling**

Several buildings with leaky roofs and a false ceiling were analysed in the last years.
Advanced single fan pressurisation was used to determine the airtightness of these roofs.

The principle is rather simple (figures 10.1 and 10.2) :

measurement 1 : a pressurisation measurement in the original situation. The pressure difference across the false ceiling is also measured.

measurement 2 : a number of panels in this false ceiling are taken out in order to have an almost zero pressure difference across this false ceiling. A pressurisation measurement is carried out again.

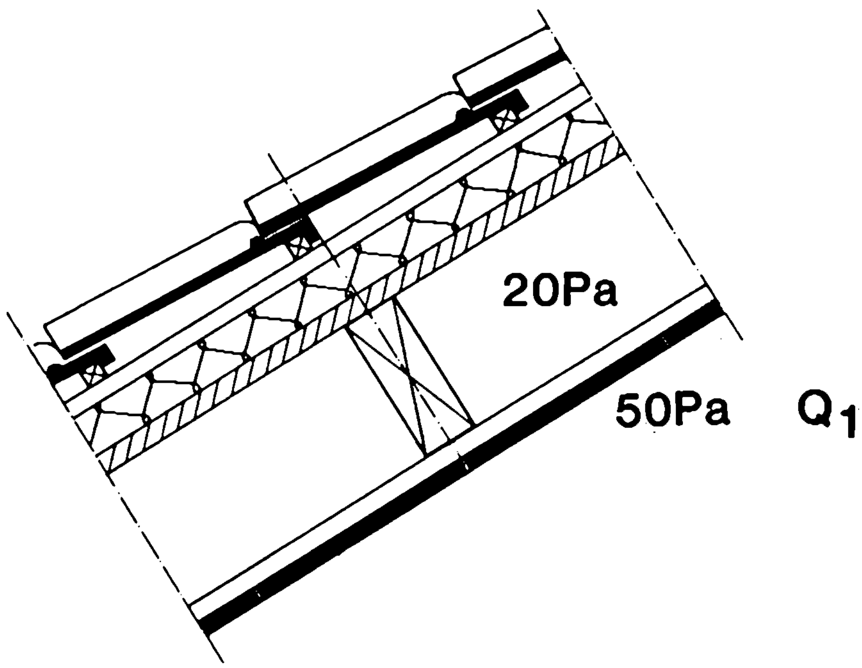


Figure 10.1

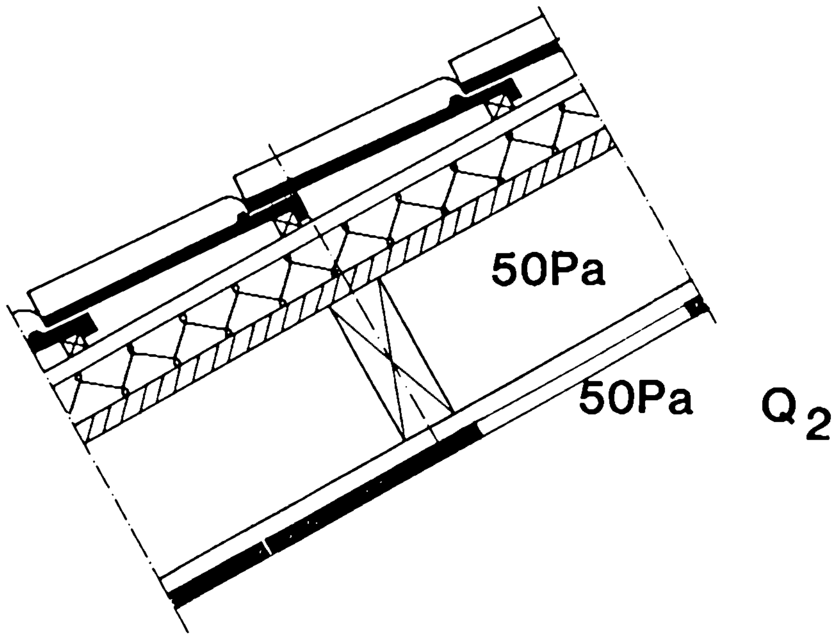


Figure 10.2

In most cases of leaky roofs is the pressure difference across the false ceiling in measurement 1 significant, as well as the changement in air flow between the 2 measurements.
In these circumstances it is possible to determine the air-tightness of the roof in a similar way as described in 3.3.1.

3.3.2. General classification

Table 8 classifies the measurement situations with respect to the quality of the information obtained.

		$Q_2 - Q_1$ (= changement of air flows between 2 measurements)	
		≈ 0	Other cases
ΔP (= changement of pressure difference between 2 measurem.)	≈ 0	Internal walls "too leaky"	Outside walls "very leaky"
	Other cases	Outside walls "very airtight"	

Table 8

Explanation :

1. It is clear that a good analysis is impossible in the case of no changement in air flow AND no changement in pressure differences between the 2 measurements.

2. In the case of a negligible air flow changement or a negligible pressure difference changement is an analysis possible but is the accuracy of the information limited.

3. In the other cases is a good analysis possible.

It is important to mention that it is possible in several situations to improve the measurement conditions so that a situation 1. becomes 2. or even 3. and that 2. becomes 1. An example is given in 3.3.3.

3.3.3. Changement of boundary conditions to improve the quality of the measurements : example

Figure 11 shows a groundplan of a school-building with rather leaky walls, of which the airtightness as well as the leakage distribution, has to be determined.

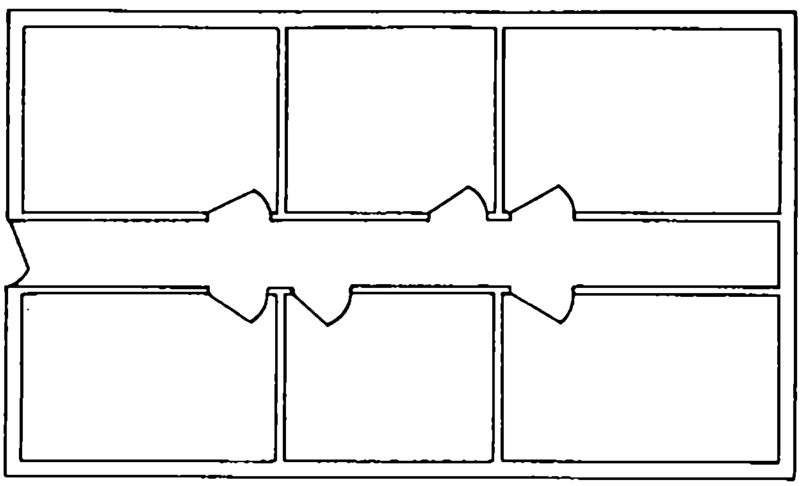


Figure 11

Figure 12 shows the situation for the reference measurement and figure 13 for the modified situation. The aim was to determine the leakage between room A and the outside.

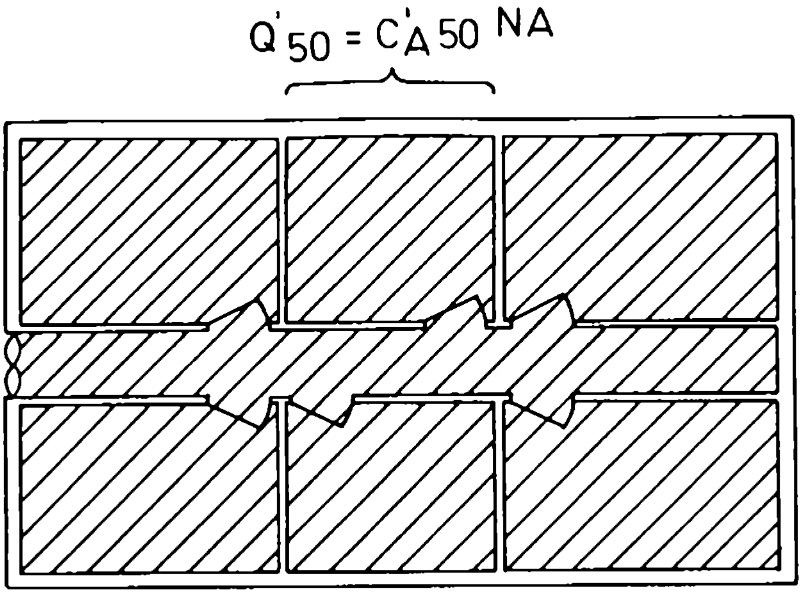


Figure 12

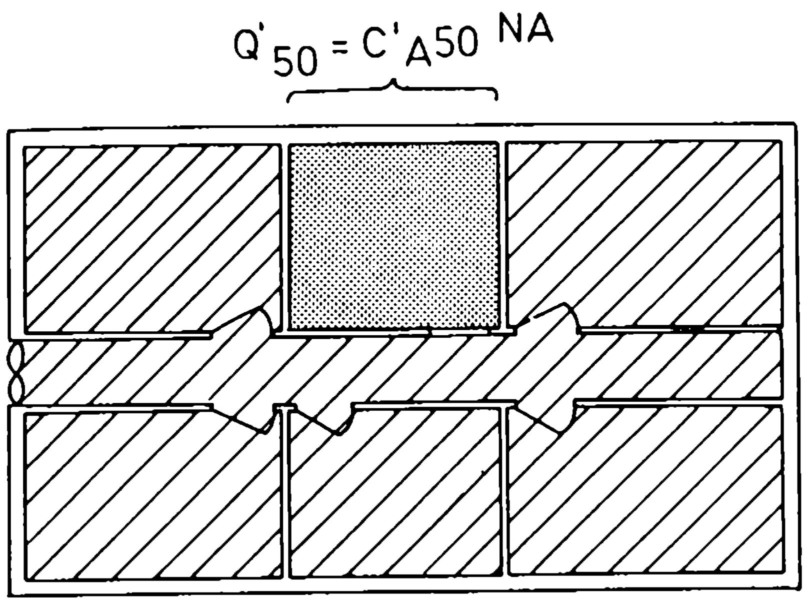


Figure 13

A significant pressure difference across the internal door in the situation with the closed door was found but the changement in air flow was within the accuracy of the air flow.
In order to get better measurement conditions were the 2 measurements repeated AFTER closing all the doors of the other classrooms NOT adjacent to the classroom 1 (figures 14 and 15).
This changement reduces the total air flow through the blower door in a significant ways and allows to determine the changement in the 2 air flows in a much more precise way.

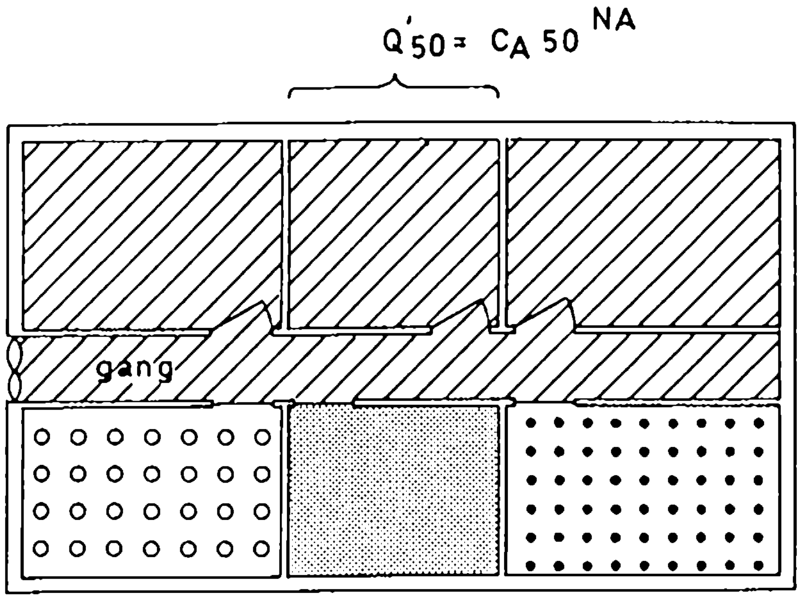
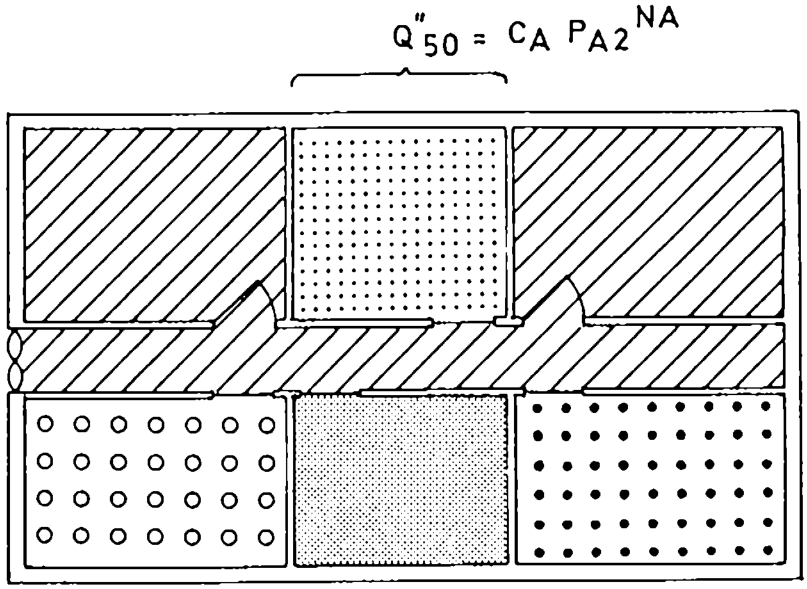


Figure 14



- area with equal pression (example : 50 Pa)

- area with lower pression P_{A2} $(0 < |P_{A2}| < 50)$

- areas with unknown pression

Figure 15

3.3.4. Measurement accuracy

Advanced fan pressurisation is in may cases based on the variation in air flows.

In the case of a small air flow difference in comparison with the absolute value of the air flows, a good accuracy is not evident.

Advanced error analysis may therefore become necessary in application where high accuracies are requested (e.g. model validation data).

4. CONCLUSIONS

- Advanced pressurisation measurements are an important tool for future ventilation research. Advanced single fan pressurisation gives in many circumstances good results.

- Advanced single fan pressurisation is in many situations not in competition with, but complimentary to multifan pressurisation.

  Advantages of single fan pressurisation are :

  - very suitable for qualitative information
  - very quickly
  - application independant of absolute value of the air flow where a multifan pressurisation needs in larger buildings 2 important blower doors
  - low investment costs.

  Disadvantages are :

  - not applicable for all situations (see 3.3.2) but this is partly also true for multifan pressurisation
  - a better knowledge by the user is needed because the procedure to be followed depends on the situation
  - more calculation time.

- Accurate results require low variations due to wind effect.

- More research is needed to make these techniques better.

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Discussion

C A Roulet (Switzerland) Comment	A limitation of these methods has been shown at the LESO building (Switzerland), where a large number of conductances had to be measured. Experiments were planned in order to obtain various conductances with the single fan technique. When the results were obtained it was seen that in many cases, the confidence intervals were not significant. It is proposed that a full error analysis be performed when using advanced single fan techniques.
P Wouters (Belgium)	The advanced single fan pressurization technique does have its limitations. In the LESO building the internal walls were probably very leaky as compared to the external envelope. This will make the method less accurate. A full error analysis method will be developed in the future.
R Dietz (USA)	To what extent does any variation in the assumed pressure exponent affect the results of the difference measurement approach?
P Wouters (Belgium)	A few simple calculations have been made to test the effect of assuming different values for N (e.g $N = 0.55$ instead of $N = 0.66$). These seem to indicate a rather small variation in the air flow estimation at 50 Pa.
P Charlesworth (UK)	Do advanced single fan pressurization techniques require the use of more sensitive pressure and flow rate measurement equipment? If so what sensitivity is required, what instruments are used and what accurancy is achieved?
P Wouters (Belgium)	An electronic micromanometer must be used for both pressure and flow rate measurement. The sensitivity must be 0.1...0.2 Pa. A Furness Controls Ltd device is used which has automatic zero-drift correction and integrating functions. The accurancy of the result depends upon several parameters and no detailed analysis has yet been performed.

AIR INFILTRATION AND VENTILATION CENTRE
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PAPER 5

A MULTIPOSITION TRACER GAS SAMPLING SYSTEM FOR BUILDING AIR MOVEMENT STUDIES

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National Research Council
Canada

ABSTRACT

This paper describes an automated sulphur hexafluoride tracer gas sampling system which is capable of taking and analyzing the tracer gas sample at sixteen locations in a time interval of about four minutes. The gas sampler used was an electron capture gas chromatograph. Using a backflushing mechanism, this system allows only the component of SF_6 in the sample to be analyzed. All other components which are not pertinent to the analysis are backflushed to the test space, thus reducing the sampling interval. The sampling interval can be further reduced to 15 seconds or less by selecting an optimum length of the analytical column. Such a system would be useful for conducting continuous tracer gas measurements in spaces or buildings where inadequate mixing of the tracer gas with the indoor air may exist or in air-conditioned buildings where freons may be present.

This system has been used to study the mixing of the tracer gas with the indoor air in a test room with no internal mixing fans. Typical results of the study are discussed.

INTRODUCTION

Sulphur hexafluoride has been used as a tracer gas to measure air change rates in buildings for several years (1,2). It is stable, inert, non-flammable, not considered toxic in the parts billion range, not normally present in the atmosphere and can be detected in the ppb range using an electron capture detector. This detector is, however, sensitive to freons that are usually present in air-conditioned buildings. These compounds are detected at a much slower rate than SF_6 in a gas detector column, resulting in an unnecessarily long analysis time.

More recently, tracer gas techniques have been used to measure the performance of ventilation systems in buildings and the air inflows and outflows of an enclosed space (1,3). For these applications, tracer gas-air samples have to be taken at various locations in the building. The sampling interval has to be shortened to a few seconds from a few minutes so that an adequate number of samples can be collected from each sampling location in a reasonable length of time. One way to achieve this is to have an automated sampling system with a backflushing mechanism. Such a system allows only the component of interest to be analyzed. All other components in the sample which are not pertinent to the analysis are backflushed to the atmosphere, thus shortening the analysis time. Also the detector is protected from unnecessary contamination by these components. This paper describes such a system.

The system has been used to determine the dispersion pattern and rate of a small amount of SF_6 injected at the centre of a room with no internal mixing fans. The information is useful in determining where and when to obtain representative samples when conducting tests on similar spaces. Typical results of the study are presented.

TYPICAL SAMPLING SYSTEM WITHOUT BACKFLUSHING

The technique of backflushing can be illustrated by first discussing a typical sampling system without backflushing. Figure 1 shows a schematic diagram of such a system. It consists of a sampling valve, a sample loop, a 40/60 mesh 5A molecular sieve column and an electron capture detector. When the system is ready to take a sample, the sampling valve is in position A (Fig.1a), and a sample of SF_6-air mixture is pumped into the sampling loop. At the same time, the carrier gas is flowing through the column and the detector. In the detector, the carrier gas is ionized and a standing current is produced. To measure the SF_6 concentration, the sampling valve is switched to position B. In this mode, the carrier gas forces the sample into the column where the SF_6, oxygen and other constituents are separated and released to the detector one after the other. As SF_6 has an affinity for electrons, it will absorb some of the free electrons in the detector, thus reducing the standing current. The concentration of the SF_6 can be determined from the measured current.

Figure 2 shows a record of a typical SF_6-air sample obtained in an air-conditioned building. Such a record is known as a chromatogram. It indicates that using a molecular sieve column, the concentration of SF_6 is obtained in approximately 15 seconds after the sample is injected. The oxygen passes through the detector soon after. If there are no refrigerants in the sample, the complete process from the start of a sample injection to the end of the analysis would require approximately 40 seconds. If, however, there are refrigerants in the sample, more than one hour may be required. As the SF_6 is the only gas of interest the sampling interval can be greatly reduced if the processing of the oxygen and other components can be eliminated. This can be achieved using the backflushing technique.

TYPICAL SAMPLING SYSTEM WITH BACKFLUSHING

Backflushing technique has been used in many applications (4,5,6) but the use of such a technique in a multiposition sampling system for air movement studies is relatively new (6). Figure 3 is a schematic diagram of such a system. Unlike the one without backflushing, it uses two columns: I and II. When the sampling valve is at position A the sample loop is filled with a sample waiting for analysis. The carrier gas is now divided into two streams, one going to the detector through Column II to establish the standing current and the other exhausting to the atmosphere through Column I to clear the residue of the previous sample. To inject a sample for analysis, the valve is switched to position B. The SF_6 is then separated in Column I and released to Column II. Just before the next component, namely, oxygen, is released from Column I, the valve is switched back to position A. While the detector measures the SF_6 concentration the rest of the gas sample in Column I is flushed to outside. At the same time, the next sample is loaded into the sample loop. This cycle is repeated until all the samples have been analyzed. Figure 4 shows a chromatogram of a number of consecutive SF_6-air samples. A 16 port multiposition sampling valve was used and the reading from the 16 valve positions is shown. As indicated, the sampling interval with backflushing is about 15 seconds and the peaks of the oxygen and other components are eliminated.

DESCRIPTION OF EQUIPMENT

Figure 5 shows a schematic diagram of the complete set-up. It consists of a carrier gas supply unit, a sample selection unit, a dual column sampling unit with backflushing and a detection unit.

The carrier gas supply unit consists of a carrier gas supply tank, a pressure regulator, an oxygen trap and a moisture trap. The carrier gas should be of the type recommended by the detector manufacturer. The flow rate varies with the detector used and is controlled by a two-stage pressure regulator with a stainless steel diaphragm. For this detector, the gas flow rate is controlled at 30 ml/min. An oxygen trap is installed to reduce the oxygen level in the carrier gas. This is recommended because the presence of oxygen in the carrier gas will decrease the standing current and hence, reduce the sensitivity of the detector. A molecular sieve moisture trap is also installed to decrease the deterioration of the column due to moisture accumulation.

The sample selection unit consists of a 16 port multiposition sampling valve, an electro-pneumatic actuator, a timer, an exhaust and a sampling pump, a by-pass valve and a drier. The exhaust pump draws the samples from 15 locations through a 16 port multiposition valve continuously. At the same time, the timer and the actuator control the valve to allow one sample at a time to be supplied to the sampling unit. To minimize the gas travelling time from the sampling valve to the drier, a by-pass valve is installed upstream of the drier to maintain a high flow rate up to the drier. For the same reason, the volume of the drier and the sample line between the drier and the inlet of the sampling valve is kept to a minimum. A drier (Drierite) is used to reduce the amount of moisture entering the column.

The sampling unit consists of a ten-port sampling valve, an electro-pneumatic actuator, a timer, a flow meter, a sampling loop, and two molecular sieve columns. The timer controls the actuator to switch the sampling valve from position A to B or vice versa in a timed sequence. The sample loop is made of 1.6 mm O.D stainless tubing and has an internal volume of 0.5 ml. A constant sample flow of 50 ml/min through the sample loop is maintained by adjusting the bypass valve. The two columns (I and II) are both 3.2 mm O.D stainless steel tubing packed with 40/60 mesh 5A molecular sieve. Their lengths are 450 mm and 300 mm respectively. Three needle valves are used to maintain equal carrier gas flow rates through the two columns when the sample valve is switched from one position to the other. One of these valves is located on the carrier gas line upstream of the sampling valve, the second one immediately upstream of the vent and the third one upstream of Column II. Equal carrier flow rates are necessary to minimize the baseline drift.

The detection unit consists of an electron capture detector and an integrator which measures the SF_6 peak height of the sample from the output of the detector.

TEST ROOM

The test room, as shown in Figure 6, was an internal room of a laboratory-office building, 4.9 m wide by 4.9 m long by 2.9 m high. The walls, doors and ceiling of the room were tightly sealed to minimize air leakage. One of the doors was replaced by a plywood panel in which two fan pressurization apparatus were installed. The air flows into and out of the room were controlled and measured using the apparatus.

The room was divided into eight volumetrically equal spaces. A pair of tracer gas sampling tubes were installed at the centre of each of the eight spaces. Also each space was further divided into eight volumetrically equal portions. At the centre of each of the outermost portion, one additional pair of sampling tubes was installed. In addition, another pair of sampling tubes was installed at the centre of the room. One of the two sampling tubes at each location was connected to a manifold to produce an "averaged" sample. Furthermore, a tracer gas injection tube was installed at the centre of the room.

TEST RESULTS

For each test after the supply and exhaust air flow rates for the test room were carefully balanced and set, a small amount of SF_6 was injected into the room. The tracer gas concentrations at the sampling locations and at the manifold were measured one after another immediately after the injection. Because the equipment could take samples from only sixteen locations the sampling tubes at the upper N.W and the lower S.E. corner locations were not connected to the detector so that the concentrations from the manifold and at the centre of the room could be measured instead.

Figures 7 and 8 show the SF_6 concentrations at selected sampling locations as a function of time for air supply or exhaust rates of 0 and 1 air changes per hour respectively. Also shown in these figures is the concentration averaged over all sampling locations (excluding the manifold). The average concentration was calculated from the measured concentrations of the 15 sampling locations. The results indicate that the SF_6 concentrations at various sampling locations approach each other rapidly and the concentrations at the various sampling locations are almost identical less than 30 and 10 minutes after the injection for 0 and 1 air change rates respectively. The results also suggest that the concentrations measured near the centre of the room were closer to the average concentration than those measured at the corner locations, and the concentration from the manifold represented closely the average concentration of all the sampling locations.

The tests were repeated with cardboard boxes placed in the room to simulate furniture. The total volume of the boxes was about 10% of the volume of the room. Figure 9 shows the concentrations at selected sampling locations as a function of time for 0 air supply rate. It indicates that the time required to reach a uniform concentration with furniture was almost the same as that without.

DISCUSSION

The proposed dual column sampling scheme was chosen over several other designs suggested by the valve manufacturer because it eliminates the baseline upset when the sampling valve is switched to Position B during analysis (5). In this scheme, the first column (Column I) is used to separate the SF_6 which subsequently enters the detector through the second column (Column II) for analysis. While the SF_6 is being analyzed the oxygen and other components in Column I are backflushed to the atmosphere. As the separation of the SF_6 is completed in Column I, no further separation takes place in the second column. A relatively short second column would be adequate. As suggested by the valve manufacturer, a standard 0.125 mm OD 305 cm long stainless steel column packed with 40/60 mesh was selected as the second column (7).

For the same sieve size, column diameter and temperature, the length of the first column affects the sampling interval, which includes the injection and the backflushing times. The injection time is the time from injection to that when the backflushing starts. It falls between the retention time of the SF_6 and the oxygen. Here the retention time is defined as the time from injection to the peak maxima. In general, an inadequate injection time can result in either a partial peak or none at all. On the other hand, a long injection time can allow a portion of the oxygen to go through the detector, increasing the sampling time.

The length of Column I was selected on the basis of chromatograms produced by various lengths of similar columns without backflushing (Fig.10). The columns used were all 0.125 mm OD, stainless steel columns packed with 40/60 mesh Molecular sieve. Fig.10 indicates that the minimum length of

Column I that would provide adequate separation between SF_6 and oxygen was 305 cm. It also indicated that the time interval between the SF_6 and the oxygen increased with the column length. Because the timer cannot activate the backflushing in the middle of a second, a 457 cm column was used to ensure that the backflushing starts after the completion of the SF_6 peak and before the beginning of the oxygen peak.

The injection time can be further adjusted by increasing the column temperature. To achieve the desired 15 seconds sampling interval, the injection time must be about 5 seconds. This can be achieved by increasing the column temperature to about 100 C.

With a fast sampling rate the transport time of the sample from the sampling location to the sample loop is critical. One way to ensure a constant lag time for samples from all locations is to use the same length of sample tubing. To minimize the lag time, the diameter of the sampling tube should be small. Care must be taken to ensure that the flow rate is sufficient to flush the sample loop several times with the new sample before the sampling valve switches to the next position.

Separate timers are used to control the stepping of the multiposition valve and the switching of the sampling valve. It is, therefore, necessary to sychronize them so that the multiposition valve steps immediately after the sampling valve returns to Position A. This will ensure that the maximum time is available for loading the next sample.

The gas chromatograph must be free of leaks to prevent contaminants from infiltrating into the system. It is also important that the carrier gas be kept free of oxygen and moisture. This can be achieved by careful maintenance of the oxygen and the moisture traps in the carrier gas line.

SUMMARY

A multiposition SF_6 tracer gas sampling system has been developed. It utilizes a backflushing technique to allow only the SF_6 to be analyzed by the detector. All other components which are not pertinent to the analysis are exhausted to the atmosphere, thus shortening the analysis time. The main advantage of this system is that it is capable of taking samples from 16 locations at a rate of 15 seconds per sample including the analysis time. It also minimizes the equipment down time by protecting the detector from unnecessary contamination by components such as freons.

A schematic diagram of the complete tracer gas measuring apparatus and a list of the major components are given. Based on this information a similar system can be constructed using the listed components or those supplied by other gas chromatograph and valve manufacturers.

The results obtained from the test room suggest that for a rectangular room approximately 5m by 5m by 3m high, adequate mixing between the tracer gas and the indoor air may be achieved within 30 minutes. During the mixing period, the average concentration may be obtained by pumping the samples from several locations to a manifold and measuring the concentration from the manifold.

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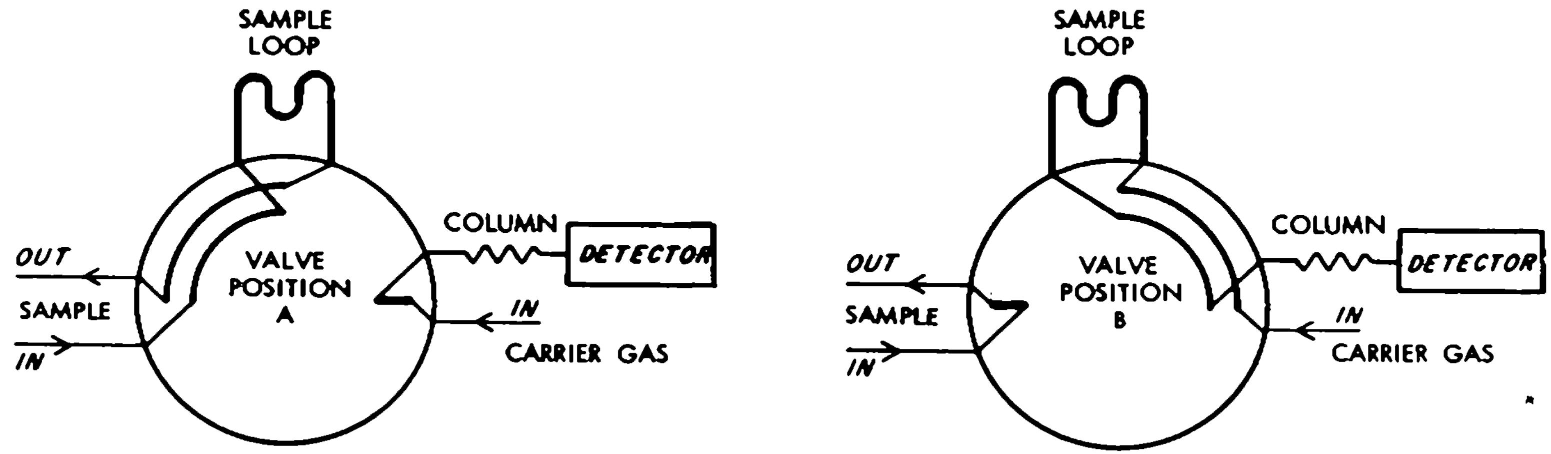


(A) LOADING MODE

(B) INJECTION MODE

FIGURE 1
SCHEMATIC DIAGRAM OF A TYPICAL SAMPLING SYSTEM WITHOUT BACKFLUSHING

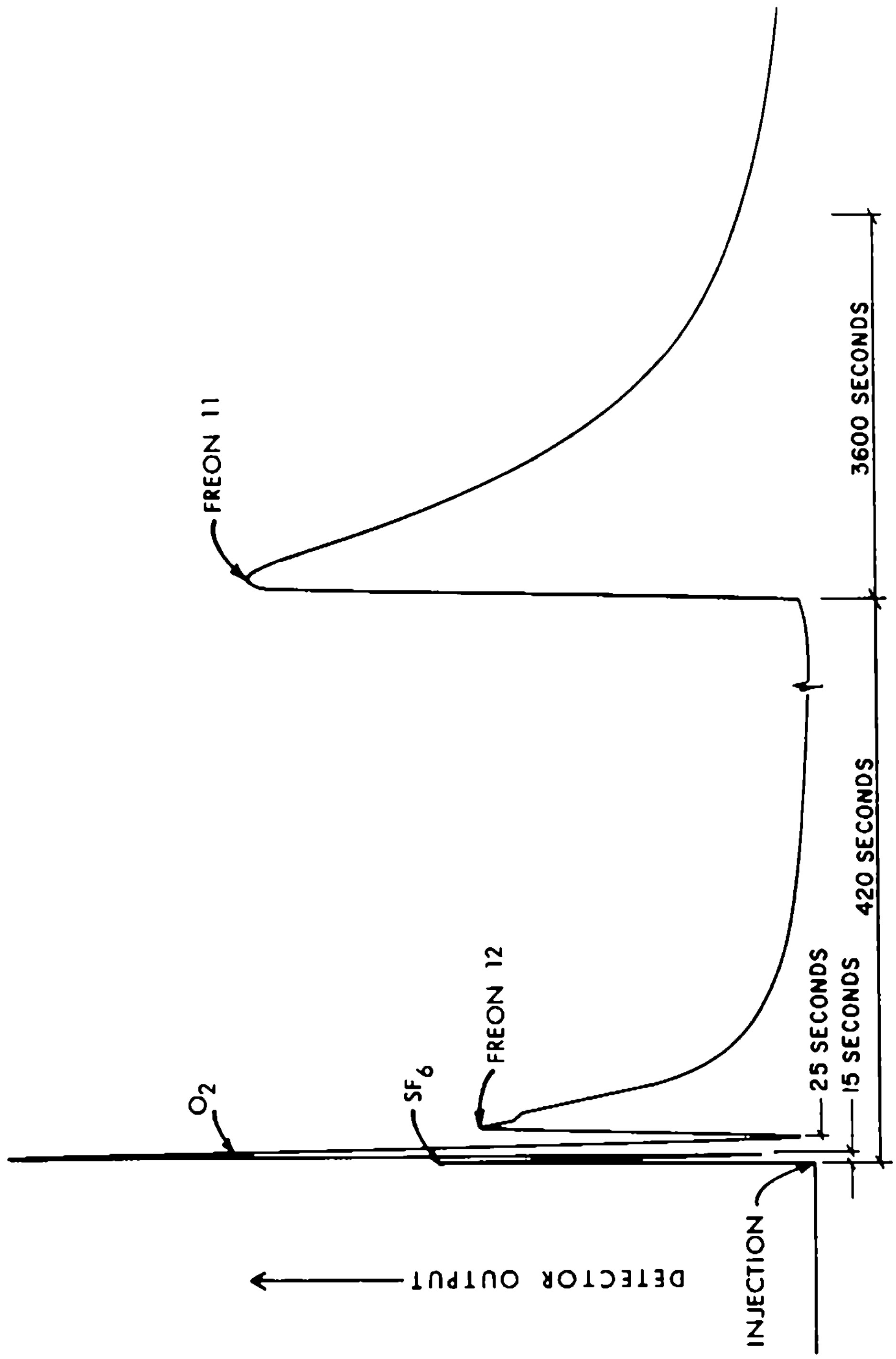
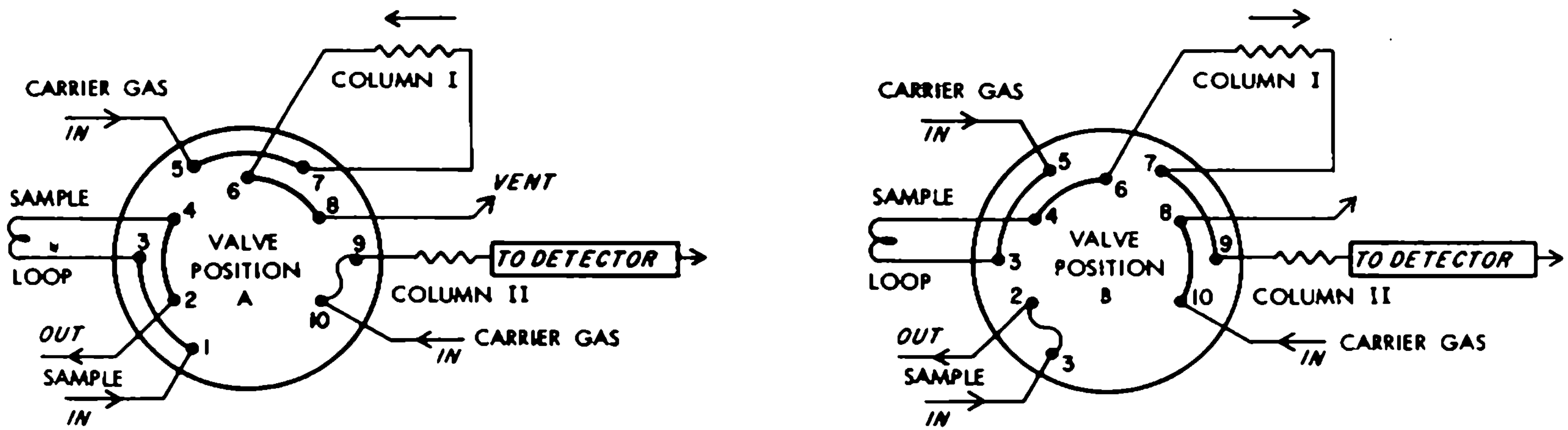


FIGURE 2 TYPICAL CHROMATOGRAM OF A SF_6 -AIR SAMPLE



(A) LOADING/BACKFLUSHING MODE

(B) INJECTION MODE

FIGURE 3
SCHEMATIC DIAGRAM OF A SAMPLING SYSTEM WITH BACKFLUSHING

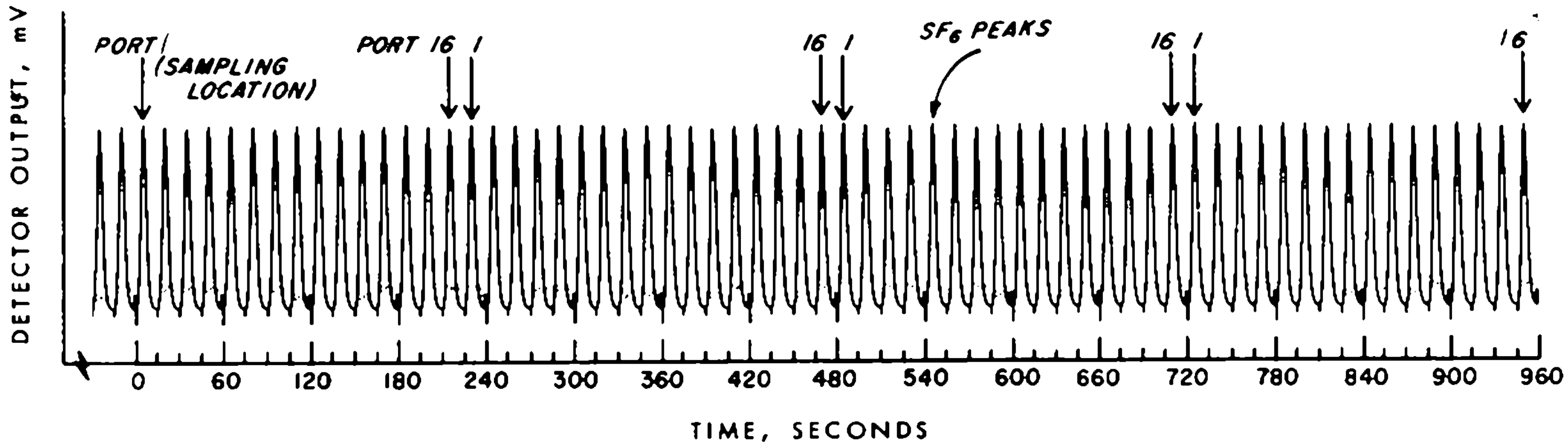


FIGURE 4
TYPICAL OUTPUT OF THE 16 PORT MULTIPOSITION SAMPLING SYSTEM WITH BACKFLUSHING

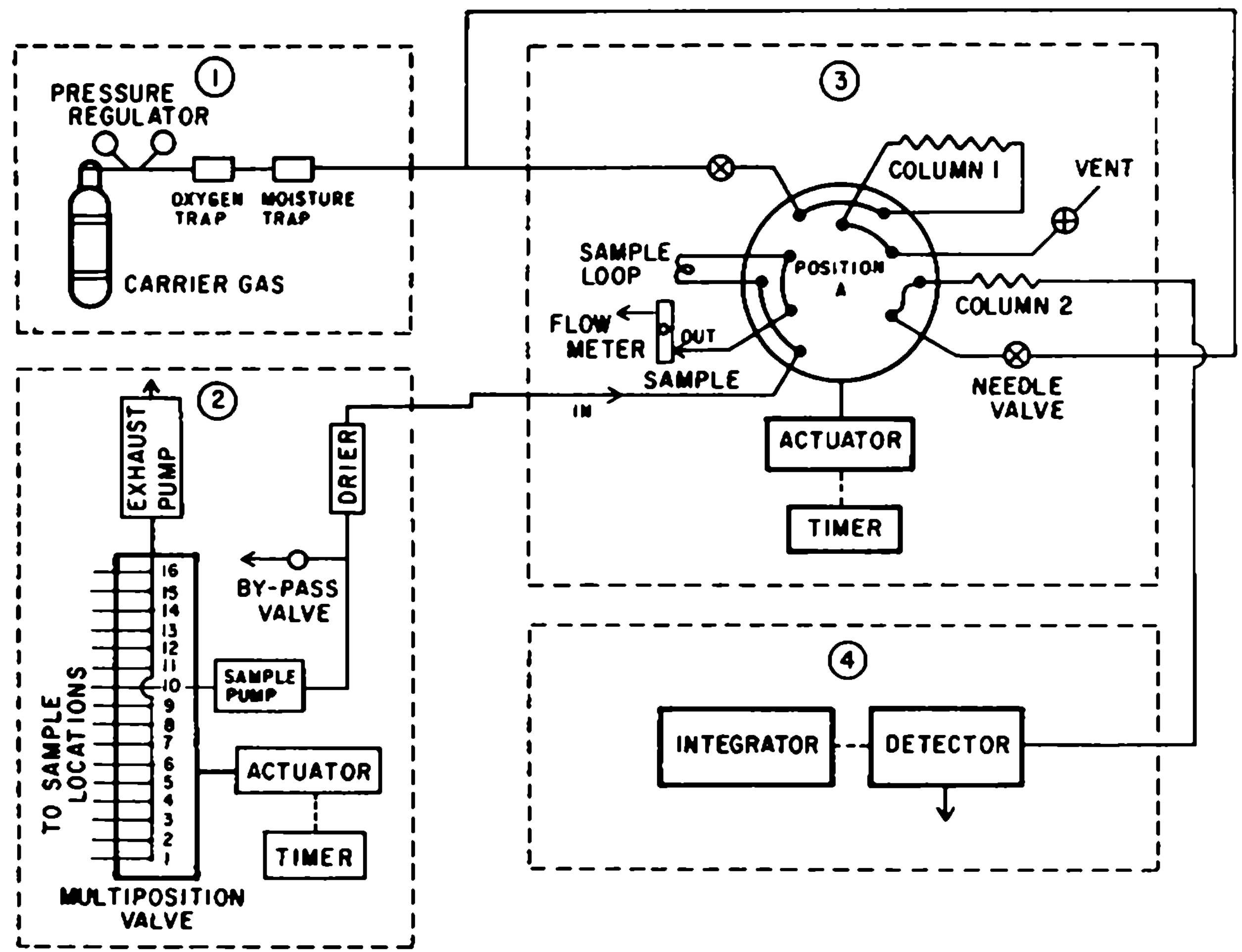


FIGURE 5

SCHEMATIC DIAGRAM OF THE 16 PORT MULTIPOSITION SAMPLING AND MEASURING APPARATUS.

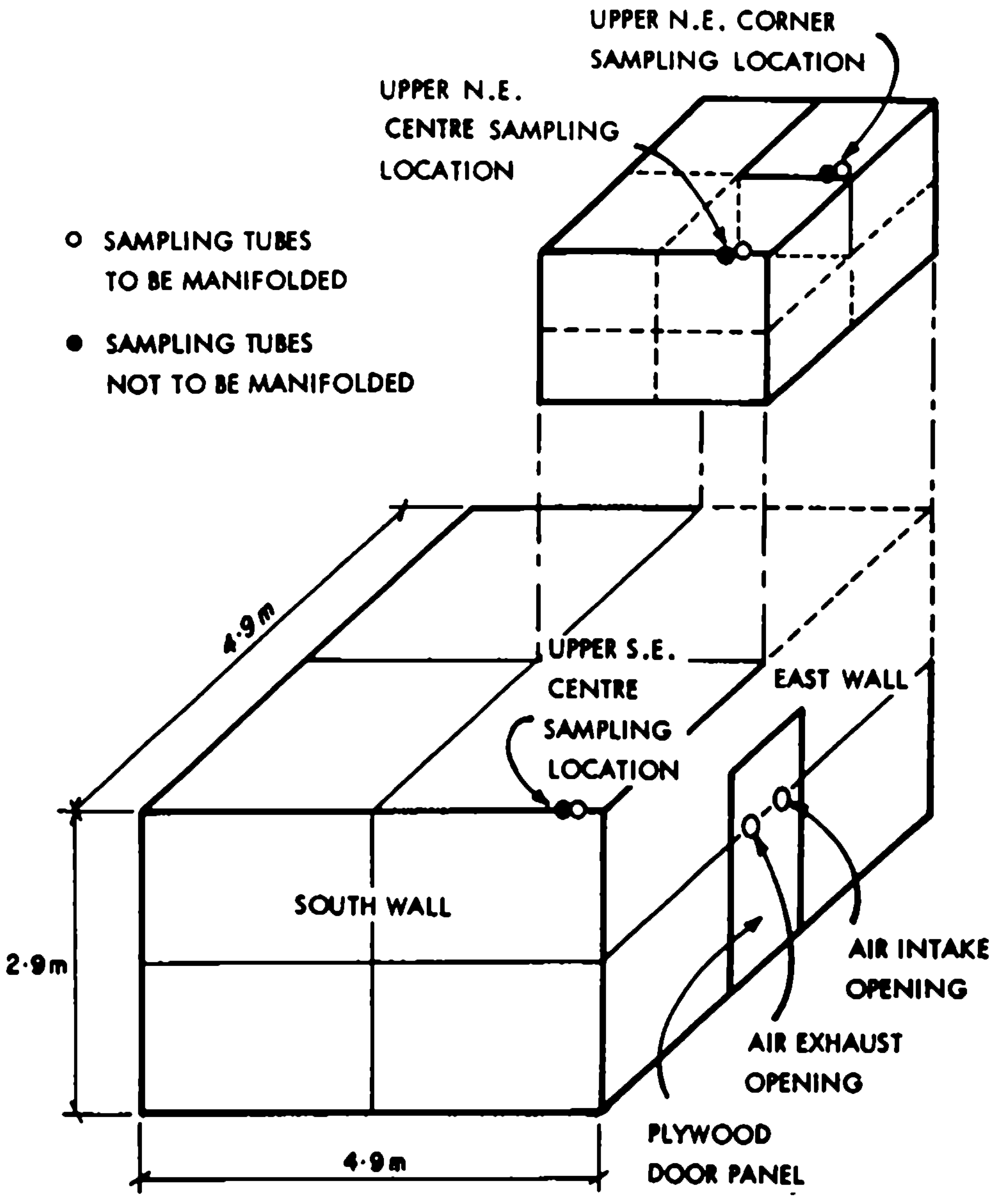


FIGURE 6
TEST ROOM SHOWING TYPICAL SAMPLING LOCATIONS

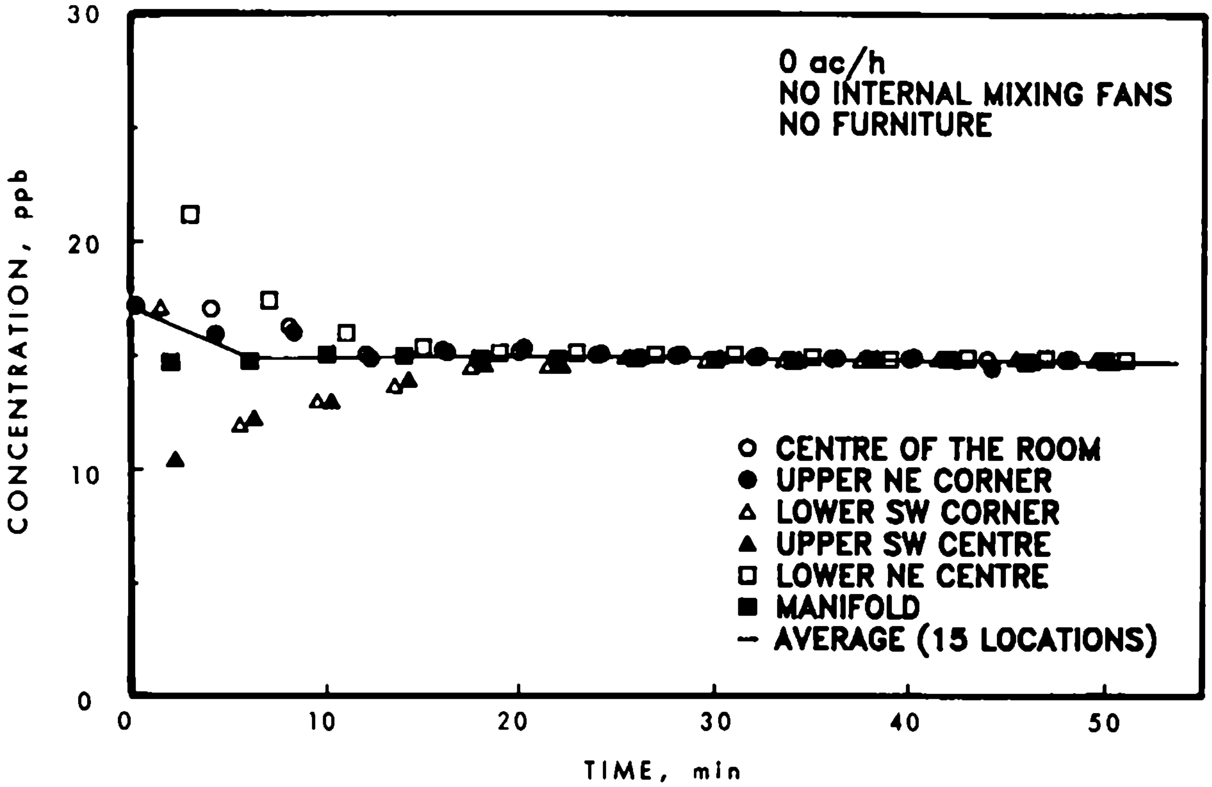


FIGURE 7 SF_6 CONCEENTRATIONS AT SELECTED LOCATIONS vs TIME

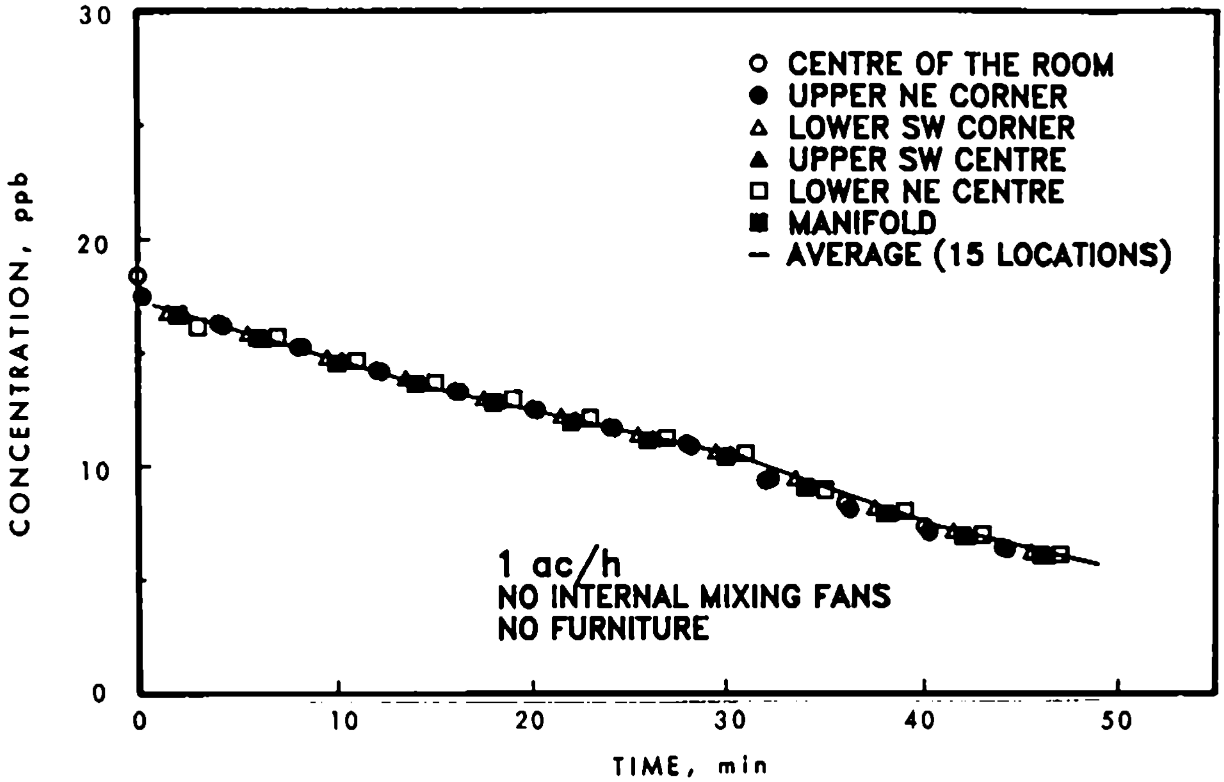


FIGURE 8 SF_6 CONCENTRATION AT SELECTED LOCATIONS vs TIME

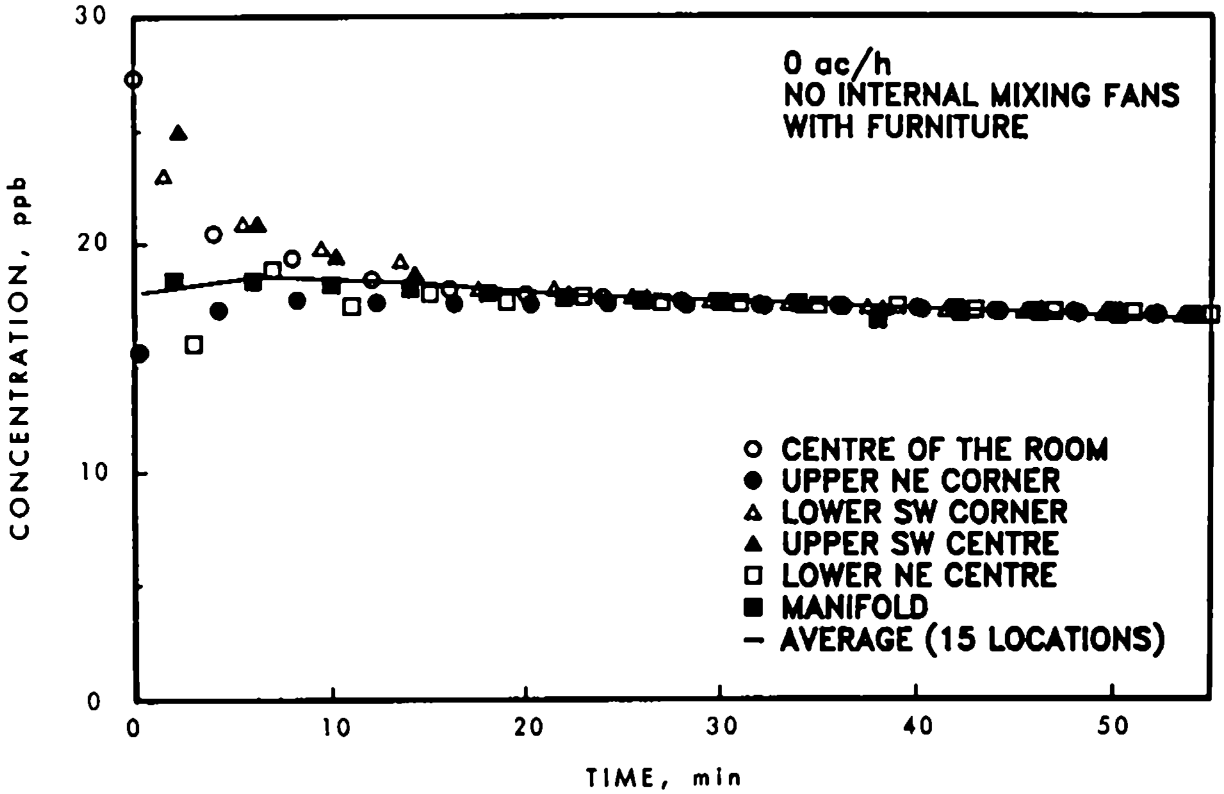


FIGURE 9 SF_6 CONCENTRATION AT SELECTED LOCATIONS vs TIME

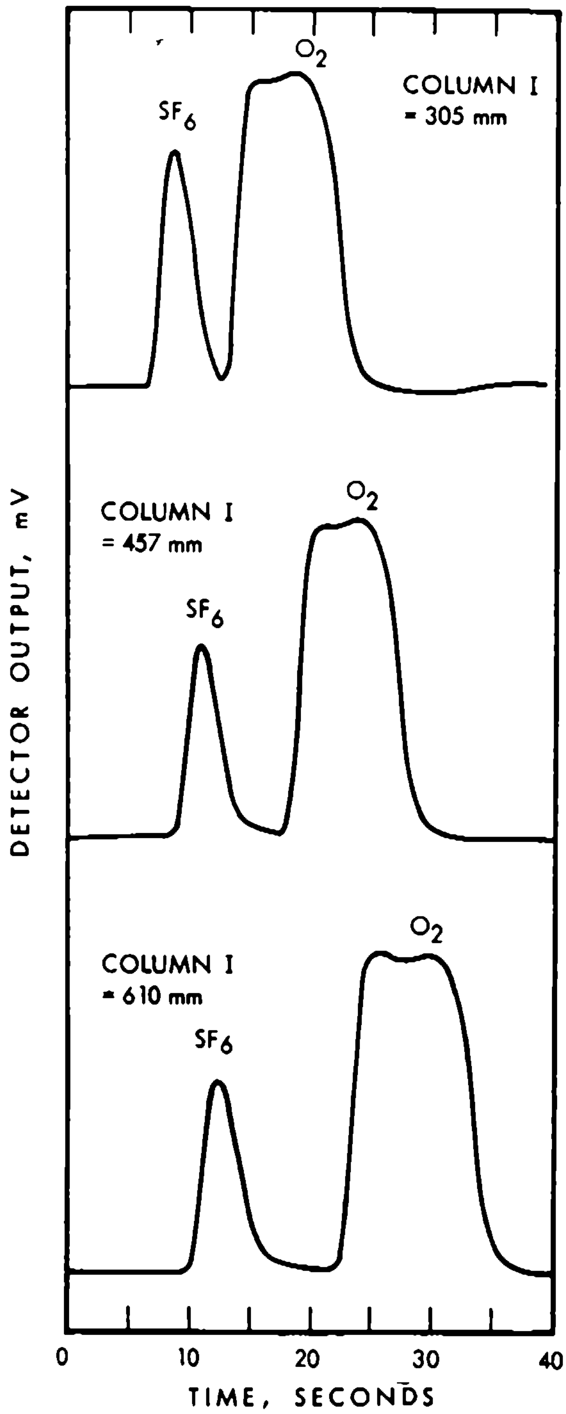


FIGURE 10

EFFECT OF COLUMN-LENGTH ON THE SEPARATION OF SF_6 AND OXYGEN PEAKS.

Discussion

L Trepte (Federal Republic of Germany)	Has this system been used in real buildings? Are you intending to produce this system commercially?
C Y Shaw (Canada)	The system has been used to study the air distribution of an eight storey office building with nine HVAC systems. It is not the role of NRC (Canada) to produce commercial equipment. However, schematics of the system are presented in the paper (figures 3 and 5) and it could be assembled by anyone with experience of routine maintenance on gas chromatographs.
C A Roulet (Switzerland)	Is it possible to shorten the measurement time by trapping the oxygen chemically before it enters into the apparatus?
C Y Shaw (Canada)	Oxygen is not the main problem. The main problem is the freons in the building; these can come from the air-conditioning system.
P Charlesworth (UK)	Can this rapid sampling system be used for multi-tracer separation?
R Dietz (USA) Comment	As the number of tracers is increased the analysis time on a GC-based analyser increases in order to resolve the tracers. For example the PFT DTA currently analyses 5 PFTs in about 10 minutes. However, work is in progress which shows promise of reducing this cycle time to 2-3 minutes.

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PAPER 6

TEN YEARS OF CONSTANT CONCENTRATION TRACER GAS MEASUREMENTS

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Ten Years of Constant Concentration Tracer Gas Measurements

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Introduction

Ten years ago the automated constant concentration tracer gas (CCTG) method was conceived at the Technological Institute, Tastrup, Denmark. This technique is now used by researchers to examine a wide variety of air infiltration and ventilation related problems. At this juncture it would seem appropriate to summarise the development of the CCTG system and examine its use in present day research.

Development

The impetus behind the development of the CCTG system was provided by the need to determine the cause of moisture problems in the roofs of dwellings and swimming pools. Part of this work involved studying the infiltration of humid air into the roof space from moisture producing areas below. In the mid 1970's a simple manual CCTG system was developed and put to use in houses and swimming pools.

In order to evaluate the energy consumption associated with air infiltration and ventilation it is necessary to continuously measure these parameters and ascertain the effect of occupancy and building usage upon them. At that time there was no appropriate technique available for the long term evaluation of occupied multi-cell buildings. Hence the need for an automated CCTG system became apparent.

Further development work was performed at the Institute and the result of this work was a computerised constant concentration system capable of making measurements in buildings with up to ten individual cells and air changes ranging between zero and 500,000 m^3h^{-1}. Continuous measurements can be made over a period of one to two weeks.

The evaluation of this sytem first took place in 1978–81 and the initial development and testing was funded by the EEC and the Danish Ministry of Energy. After this early reseach CCTG systems were developed in several countries including England (British Gas), USA (Princeton University) and Switzerland (Federal Institute of Technology). Over recent years the system has been refined to improve accuracy and the Technological Institute has built four separate CCTG systems. It is estimated that beween five and ten systems of various origin and design are now in use world wide.

Measurement Principle

The principle of the constant concentration tracer gas technique has been described by Kvisgaard (1985) and only a brief summary is presented here. A computerised system injects tracer gas into each of the rooms under test, and the information fed back from a gas analyser enables the tracer concentration to be maintained at a constant level in each room throughout the test.

The flow of outside air into each room (zone) can be evaluated from Equation [1].

$$V = \frac{Q}{c}\ m^3h^{-1} \qquad [1]$$

where V = air flow m^3h^{-1}
q = dosing rate of tracer m^3h^{-1}
c = tracer concentration m^3h^{-1}

Application

The CCTG system enables the user to examine a wide variety of ventilation related problems.

- Occupant influence on air infiltration and natural ventilation.
- Approximate assessment of air flow patterns in factories, dwellings and office buildings.
- Control of new ventilation systems.
- Control of new control methods such as demand control systems.
- Assessing potential building damage due to moisture migration and air movement.
- Indoor air quality studies.
- Measurement of ventilation efficiency.

The design of efficient natural and mechanical ventilation systems is reliant upon an accurate understanding of the influence of occupancy and air flow patterns upon air infiltration and ventilation efficiency. The CCTG system is ideally suited to the task of examining buildings under conditions of normal usage and occupancy.

Using the CCTG can be both difficult and expensive. However contract work has shown use of the CCTG system to be both efficient and cost effective. It has been found that several clients can expect a payback of at least ten times the initial outlay by following the course indicated by the CCTG tests.

Case Studies

This section contains several case studies which illustrate how the CCTG system has been used to examine a variety of air infiltration and ventilation related problems.

Dwelling: Energy Loss

In Denmark the users' influence on the airing of buildings is considerable (see figure 1). This influence should certainly be taken into account when designing natural or mechanical ventilation systems.

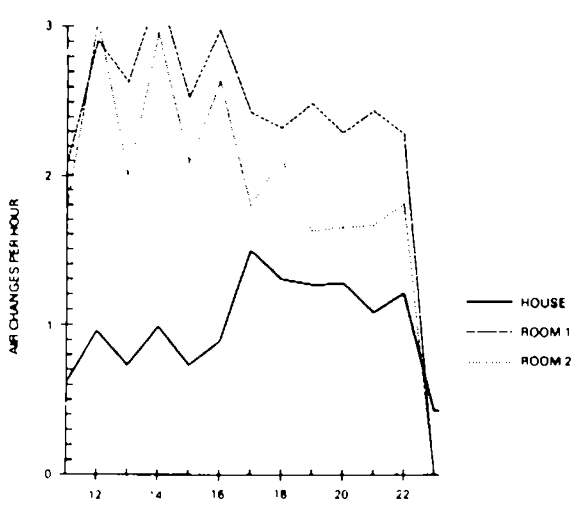

Figure 1: Variation of air change rate with time as measured by CCTG (occupant influence)

Brewery: Dust Problem

Figure 2 shows a plan of a three hall brewery. The central clean area had a dust problem and the CCTG system was used to assess the situation. Tracer gas was injected to a constant concentration in all three areas simultaneously and in only one hall at a time (see figure 3). This showed that only 17% of the air entering the clean room was due to the designed mechanical ventilation system. 67% was due to air flowing from the two adjoining 'dirty' rooms and 16% was due to infiltration of outside air.

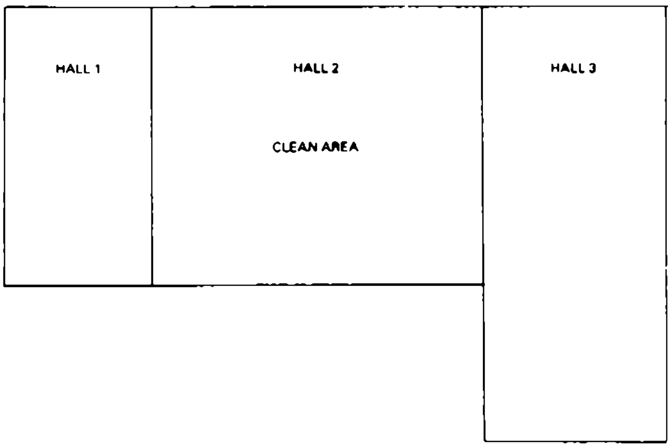

Figure 2: Plan of three hall production area with central clean room. Total area 10,000 m^3, volume 50,000 m^3

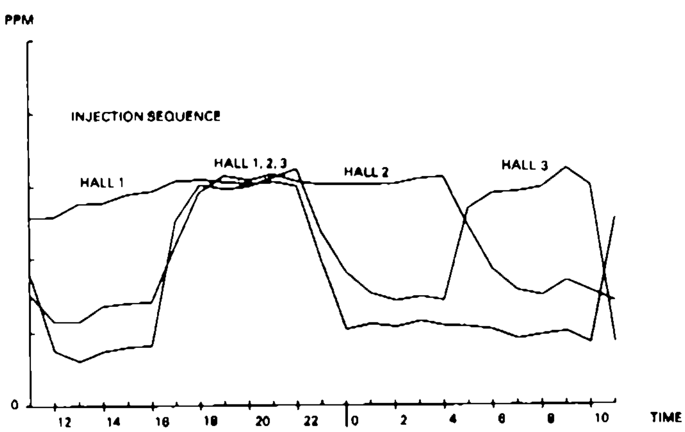

Figure 3: Dosing of tracer gas in different production halls and variation of tracer concentration

Office Building: Indoor Air Quality

The office building consisted of three floors with a total volume of 15,000 m^3. Measurements were made at a symmetrical cross-section containing 22 offices with a floor area of 400 m^3 and a volume of 1000 m^3. Using the CCTG system showed a natural ventilation rate of 2–8 m^{3}h^{-1} per person and a significantly increased infiltration rate when the staircase was used to promote the stack effect.

Semi-Detached House: Moisture Problem

The semi-detached house had moisture problems on two floors. The CCTG system was used to examine the building. The evaluated air flow patterns showed that refitting the second floor bathroom with exhaust ventilation had served to increase the infiltration rate of the first floor, but had done nothing to alleviate the moisture problems of the second floor bedrooms.

Kindergarten (School): CO_2 Concentration

Measurements were made in 25 kindergartens (see Figure 4). These showed a natural ventilation rate of 0.5 – 1.0 h^{-1} which is equivalent to 2–8 m^{3}h^{-1} per person. It was also found that the CO_2 concentration exceeded 1500 – 2000 ppm for much of the day in most kindergartens (see Figure 5).

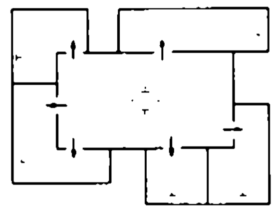

Figure 4: Plan of kindergarten typical of test area 3–400 m^2, volume 700–1000 m^3, 60–80 pupils natural ventilation

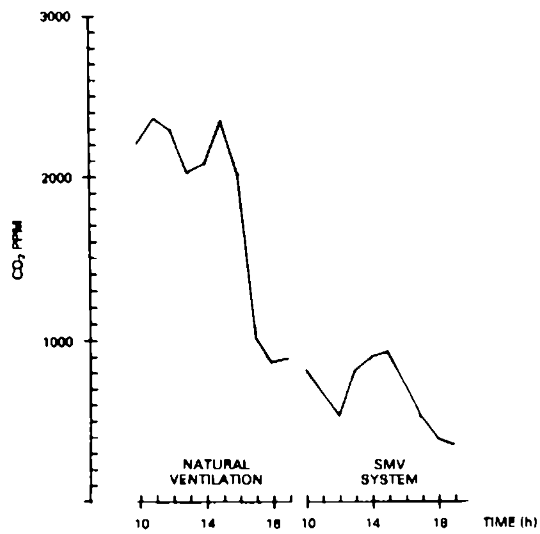

Figure 5: CO_2 concentration in kindergarten with and without SMV system

A new simplified mechanical ventilation (SMV) system was developed at the Institute and this system costs about 30% of conventional installations. Evaluation of the new system showed that air flow patterns were created which increased the efficiency of CO_2 removal. The nominal flow rate can be reduced to 50% of that of traditional designs and still keep the CO_2 level below 1000 ppm.

When the SMV system is equipped with demand control the exhaust from the CO_2 concentration is kept well below 1500 ppm during the day with a ventilation rate of only 4 – 8 m^{3}h^{-1} per person. The range is due to variation in the number of children present and their behavioural influence on the natural ventilation.

References

Kvisgaard (1985)
Bjorn Kvisgaard
The User's Influence on Air Infiltration,
Air Infiltration Review, Vol. 6, No. 4, Aug 1985.

<u>Discussion</u>

R Dietz (USA)	Why does the CCTG system require a 2 hour (approx.) stabilising period before it provides reliable results?
<u>P Collet (Denmark)</u>	In a building with 10 rooms the measurement cycle would be 10-15 minutes. If flow paths and rates were deliberately changed then this would be done mid-cycle. Two cycles are required to stabilise and 2-4 cycles required to give results. This gives about the 2 hour period (4-8 cycles). A one zone measurement could be completed in 5-10 minutes.

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PAPER 7

OVERVIEW OF TRACER TECHNOLOGY INSTRUMENTATION FOR SHORT-TERM AND REAL-TIME BUILDING VENTILATION DETERMINATIONS

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ABSTRACT

An intercomparison of three real-time tracer technologies demonstrated the potential of in-the-field feedback on the determination of air infiltration and air exchange rates between multiple zones in buildings influenced by occupancy behavior and ventilation system changes. Some tracer technologies can also employ less-expensive, short-term measurement methods for subsequent laboratory determination of flow rates in these steady-state modes. In the build-up mode, both short-term and real-time measurements with these technologies can provide ventilation efficiencies and local ages of air.

For short-term measurements, all but one of the technologies can use whole-air sampling; only the perfluorocarbon tracer (PFT) methodology is capable of adsorbent sampling. For real-time measurements, each technology uses field-deployable sampling and analyzing equipment.

Tracer costs for implementing the PFT technology are more than 1000-fold less than for the SF_6 constant concentration tracer gas (CCTG) technique, more than 10,000-fold less than for the halocarbon (HC) electron capture detector-gas chromatograph (ECD-GC) technology, and more than 100,000- to 1,000,000-fold less than for the HC mass spectrographic (MS) approach. The number of tracers available in both the PFT (7), ECD-GC (6), and MS (4) technologies are potentially comparable, although cost and toxicity might limit the selection of HCs; the CCTG technique requires only 1 tracer but cannot readily measure multizone air exchange rates.

Typically, 1 to 1.5 h is required by the CCTG and MS systems to accurately characterize a ventilation change in real-time using their less than 1 min zonal scanning time. However, both require deployment of tubing, running to each zone from a centrally located field laboratory, for both injecting tracer and sampling the air.

One version of the PFT technology precludes the need for tubing by using distributed passive tracer sources and programmable air samplers which collect samples in the short-term mode; however, the analysis and flow results are not available in the field. The other version of the PFT technology requires tubing for air sampling with a real-time dual-trap analyzer, which could then generate flow data in real-time. Recent tests have demonstrated that the PFT technology provides stable results to step changes in ventilation rates in less than 15 min.

Introduction

Recent participation in an intercomparison of tracer techniques in a Princeton University faculty residential building [1], demonstrated that, in the steady-state mode, in addition to inexpensive moderate-term (4- to 6-h) passive PFT measurements, short-term or real-time tracer-determined air infiltration, ventilation, and air exchange between zones could be very useful in diagnosing the performance of air-handling (AH) equipment and in quantifying the effects of occupancy behavior such as operating doors, windows, and ventilation equipment. In the build-up or step-up mode, which was not tested, such tracer techniques also have the potential of determining nominal and local ventilation efficiencies or, conversely, mean and local ages of the air [2].

For the purposes of the discussions to follow, "short-term" refers to air sampling in each of the zones of a building being tested with a frequency of 15 min or less followed by laboratory analysis at a later time for the tracer concentrations and ventilation results, whereas "real-time" refers to the same minimum air-sampling frequency per zone but with in-the-field determination of both zonal tracer concentrations and ventilation results.

For the modes of operation, "steady state" refers to the more-or-less constant release of tracer into the various zones of a building followed by short-term or real-time determination of the zonal tracer concentrations after steady state (about 2 to 6 h) concentrations have been achieved whereas "build-up" refers to the same short-term or real-time tracer determinations but from time zero until steady state where time zero is the onset of the constant release of tracer.

The steady-state and build-up mode definitions are fine for a situation of a constant building ventilation scenario. But, in practice, in many buildings this is frequently not the case. Thus, the steady-state mode, in reality, becomes a series of multizone tracer build-up and tracer-decay experiments. Strategies for solution of the steady-state equations with the inclusion of changing concentrations with time can be accommodated.

Of the three tracer technologies deployed, the Princeton 10-zone CCTG system [3], the Lawrence Berkeley Laboratory (LBL) mass-spectroscopy (MS) system, and the Brookhaven National Laboratory (BNL) PFT technology [4], as well as the LBL HC-based ECD-GC system [5], which was not tested but is being developed for large buildings, each is capable of short-term and real-time measurements with the exception of the CCTG which is inherently a real-time technology only.

This paper briefly compares the various technologies' strategies for tracer tagging, sampling, and analysis, presents the advantages of the PFT technology, and describes specific developments that would result in field-deployable PFT instrumentation for short-term and real-time building ventilation determinations in both the steady-state and build-up modes. This one technology will be applicable to buildings of all sizes, from homes to the largest commercial buildings.

Strategies for Tracer Tagging, Sampling, and Analysis

The purpose of this section is to briefly review the four technologies' strategies for tracer tagging or injection, air sampling, and tracer analysis and to emphasize the advantages of the PFT technology. A complete review of tracer technology is beyond the scope of this proposal and is available elsewhere [6-8].

Quite obviously, there is a strong interdependence between the three strategies. For example, if the analytical limits-of-detection are poorer or indoor air background concentrations are higher for one analytical technique or family of tracers compared to another, then more tracer will have to be released (increased tagging rate) and/or more air sampled (greater quantity of tracer collected). In addition, the amount of air sampled is dependent on the sampling techniques chosen, the sampling frequency requirements, and whether "short-term" or "real-time" ventilation determinations are being performed.

The number of tracers available directly limits the number of building zones that can be fully characterized in a single measurement period. But for a greater number of tracers, the analytical system becomes more complex and the analysis time increases; for "real-time" systems, this means a decreased sampling frequency. Finally, the impact of the three strategies on the overall system cost-of-implementation must be considered.

Sampling Requirements

The frequency with which air samples must be collected, their representativeness of the air within the zone, whether local or remote collection is performed, and the manner in which the aliquots of sampled air are collected, measured, and/or contained (i.e., is the sampler "home made" or commercially available) must be considered along with the methods for recovering the tracers from the aliquots.

Sampling frequency. The median air change per hour (ACH) rate of homes is about 0.5 h^{-1} and slightly higher for large buildings. Thus, for a disturbance (e.g., changing openings or fans) to a building ventilation at steady state, the time to achieve a new steady-state tracer concentration is of the order of a few hours. In practice, field determinations with the LBL MS and Princeton CCTG have shown that about 1.5 hours is required to adequately characterize a new ventilation scenario after a change. Thus, it would appear that "short-term" measurements in building ventilation determinations require on the order of about 6 tracer determinations per zone in 1.5 hours or about 15 min per determination per zone for proper characterization. For "real-time" multizone measurements with a single real-time analyzer, this 15-min frequency would require an analyzer cycle time of less than 4 min when scanning just 4 zones.

For the Princeton and LBL MS real-time technologies, the 1.5 hours is required for their linked tracer injection/tracer analysis systems to stabilize at new rates in each of the zones after changing the building ventilation. However, unpublished results of short-term measurements (15-min integrated samples) with the PFT technology [1] demonstrated that only 15 min or less will be required to adequately determine the rate of change of tracer concentration with time in each zone for calculation of the new air infiltration and air exchange rates in the steady-state mode using the constant emission rate approach. Thus, a real-time PFT analyzer with a cycle time substantially less than 4 min may be desirable. Changes in ventilation rates more frequently than every two hours or so would probably significantly confound the flow result calculations in the tracer build-up mode.

Sampling representativeness. When performing multizone flow determinations, sampling air that is representative of both the zone and the mode of analysis (i.e., steady-state or build-up) is very critical. The sampling point(s) must not be influenced by outside air, air from another zone, or improper deployment of tracer within the zone.

Clearly, single point sampling within a zone could lead to non-representativeness, depending on how tracer tagging is performed; multi-point sampling would be better. The latter requires either multiple sampling devices or tubing to be run from multiple locations to a single sampler. In most cases, each of the four tracer technologies can deal with representativeness in equal fashion.

Local sampling. In short-term ventilation determinations, a sequential sampling device is generally placed locally within each zone of a building in a representative way. Numerous programmable sequential sampling devices, including whole air (bags, syringes, tubing, bottles, etc.) and room temperature and cryogenic adsorbent-based systems, have been developed and many are commercially available [6,7]. In addition, such devices should be time-integrating samplers, collecting the sample continually at a constant rate over the sampling period; point-in-time samplers (i.e., a grab sample at one time in the sampling period) could lead to non-representativeness.

Although each of the three short-term-capable tracer technologies can use any of the commercially-available, whole air sequential samplers, only the PFT technology has a proven adsorbent-based sampler. This is because most of the HCs are too volatile for room temperature adsorption. The commercially-available (Gilian Instrument Company, Wayne, NJ) Brookhaven Atmospheric Tracer Sampler (BATS), costing about $8,000, can collect up to 23 integrated sequential samples of from 1 to 9999 min duration and thus are capable of meeting the 15-min sampling frequency. At least one other company (Scientific Instrumentation Specialists, Moscow, ID) makes a 36-multiple programmable sampler, costing about $10,000 and can make use of the existing Capillary Adsorption Tube Sampler (CATS) passive sampler, developed by BNL, but in an active (pumped) mode.

Several companies make whole-air syringe, bottle, or bag programmable samplers, capable of collecting up to 12 sequential air samples of from 30 mL to several liters in 15 min. Such commercially-available samplers cost about $2,500 to $4,000 and are time-integrating. LBL designed and built a 15-sample sequential sampler at comparable cost, but it is not commercially available and it does not use time-integrated sampling but, rather, the less-preferred point-in-time sampling [5]. The PFT technology as well as the two LBL technologies (MS and ECD-GC) can use these whole-air samplers in short-term building ventilation determinations.

Remote sampling. Real-time ventilation determinations require remote sampling of air from a representative location within each zone via tubing running back to a central location within or near the building where a real-time analyzer is located. This remote-type sampling will always be needed because the real-time analyzer systems of each of the four tracer technologies are too expensive and large to deploy individual units in each of the multizones of a building. Further, the techniques for remote sampling through tubing are essentially the same for each of the four technologies, with no clear advantage of one over another.

Tracer Requirements

The important aspects of performing many multizone-tracer building ventilation determinations include tracer use and implementation costs, number of tracers available, release (also called injection or tagging) procedures, and toxicity. Generally, the amount released in each tagged zone must be about 250 times greater than either the ambient air indoor background concentration or the sampling and analysis system limits-of-detection (LOD), whichever is greater; the 250-fold factor provides for reasonable tracer detection in its non-tagged zones. In many cases, the HC tracers have higher indoor air concentrations, compared to outdoor air, because of leakage from refrigerant (e.g., air conditioners) equipment [5]. A more extensive review of gaseous tracer requirements is available [7].

Tracer use costs. In addition to the costs per unit weight, which are within a factor of 30 of each other for the four technologies' tracers, the concentrations at which a building must be tagged to be 250 times background or LOD (i.e., the tracer design concentrations) has a direct influence on the total amount and, therefore, use cost per building ventilation study.

Considering a modestly large commercial building (50,000 m^3) with an outside air rate of 0.7 h^{-1} (35,000 m^3/h), Table 1 shows the tracer design concentrations, injection rates, unit costs, and annual use costs (assuming 36 continuous days of field measurements per year per system). The requisite tracer design concentrations for the PFTs is only 1 nL/m^3 (ppt), about 5 to 9 orders-of-magnitude less than that for any of the other technologies' necessary tracer levels.

To meet these design concentrations, the amount of tracer that would have to be injected annually for each system deployed is from trivial for the PFTs (<1 g/yr) to modest for the CCTG and LBL ECD-GC systems (17 to 200 kg/yr) to significant for the LBL MS system (2000 to 6000 kg/yr).

Thus, although the unit cost of the PFTs is the largest for all the tracers considered, its cost to use is by far the smallest; at 7 cents/yr, the PFT use cost is trivial. For the Princeton CCTG system, the SF_6 use cost is not significant. For the LBL ECD-GC system, the tracer use costs range from not significant (~$200/yr per system deployed) to moderately significant (~$10,000/yr) and for the LBL MS system, from moderately (~$16,000/yr) to highly significant (~$275,000/yr).

Table 1. Relative Cost of Tracer for 35,000 m^3/h Ventilation Rate Studies (assuming 36 measurement days per year)

Laboratory Technol.	Tracer Types	Tracer Design Conc.[a] nL/m^3	Tracer Injection Rate Bags/exp.[b]	Tracer Injection Rate kg/yr	Unit Costs, $/kg	Use Costs, $/yr	Multizone[c] Relative Cost Factor
BNL PFT	PFTs	1	na	0.0004	175.00	0.07	1
Princeton CCTG	SF_6	1×10^5	0.2	17	13.00	220	3,000
LBL ECD-GC	SF_6	1×10^5	0.2	17	13.00	220	15,000 to 57,000
	HC 12	1×10^6	2	142	5.50	780	
	HC 12B1	1×10^5	0.2	19	13.00	250	
	HC 13B1	1×10^6	2	175	53.60	9,400	
	HC 114	1×10^6	2	201	15.40	3,100	
	HC 115	1×10^6	2	182	15.20	2,800	
LBL MS	HC 12	2×10^7	41	2,841	5.50	15,600	1,800,000
	HC 22	2×10^7	41	2,033	8.40	17,000	
	HC 13B1	2×10^7	41	3,499	53.60	188,000	
	Helium	1.3×10^9	2,652	6,110	45.00	275,000	

[a] nL/m^3 (nanoliter per cubic meter) = pL/L (picoliters per liter) = ppt (parts per trillion).
[b] Number of 100-L gas bags required per 6-h experiment; not applicable (na) for PFTs.
[c] Assumes average of four tracer use costs relative to unity for PFTs.

The last column in Table 1 demonstrates that for multizone studies requiring 4 tracers (the CCTG needs only 1 tracer), the use cost of the other technologies' tracers relative to unity for the PFTs is more than 3 to 6 orders-of-magnitude higher. If these technologies are to someday become more than just single research laboratory building ventilation measurement systems, then serious attention must be given to the tracer use cost.

Note that of the four technologies, the PFT technology is the only one commercially available (National Association of Home Builders/National Research Center, Upper Marlboro, MD), at least in its moderate-term passive mode. Tracer use costs preclude the use of the LBL MS system in large buildings. It might be argued that the MS system was developed for homes and small buildings and that the LBL ECD-GC system was developed for large buildings. However, the PFT technology is a single, multifaceted technology capable of passive, short-term, and real-time ventilation measurements in buildings of any size with the lowest tracer use costs by orders-of-magnitude.

Number available. For all but one of the technologies, the number of tracers available determines the number of building zones that can be characterized. The Princeton constant concentration technology is inherently a single-tracer system used primarily to measure air infiltration only in up to 10 zones of a building. It cannot directly measure the air exchange rates between zones.

The LBL MS system used 4 tracers in the recent intercomparison, thereby providing a measure of both zonal infiltration and air exchange. In principle, a large number of tracers could be used simultaneously, limited only by the uniqueness for detection without interference from other tracers, cost necessary for detection above instrument threshold or ambient levels, and toxicity.

The LBL ECD-GC system was used to test 6 tracers in two building tests [5]. The PFT technology used 5 PFTs in the recent intercomparison [1], but up to seven types have been used routinely and as many as 14 types have been studies [8]. Since both are GC systems, the number is limited by the ability to resolve the tracers on the GC column. The LBL system must concern itself with tracer cost and threshold limit values of exposure. As shown above, the cost of PFTs is trivial and there is no toxicity concern. New PFTs are continually being sought because of their many applications being studied within the Tracer Technology Center at BNL.

Tracer tagging. The process of releasing tracer within a building to establish a design concentration is called tracer tagging. For both the steady-state and build-up modes, the tracer tagging or release equipment must be designed to inject or tag the zone at a constant rate. In some real-time cases, the tagging rate is adjusted automatically to maintain zonal concentrations at a pre-set level as indicated by the real-time analyzer; this is primarily to keep the concentrations within the operating range of the analyzer, either real-time or laboratory. Other modes of tagging, such as for tracer decay building ventilation determinations, are not being used by the four tracer technologies in the current scenarios.

Table 1 shows the tracer tagging rate, in units of 100-L bags per 6-h experiment, required to achieve the design concentration for three of the technologies. For the Princeton CCTG and LBL ECD-GC, that volume is ~0.2 to 2 bags, and for the LBL MS system, 40 to 2600 bags. Clearly, the former two could release from bags but the latter requires release from a bigger reservoir, namely, a gas cylinder.

The PFT technology requires a release rate of just 0.2 mL/6-h experiment in such a building, which can be achieved with from 15 to 100 of the passive PFT sources previously developed for use in homes [4]. The emission rate of the device is essentially constant; it increases with increasing temperature in a precisely known fashion (~ 4%/°C). All that is required is deployment of the small sources (~ 1 $^1/_4$-in. long by $^1/_4$-in. diameter aluminum shells) and a record of the room temperature. Thus, this technology has the least expensive release equipment.

Two of the other technologies, the Princeton CCTG and the LBL MS, require injection equipment which meters the tracers in response to the concentrations measured within the zones. This requires computer-interactive metering equipment and delivery tubing to be run to the appropriate location within each zone. With these systems, if tagging is desired at more than one location per zone, the delivery lines must be equally divided. With the PFT technology, a separate source (~ \$6 each) could be placed at each location, as long as the temperature is known within a few degrees at each site. Multiple siting may not be required if tagging is being done via the air-handling (AH) equipment.

The LBL ECD-GC technology uses a stand-alone pumped-tracer injection system [5]. Tubing does not have to be run, because each device can be placed within the zone. The device is not available commercially but is estimated to cost ~ \$4,000 to \$5,000. A 4-zone study would require 4 devices at ~ \$16,000 to \$20,000.

To tag a 50,000-m^3 4-zone building with PFTs (cf. Table 1), would require ~60 sources at a total cost of \$360, which includes the tracer cost. Thus, the PFT tracer release equipment is typically about 100-fold less than the LBL ECD-GC devices and probably the other two technologies' devices as well.

Background interference and toxicity considerations. Most large commercial buildings have air conditioning (AC) systems using two or more of the HC tracers. Thus, local indoor sources may be a problem in many buildings with AH equipment or portable ACs. The PFTs are mainly used commercially as an electrical insulator in high voltage electronic equipment and in compact power supplies. They are much less likely to be found in the indoor air of most buildings.

The toxicity issues raised for the use of HCs [5] is trivial for the PFTs. They are significantly more inert and chemically and biologically more stable and non-toxic even when breathed at 80% levels. In addition, they are used in buildings at concentrations 10- to 100-fold lower than current ambient air levels for HC 11 and HC 12.

Analysis Requirements

The determination of tracer concentrations in building air followed by the calculation of flow rates and the estimate of the errors associated with those flow rates is required for proper assessment of building ventilation performance. The ability of each of the four tracer technologies to meet these analysis requirements in both the steady-state and build-up modes and for short-term as well as real-time building ventilation determinations using the tracer tagging and sampling requirements will be discussed.

Short-term measurements in the steady-state mode. By definition, short-term excludes real-time measurements and thus the Princeton CCTG, which is only a real-time technology, is excluded from comparison here. In addition, the short-term mode requires collection of air samples for subsequent laboratory analysis; but the LBL MS technology, which is capable of such operation, was not equipped to operate in that mode.

For short-term measurements, both the remaining BNL PFT and LBL ECD-GC technologies make use of the same type of laboratory analytical system, namely, an electron capture detector-equipped gas chromatograph (ECD-GC). Such systems consist of a commercial GC with an ECD, automated valves for sampling, backflushing and other features, recorder, peak integrator, carrier and calibration gases, and other miscellaneous items. The GC output, namely, tracer concentrations, is then combined in a computer system with the appropriate building information such as zonal volumes, tracer injection rates, etc., to yield the building flow rate and error analysis information.

The BNL GC system contains 4 automatic valves [8] compared to one in the LBL GC [5] as a fundamental hardware difference. The GC hardware costs are ~$23,000 versus ~$16,000, respectively. Since both systems must also use the additional hardware indicated above, estimated at about $15,000, including an IBM PC, the total hardware costs are estimated at $38,000 and $31,000, respectively, for the BNL and LBL ECD–GC systems. Finally, the manpower required to fabricate all the components into an operating system is estimated at 2 months ($20,000) and 1 month ($10,000), respectively, higher for the BNL GC since it is significantly more sophisticated [8] than the LBL GC system [5].

The overall costs are estimated to be $58,000 and $41,000, respectively, for the BNL and LBL completely-operational laboratory ECD–GC systems; this difference in start-up costs is not significant over the 5-year lifetime of the equipment.

For short-term measurements, both of these systems can be used with their own or other locally-deployed programmable samplers, either adsorbent- or whole-air-based. Tagging with tracer would be with their respective PFT sources and HC-pumped tracer-injection systems.

Short-term measurements in the build-up mode. The same technologies described above can be used in the build-up mode to determine ventilation efficiencies and ages of air. This mode is accomplished simply by sampling the air at the appropriate frequency, without tracers present, and then, at time zero, commence constant tracer tagging. The sampling then continues as the tracer concentrations build-up for several hours. Laboratory analysis remains the same, but different software is used to calculate the efficiencies and ages.

Neither the Princeton CCTG nor LBL MS technologies are designed to operate in the build-up mode.

Real-time measurements in the steady-state mode. All four of the technologies in principle can perform in-the-field tracer tagging, sampling, analysis, and flow calculations. However, because of the 8-min analysis time for the LBL ECD-GC [5], that technology was deemed best suited for short-term measurements only. If the analysis time could be reduced to 2 to 4 min, then 4 to 8 zones could be accommodated within the desired frequency of about 15 min per zone.

The other three technologies each have field analyzers that operate in real-time. The Princeton CCTG system performs an analysis every 0.5 to 1 min using a point-in-time sample injected into an ECD-GC for the analysis of their single tracer, SF_6.

The LBL MS system also uses point-in-time sampling to analyze for multiple tracers on their mass spectrograph with frequencies of just a few seconds per analysis. Both of these two technologies average the results of their point-in-time sample analyses over a period of about 1 h to avoid the problems of non-representative sampling and tracer injection instabilities.

The BNL PFT technology has a field-deployable dual-trap analyzer (DTA) which uses the preferred time-integrated sampling to collect an air sample on one adsorbent trap while the other is being desorbed and analyzed on the in situ ECD-GC. Current analysis times are 5 to 10 min, but various techniques are being studied to reduce that time to 2 to 4 min or less.

In principle, then, the latter three technologies should each be capable of the determination of real-time flow measurements in multizoned buildings. The overall equipment costs are also about comparable. The BNL technology for use in the field will be just slightly less expensive than the laboratory equipment; only the GCs are different. The GC system used for the Princeton single SF_6 tracer system probably also costs the same, especially when factoring in the tracer release equipment. The basic cost of a mass spectrograph is about twice that of a basic GC (~ $30,000 versus $15,000, respectively), so its overall equipment cost is probably higher by about that difference.

Real-time measurements in the build-up mode. The build-up mode presumes that no tracer is present at time zero when a constant emission rate of tracer commences and the building zonal concentrations increase to a steady-state level in about 2 to 6 hours. The LBL ECD-GC cannot make real-time measurements but it may be possible. In addition, neither the CCTG nor the MS system is designed to operate in a build-up mode although, in principle, the MS system could easily operate in that mode.

The PFT technology's DTA can be used readily in both the build-up as well as the steady-state modes if the analysis time can be shortened as planned.

Error analyses. A complete discussion of the need for an error analysis of all calculated flow information is beyond the scope of this proposal, but the experience at BNL has demonstrated that only with the error analysis can it be determined that the flow rates have been properly quantified or that they can even be quantified and whether or not zones need to be calculationally combined (because they are too well mixed) in order to reduce the flow rate uncertainties [9]. The BNL zonal condition number routine, a further development of the overall condition number [9], was demonstrated in the recent Hibben apartment building measurements [1]. It is not known to what extent the other technologies make use of error analysis routines in assessing the validity of their results.

Summary of Various Tracer Technologies' Capabilities

Two tables provide a summary of the discussions in the previous section. Table 2 provides an overview of the four technologies' capabilities to perform a particular measurement, what building flow information is obtained, and to what extent the technology is commercially available. Note that the only "non-yes" responses for the BNL PFT technology are the subject of ongoing research. Real-time measurements have been demonstrated with the DTA, but the analysis time must be shortened. Most of the technology is commercially available with the exception of the short analysis time version of the DTA.

Table 2. Overview of Building Ventilation Measurement Technologies' Capability

	BNL PFT	LBL ECD-GC	LBL MS	Princeton CCTG
Steady-state passive[a]	Yes	No	No	No
Steady-state short-term	Yes	Yes	Possible	No
Steady-state real-time	Almost	Possible	Yes	Yes
Build-up short-term	Yes	Yes	No	No
Build-up real-time	Almost	Possible	Possible	No
Zonal infiltration rates	Yes	Yes	Yes	Yes
Interzonal flow rates	Yes	Yes	Yes	No
Commercially available	Mostly	No	No	Partially

[a] The steady-state passive mode is inherently a long-term (greater than a few hours) measurement.

None of the other three technologies have a steady-state passive measurement capability. All the technolgies give zonal air infiltration rates, but the CCTG is the only one not to give zonal air exchange information. Some of the CCTG equipment is commercially available in its building ventilation measurement form, but both the LBL systems' equipment is one-of-a-kind.

Table 3 provides a more detailed summary of the important considerations in the deployment of the four technologies. Under sampling parameters, the BNL PFT technology is the only one with all affirmative responses, the exception being the need for shortened analysis time in the DTA real-time analyzer; techniques are being studied. Note that both the passive and programmable samplers are commercially available; reducing the cost of a programmable sampler may be possible with a programmable passive sampler.

None of the other three technologies use time-integrated sampling. Their point-in-time sampling is generally representative of the concentration of a single location during a 0.1-to 1-second period and, therefore, may be subject to non-representativeness.

Tracer use costs, although trivial for the PFT technology under the given scenario, are only significantly high for one technology, the LBL MS. The PFT technology also has the lowest tracer tagging equipment costs and has the most tracers available.

The analysis systems, which comprise both the tracer measurement and the flow rate determination equipment, are about comparably priced. The PFT laboratory system for short-term measurements is available commercially as a service; a price is charged for each analysis. The required minimum analysis time of 4 min is not met by the BNL PFT DTA (real-time analyzer), but a number of developments under study should provide a cycle time of 1 to 4 min.

Table 3. Summary of Sampling, Tagging, and Analysis Parameters for Four Tracer Technologies

	BNL PFT	LBL ECD-GC	LBL MS	Princeton CCTG
<u>Sampling Parameters Met</u>:				
Frequency (short-term)	Yes	Yes	Possible	No
(real-time)	Possible	No	Yes	Yes
Representativeness	Yes	Yes	Yes	Yes
Local sampling	Yes	Yes	Possible	No
- Time-integrated	Yes	No	No	---
Remote sampling	Yes	Yes	Yes	Yes
- Time-integrated	Yes	No	No	No
Passive sampler	Yes(ca)[a]	No	No	No
- Cost	$5.00	---	---	---
Programmable sampler	Yes	Yes	Possible	No
- Costs (adsorbent)	~$8000(ca)	---	---	---
(whole air)	~$3000(ca)	~$3000(ca)	~$3000(ca)	---
<u>Tracer Tagging</u>:				
Avg. annual use cost[b]	$0.07	~$3200	~$130,000	$220
No. available	14	6	4	---[c]
- Used at one time	6	6	4	1
Tagging devices	Passive(ca)	Local inj.	Remote inj.	Remote inj.(ca)
- Equip. cost[d]	$360	~$18,000	~$10,000	~$10,000
<u>Analysis System</u>:				
Short-term lab system	Yes(ca)	Yes	Possible	No
- Equip. cost	~$58,000	~$41,000	---	---
- Sample anal. time	13 min	8 min	---	---
Real-time field system	Yes(ca)	No	Yes	Yes
- Equip. cost	~$50,000	---	~$65,000[e]	~$50,000[e]
- Sample anal. time	10 min	---	<1	~1

[a] (ca) means the item or service is commercially available for building ventilation measurements.
[b] Based on 36 continuous tagging days per year to achieve necessary tracer concentrations in a 50,000 m^3-building at 0.7 h^{-1}.
[c] The CCTG only requires 1 tracer.
[d] Cost to tag 4 zones. The BNL PFT and LBL ECD-GC costs scale with the number of zones; the other two are independent.
[e] Includes the tagging device equipment costs.

Intercomparison of Three Tracer Technologies

In the recent intercomparisons of all but the LBL ECD-GC technology, two tests were successfully performed with the PFT technology before the other systems were installed. Passive samplers were deployed in the two 5-zone tests and the results are available in a separate memo dated February 24, 1988 [1]. Real-time PFT sampling was done in three zones and will be compared to the passive sampling results.

A third 4-zone test was performed a week later on February 24, 1988, in which the PFT technology, including the CATS passive sampler, the BATS programmable sampler, and the real-time dual-trap analyzer (DTA), is to be compared with the Princeton and LBL real-time systems. Although results from the other technologies are not yet available for intercomparison, recent interpretation of the BATS 15-min interval data during which three substantial changes in either air infiltration or interzonal air exchange were induced, showed that the technology was able to measure the new rates to better than ±15% in just one interval. Thus, the PFT technology responds and stabilizes in less than 15 min to large step changes in ventilation rates when measured in the steady-state mode. This means that there is a real need for a very short cycle time (~1 to 2 min) real-time PFT analyzer.

This section will present results from these recent tests of halocarbon interference with the BNL DTA and of the response and accuracy of the PFT technology in measuring rapid changes in ventilation.

Halocarbon Interference in the BNL DTA

There was concern that the high tracer design concentrations of the other technologies (see Table 1) would mask the low PFT concentrations in the DTA and possibly the laboratory analyses of the CATS and BATS as well. Indeed, with the current-technology BNL PFT DTA, SF_6 interfered modestly with the first of the 5 eluting PFTs, but the HCs masked all but the highest of all PFT concentrations (cf. Figure 1). However, analysis of CATS passive samplers on the laboratory GC demonstrated no such interference; each of the PFTs were determined accurately because the laboratory system is designed to exclude unwanted, low boiling freons (those used by LBL boiled between -58° and -30°C). Figure 2 shows that for the same sampled period, but collected on a BATS and analyzed in the laboratory, each of the 5 PFTs are clearly resolved. Even expanding the DTA gas chromatogram (GCG) of Figure 1 so that the PTCH is comparable in size to that in Figure 2 does not produce the proper pt PDCH peak (cf. Figure 3). All three halocarbons (HC 12, HC 13B1, and HC 22) were present at about equal levels in the zone, but the large peak is due primarily to HC 13B1 since it has the largest ECD sensitivity.

That the BNL DTA can resolve multiple PFTs in the absence of high concentrations of HCs is shown by the GCG in Figure 4. All five PFTs were clearly discernible; about 100 ppb of SF_6 was present, but it only marginally affected the first PFT, PMCP. By redesigning the DTA to include the features of the laboratory GC, a much-improved and more field-adaptable DTA will result.

PFT-Determined Rapid Ventilation Changes

The third test at the Hibben apartment building was conducted for a 5.75-h period during which a single long-term passive sampler measurement period was conducted plus 23 short-term (15-min each) measurement periods using the BATS programmable sampler, neither of which were effected by the presence of the HCs. The four zones studied were the living area of the basement apartment, the bedroom area, a storage room on the same level, and apartment 1B on the floor above.

The test commenced at 1440. At 1710 the window in the living area was opened; at 1825 the door slightly ajar to the bedroom area was fully opened; and at 1940 the window was closed and the door was again placed slightly ajar. For each measurement period, three calculated modes were performed assuming that 1) the concentrations were continually at steady state, 2) the average change in concentration with time during any one period was equal to the average dC/dt of the period before and the period following, or 3) the appropriate forward or back projection (F/B) was applicable at the time of the ventilation change.

Figure 5 shows the concentration of the tracer deployed in the living zone plus the total basement apartment calculated air infiltration rates, just one of the many interzonal flow rates determined, using the three calculational modes. From 1600 to 1700 the tracer concentration increased under influence from changes in interzonal flows due to ventilation changes in adjacent zones; the calculations correctly showed no change in the apartment infiltration rate during that period. Note that, for example, a point at 1700 represents a sampling interval from 5 min before (e.g., 1655) to 10 min after (e.g., 1710) the indicated time.

The infiltration rates (m^3/h) calculated from the assumption that the concentrations were at steady state (clearly wrong when the window was suddenly opened about 5 cm at 1710) show only a gradual increase with time from 1710 to about 1830. The rates are underpredicted for a step increase in ventilation and overpredicted for a step decrease. The error estimates, which were about the same for the three calculational modes, are shown by the bars. By incorporating the non-steady-state term, dC/dt, Figure 5 shows a calculated 2.2-fold increase in the infiltration rate determined in just 3 measurement periods (45 min).

Since it was known that the ventilation change occurred at 1710 (the last measurement period before the change is indicated by the arrow at 1700), forward projection (rather than averaging) was used to calculate the dC/dt at that period and back projection was used for the period following the ventilation change. The F/B calculated infiltration rate change of 2.2 fold now is clearly seen in just one measurement interval (15 min).

These results imply that by using time-integrated sampling and including the appropriate dC/dt term, significant changes in ventilation rates can be rapidly determined. It is anticipated that such step changes in ventilation should be determinable with short-term and real-time measurement technology in as little as 5 min when time-integrated, rather than point-in-time, sampling is used and the tracer injection rate is held constant (the procedures used with the PFT technology). When using point-in-time sampling and when allowing the injection rate to vary (as well as to not be continuous) under automatic feedback control, such as with the LBL MS technology, it is expected that rapid stability will be much more difficult to attain; this was confirmed by recent measurement experience with the LBL MS system [10].

Needed Short-Term and Real-Time PFT Instrument Developments

As shown above, the PFT technology is the one tracer system capable of steady-state passive, short-term, and real-time measurements for building air infiltration and air exchange rate determinations in multizoned buildings, plus short-term and real-time build-up mode measurements for ventilation efficiency and local age of air determinations. Developments needed to improve and complete the technology include (1) real-time DTA developments, (2) multizone air sampling valve, (3) software changes, (4) large building PFT sources, and (5) a programmable CATS tube device.

Real-Time PFT DTA Developments

The current real-time analyzer was developed for atmospheric sampling down to ambient levels for multiple tracers in 5 min cycles because it was to be used primarily by aircraft in locating and tracking released puffs of up to three tracers [11]. The instrument sampled air for 5 min in one trap at 1 L/min while the second trap was being desorbed and analyzed on an *in situ* GC [12]. To resolve 5 tracers, the analyzer requires a cycle time of about 10 min.

In operation, the present real-time analyzer adsorbs tracers and other constituents onto one of the dual-sampling traps and in the next cycle, they are desorbed, passed through a pre-cut packed column, and then on into a main packed column for separation of the PFTs. The pre-cut column is back-flushed to exclude heavier constituents and the sample is catalytically treated at several points to remove unwanted constituents prior to detection.
This approach works well for ambient air sampling where the largest HC levels are less than 0.5 nL/L (cf. Figure 4), but does not in the indoor environment if HCs are present from leaking air conditioners and refrigerators or if another group is intentionally releasing them at 4 to 5 orders of magnitude higher levels (cf. Figure 1).

The laboratory PFT GC, which does work well with high HC levels, has two extra valves and a consolidation trap (Florasil trap--cf. Figure 6), which uses one of those valves. The other "window" or FD valve allows the early eluting HCs from the pre-cut column to be vented away; only when the PFTs start to elute from the pre-cut column are they focused onto the consolidation trap. The PFTs on this second trap are then desorbed and analyzed on the main column without any interferences (cf. Figure 2).

For use in real-time building ventilation determinations with PFTs, the DTA needs to be modified in the following areas to emulate the laboratory GC system:

- Sampling rate and frequency
- Sampling and consolidation traps
- Pre-cut column temperature programming
- Window valving
- Main column changes

The temperature programmed pre-cut column and window valving will be essential to incorporate. Consolidation trapping (CT) may not be necessary if the dual-traps can be miniaturized to emulate the CT, which is quite possible since the sampling rate can be 25-fold lower (40 mL/min) for indoor use. The sampling frequency can be as short as 2 to 4 min if a CT does not have to be used. Very recent exploratory work with capillary porous layer open tubular (PLOT) alumina columns shows promise of both improved sensitivity and reduced analysis time (perhaps 1 to 2 min). Design concepts can be tested, where possible, on the existing BNL DTA, but a new unit, designed for control from a field-portable computer, should be built. The computer can contain all the necessary software for calibration, analysis, and computation of flow rates.

Multizone Air Sampling Valve

A prototype multizone switching valve was operated in the Princeton study in a 4-zone configuration. It consisted basically of a 24-port scanivalve with a single inlet and a stepping control which synchronized the zone sample switching with the dual-trap analyzer. A final version can be constructed for use with the modified DTA to be operated under computer control.

Software for Flow Calculations

The present PFT laboratory contains all the software necessary to convert the tracer gas concentrations to multizone flow rates with errors using the steady-state matrix solution. For the real-time analyzer, the matrix equation will also have to contain the changing concentration with time terms as well (normally zero for steady state). These solutions can be incorporated into software to be run in the field for real-time determination of multizone flows with complete error analyses.

Large Building PFT Sources

When deployed in homes up to moderately large buildings, the present PFT permeation-type sources provide emission rates adequate to reach design tracer concentrations. For example, the 50,000 m^3 building used in Table 1 would require 15 to 100 PFT sources. For larger buildings, tagging the breathing area, which might consist of many offices, might still require numerous PFT sources. However, when tagging a supply air duct, it may be beneficial to use a PFT diffusion-type source.

A PFT diffusion source would be designed with about a 100-fold higher emission rate using either a porous membrane, such as "thirsty" porous glass, or a capillary tube. The higher rates of such devices would allow the passive CATS tube to be effective in large buildings at sampling periods as short as 5 min. Both devices would still be sensitive to temperature as are the current PFT sources, but, unlike the latter, these devices should be capable of being capped to conserve tracer when not in use. A small temperature controller for PFT sources, developed by Harvard and now commercially available, could be of use with diffusion-type sources.

Programmable CATS Tube Devices

The BATS programmable sampler can provide sampling in each zone of a building without the need for running tubing to each zone. Twenty three samples can be collected with durations of from 1 to 9999 min per tube for subsequent analysis in the laboratory. However, the current BATS, developed for long-range atmospheric tracer experiments, costs about $8,000 to $9,000 each at the assembled market price. A new generation prototype is under development, but it is expected that the cost will still be about $5,000 for the 23-tube samplers.

Since CATS tubes cost only about $5.00 each (24 for $120), a device that would automatically open and close up to 24 to 48 tubes sequentially and that would cost less than $2,000 to market, would be quite useful in real-time multizone building ventilation measurements.

The limit of detection for PFTs on the laboratory GC is 0.1 to 2 fL (femtoliters or 10^{-15} liters), depending on the PFT. Since the minimum quantity collected should be 100-fold greater, the quantity sought on each CATS should be 0.010 to 0.2 pL. Using 0.07 pL as the design quantity and from the known passive sampling rate of 0.14 mL air/min, Table 4 shows that useful passive sampler results can be obtained in as little as 1 hour when the building zone is tagged at about 8 pL/L and 15 min when at 33 pL/L, typical

Table 4. Design Concentrations for Passive Sampler Use

Sampling Duration, min	Effective Sampled Vol., mL	Design Zonal PFT Conc., pL/L
5	0.7	100
15	2.1	33
60	8.4	8
240 (4h)	33.6	2

of design concentrations in homes and small commercial buildings when tagging with the current design PFT sources. Thus, an inexpensive passive programmable sampler is an attractive device for these buildings.

To achieve a 5 min sampling period in the passive mode requires a design zonal concentration of 100 pL/L. This can be achieved in large buildings only through the use of the PFT diffusion source discussed above. Alternatively, short-term measurements would continue to be performed with the more expensive, but available, BATS. A 100-fold increase in the PFT tracer use cost would raise it from trivial ($0.07/yr; cf. Table 1) to negligible ($7/yr).

Conclusions

Tracer technologies are available to measure building infiltration and multizone air exchange rates based primarily on the steady-state tracer mode and to measure ventilation efficiencies and local ages of air using the tracer build-up mode. Steady state can be either the constant emission of tracer with subsequent measurement of the varying tracer concentration due to ventilation changes or a variable emission rate adjusted to maintain the tracer concentrations constant. Build-up refers to the rise in tracer concentration following the start of a constant release of tracer.

Short-term measurements, the field collection of air samples of 15 min or less duration followed by laboratory determination of flow rates, can be performed by most tracer technologies with the exception of the Princeton CCTG. Moderate term (4-6 h duration) and long-term (6 h to several weeks duration) ventilation determinations are effectively restricted to the passive PFT technology.

Real-time measurements, the field collection of multizone air samples of only a few minutes duration followed by in-the-field determination of flow rates, can be performed by most of the technologies with the possible exception of the LBL ECD-GC system based on HC tracers.

The frequency with which short-term or real-time measurements are made must be of the order of 15 min in order to accurately characterize ventilation changes due to AH system changes or occupancy behavior. For one real-time instrument scanning multiple zones, a cycle time of 4 min or less is needed. The sampling point should be representative of the zone and samples should be time-integrated rather than point-in-time quantities. Numerous portable programmable samplers are commercially available.

Despite not too much variability in tracer cost per unit quantity, the cost to use tracers in the various technologies can vary over 6 orders of magnitude with the PFT use cost being the lowest. All have appropriate selection of tracers but the apparatus and costs for field tracer tagging can vary, with the PFT passive sources being the least expensive by far.

Tracer analysis system hardware and software, which comprise the equipment needed to determine the tracer concentrations and to use those results with the appropriate tracer release and building information to determine building flow rates, cost about the same for each of the four technologies discussed.

The PFT technology appears to have the lowest field materials and manpower requirement costs and, in addition, is the only technology capable of performing both real-time and short-term to long-term measurements, the latter including both active as well as the very inexpensive passive approach. Rapid response (<15 min) to step changes in ventilation were demonstrated.

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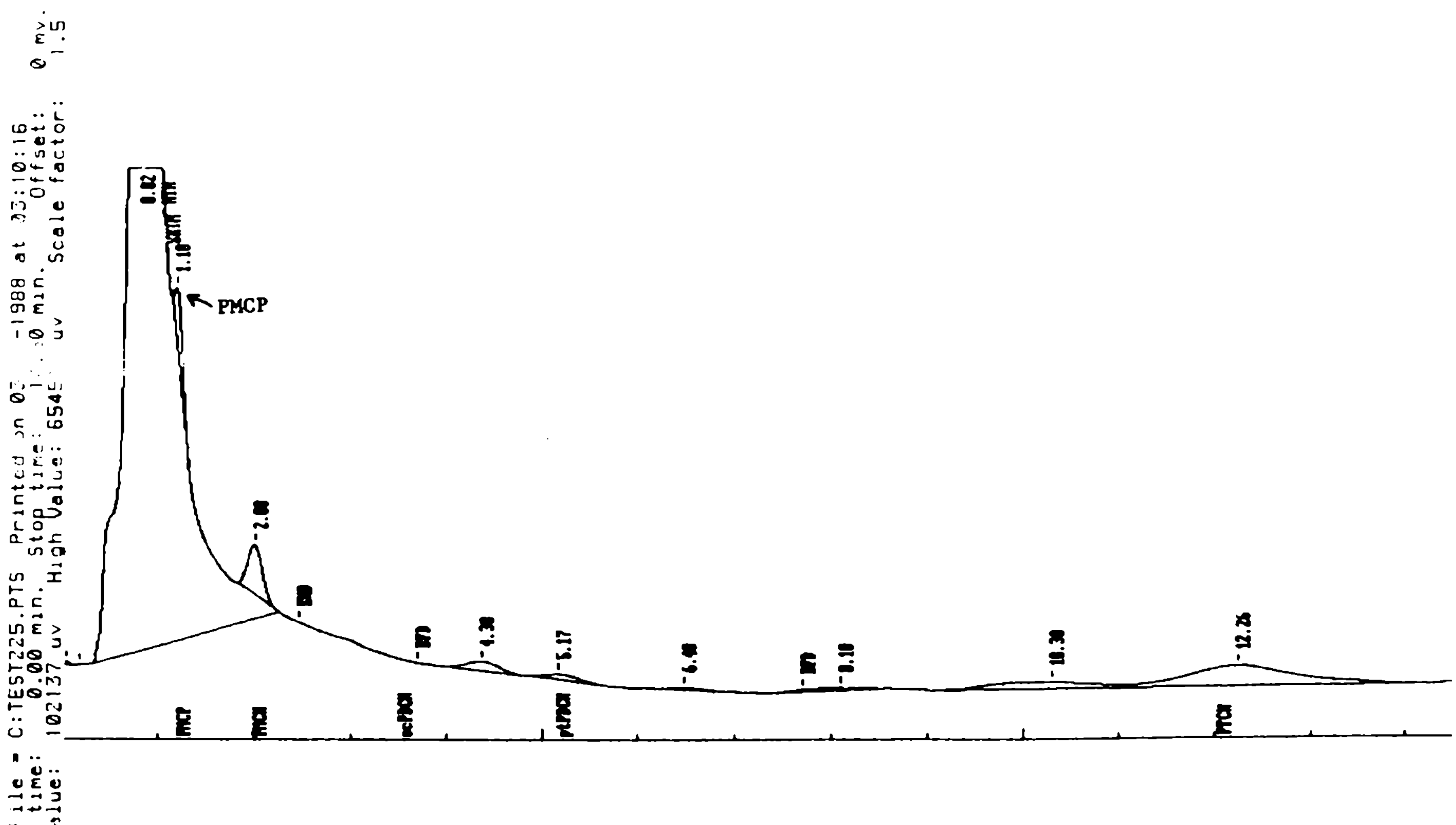

Fig. 1. Dual-Trap Analyzer (DTA) chromatogram of Period 5 (1540 to 1555 on 2/24/88) showing 5 PFTs on the tail of large halocarbon peaks. Sample was taken from the Living, Dining, Kitchen zone.

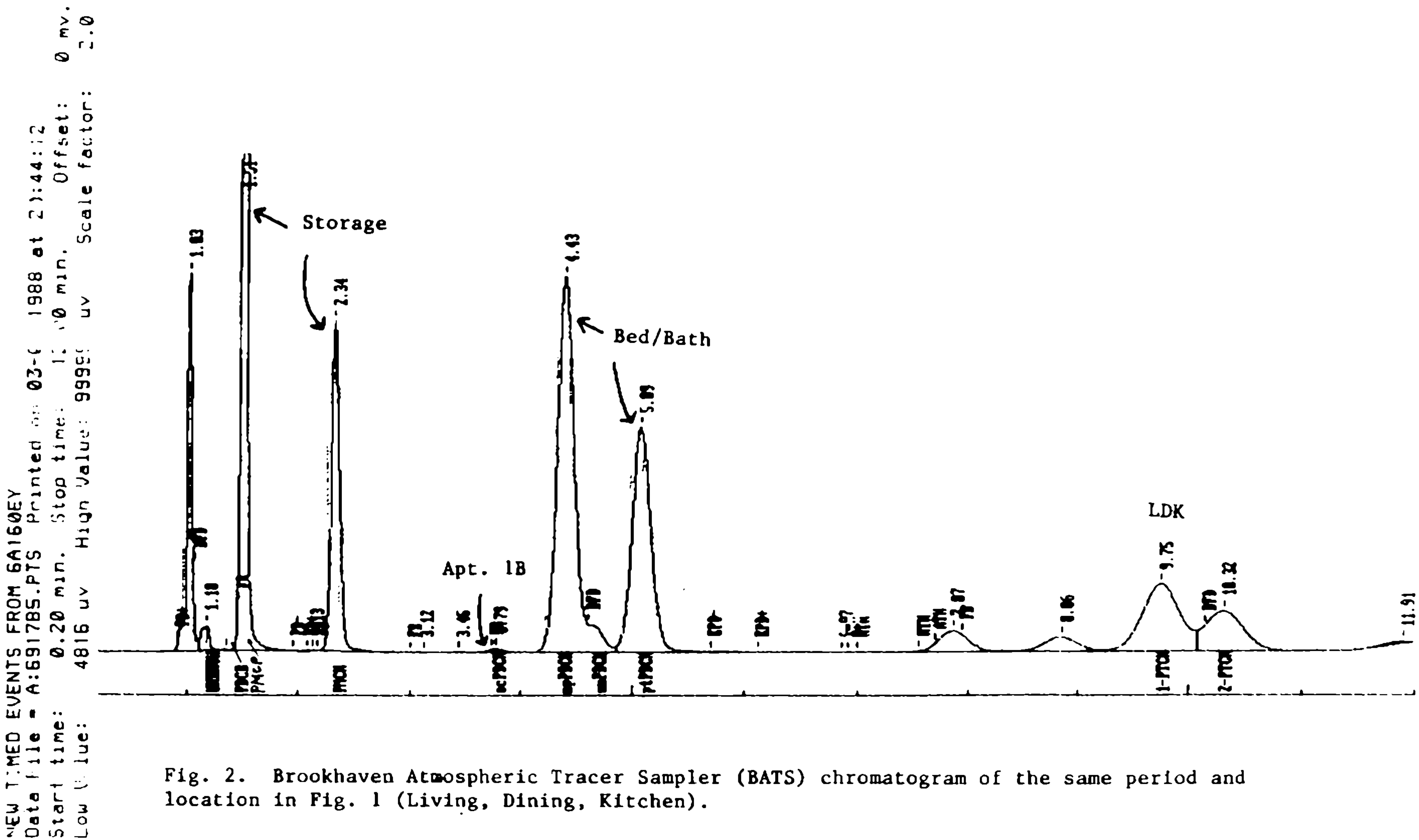

Fig. 2. Brookhaven Atmospheric Tracer Sampler (BATS) chromatogram of the same period and location in Fig. 1 (Living, Dining, Kitchen).

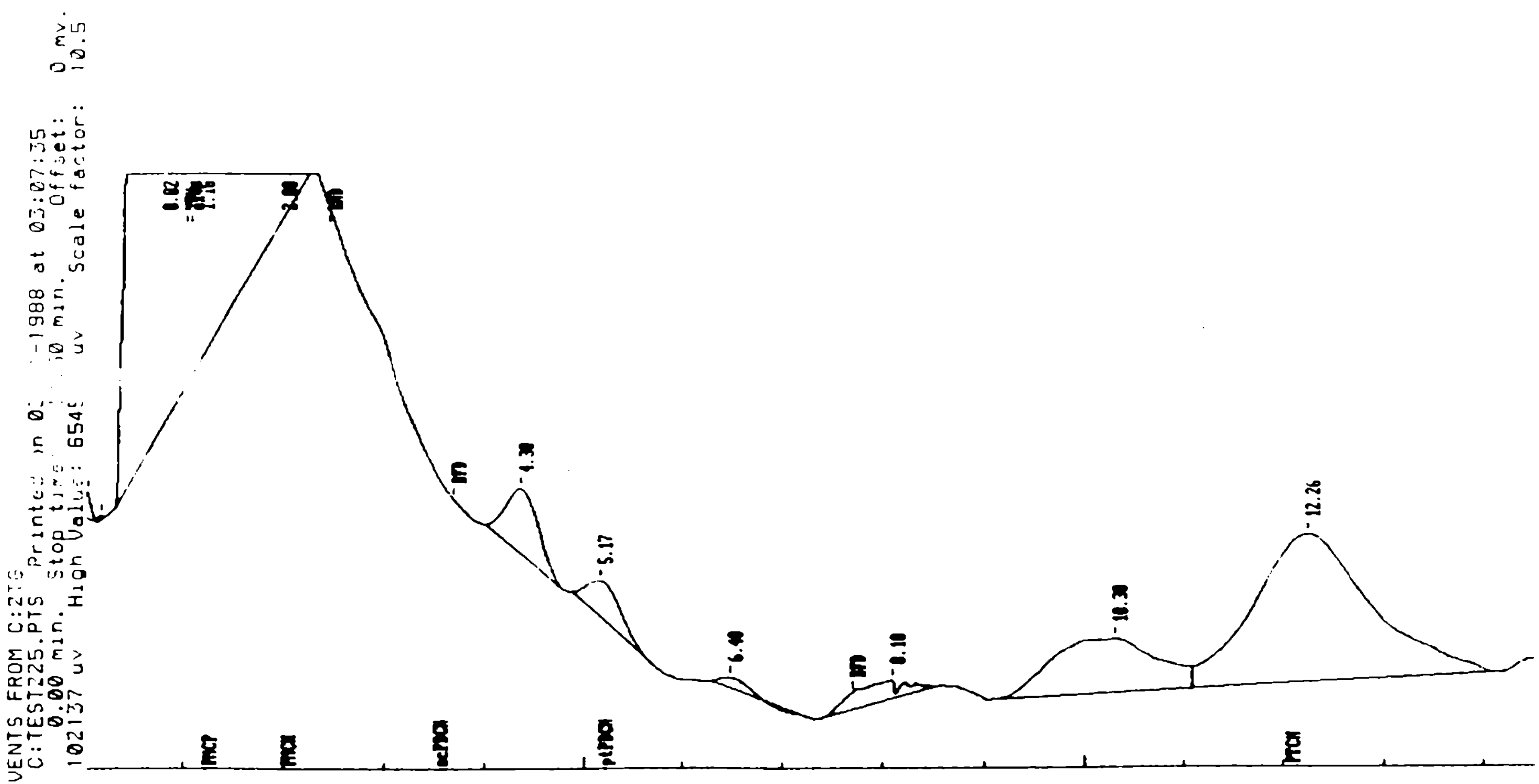

Fig. 3. Seven-fold expanded view of DTA chromatogram of Fig. 1. Note that the p-PDCH peaks are masked by the large halocarbon peak (they are much smaller than the comparable BATS results - Fig. 2).

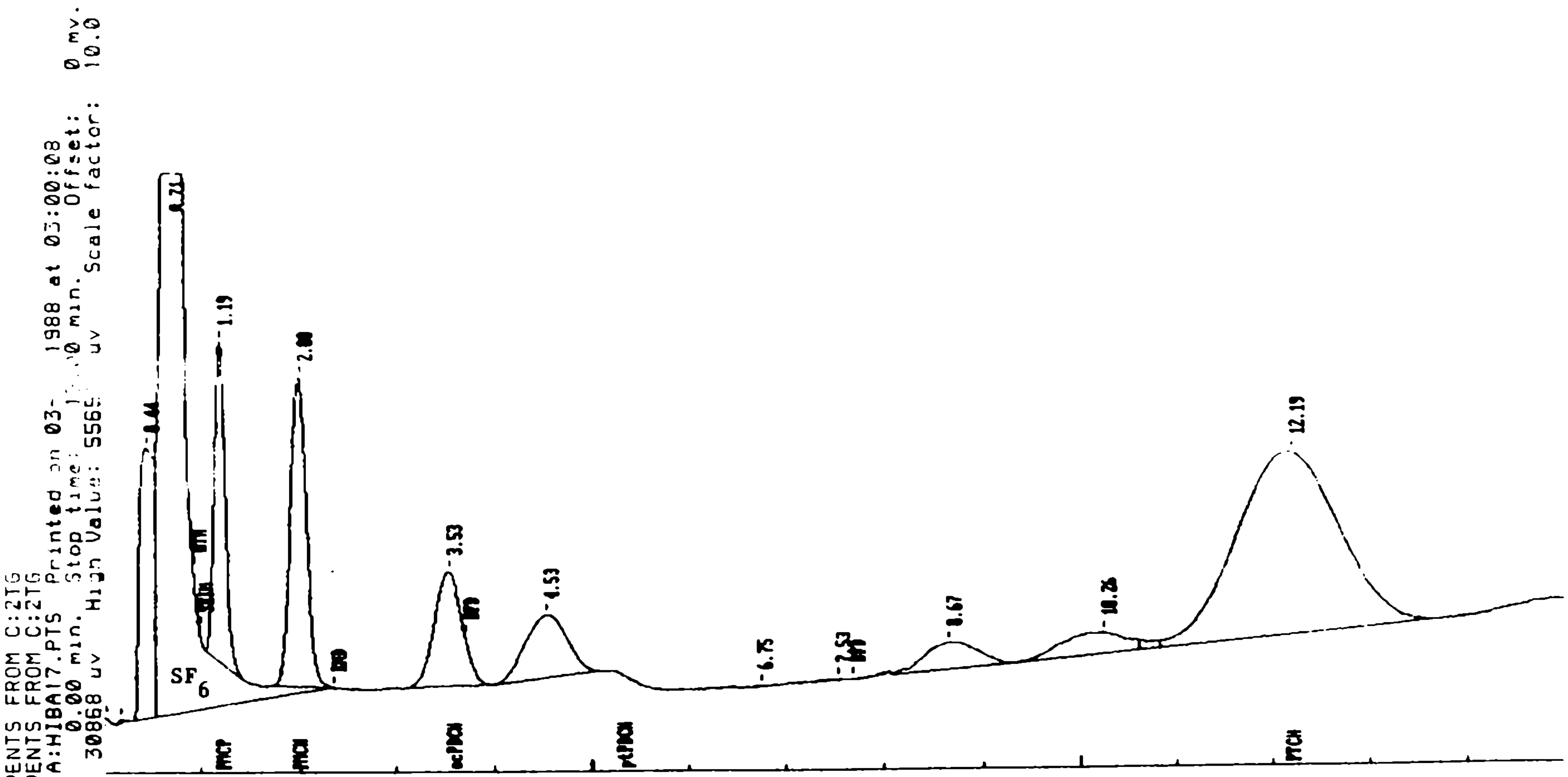

Fig. 4. DTA chromatogram in basement apartment (~ 1900 on 2/17/88) during change of PFTs (all present in apartment). About 100 ppb of SF_6 was present, but no halocarbons. PFT concentrations about 2 to 10 ppt.

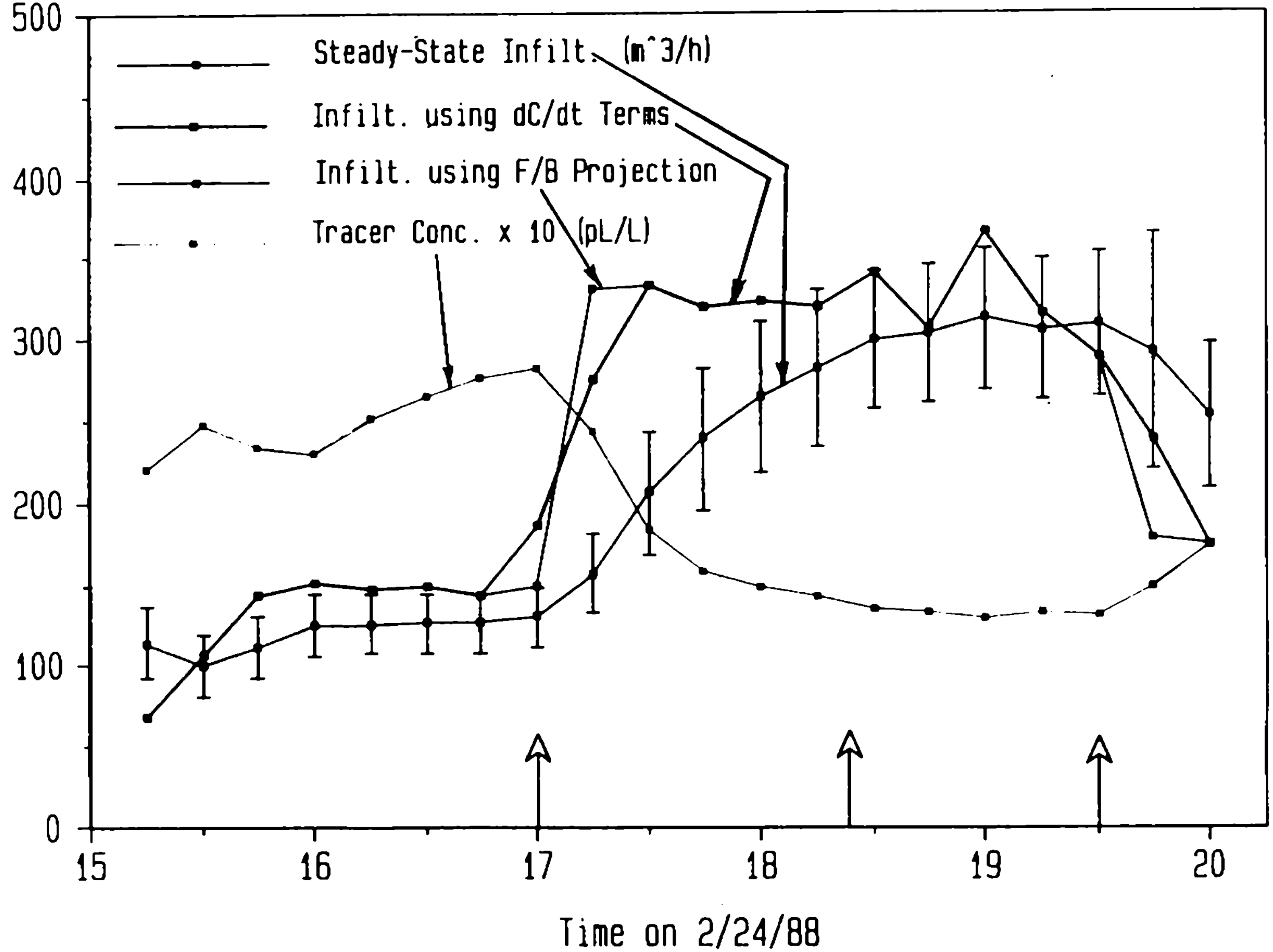

Fig. 5. Apartment tracer concentration and air infiltration rate results using BNL PFT programmable sampler for short-term (15 min) integrated samples. The forward/back (F/B) addition to the dC/dt gives a 15-min or less response time.

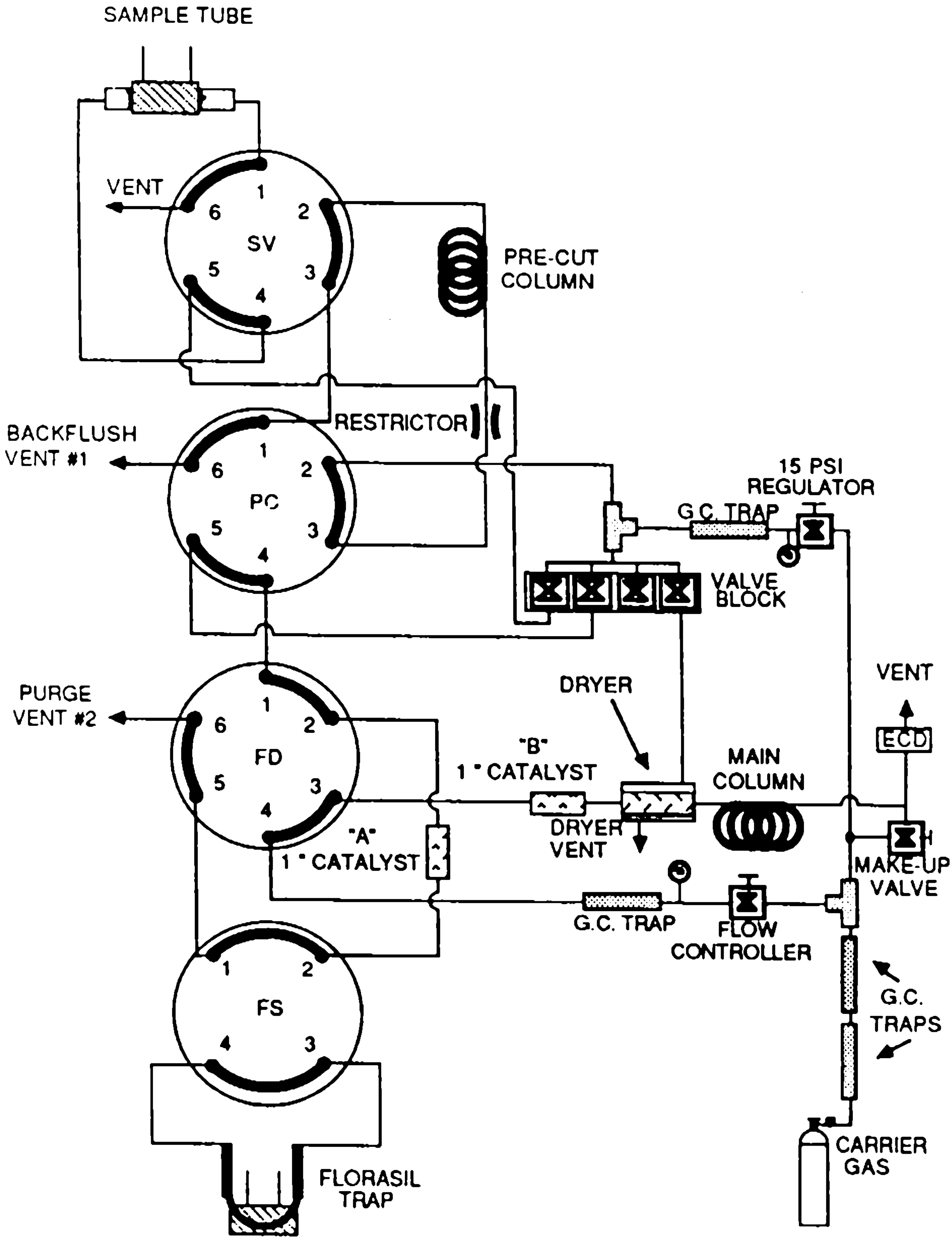

Fig. 6. Schematic of the laboratory GC plumbing. (SV) Sample valve. (PC) Pre-cut column backflush valve. (FD) Flow direction value to isolate the chromatography occurring in the main column from the loading of the next sample. (FS) Florasil trap valve. All valves are shown in their "off" position.

Discussion

P Charlesworth (UK)

What is the ideal position for sample tubes and emission sources during a PFT test?

R Dietz (USA)

Generally, in dwellings, one PFT source is placed in the smallest bedroom and this is then the unit sized room. Then one source/unit size is placed in each of the other rooms. In a one storey house the sources are placed near the middle of an interior wall. In a two storey house the sources are placed towards an outside wall on the 1st floor and towards the door to the room on the second floor. If the house is being treated as a single zone then no sources are placed upstairs. Samplers are generally placed 1-2 to a zone on a wall opposite the source location, and at least 1-1.5m away from any source.

(More detailed information on the deployment of PFT samples and sources is presented in Appendix 1.)

W de Gids (Netherlands)

Has the variation of PFT emission rate with temperature been studied?

Are single or double (duplicate) sampling tubes used during measurements? How is this analysed? Use just one or the mean of two samplers?

R Dietz (USA)

Temperature cycling over short frequencies (less than one day) will give an average emission rate equal to that calculated from the average temperature. An error in the average temperature of 1 degree Centigrade will cause an error in the emission rate of about 4%.

A full account of the temperature dependency of emission rate can be found in : "Evaluation of the Perfluorocarbon tracer technique for determining infiltration rates in residences". Leaderer B.P., Schaap L, Dietz R.N. Environ. Sci. Technol. V19, No.12, 1985, p1225-1232. (This is presented here as Appendix 2.)

When performing multi-zone ventilation measurements with PFT passive samplers (CATS) 1-3 samplers are used per zone. If only one sampler is present in the zone then its tracer concentration is used, with 10% used as an estimate of the standard deviation. When more than one sampler is present the average concentration and the standard deviation of the average is used.

An example of a 4-zone output sheet and its description is given in Appendix 3.

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PAPER 8

ANALYSIS OF ERRORS ASSOCIATED WITH PASSIVE VENTILATION MEASUREMENT TECHNIQUES

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ABSTRACT

In small buildings where ventilation is the primary mechanism for removing indoor air pollutants, interest in converting the resulting energy load on the heating or cooling system of the building is significant. The desire of making field measurements of this time-varying quantity has led to the development of many approaches. The simplest one is called the *passive ventilation measurement technique* which typically measures the average concentration of a constantly emitted tracer gas from which the average ventilation rate can be estimated. This study relied on mathematical models combined with typical weather data to calculate how an ideal passive ventilation measurement would perform; simulations were then conducted based on two house types in four seasons and six climates. It was found that the passive technique significantly underpredicted the average ventilation and that the use of multiple tracers accomplished marginal improvement. Inadequate mixing was found to be a major impediment to the interpretation of the results and could completely invalidate the measurement. Not covered in this report are the additional errors associated with measurement uncertainty, instrumentation limitations, and non-ideal experimental conditions.

Keywords: Ventilation, Infiltration, Multizone, Passive Measurement Techniques Ventilation Efficiency.

NOMENCLATURE

A	Air change (ventilation) rate (ach) [h^{-1}]
$\mathbf{A}$	Air change rate (matrix) [h^{-1}]
C	Instantaneous tracer volume concentration [-]
$\mathbf{C}$	Multizone tracer volume concentration (matrix) [-]
ϵ	Instantaneous ventilation efficiency [-]
$\boldsymbol{\epsilon}$	Multizone ventilation efficiency (matrix) [-]
ϵ_m	Mean ventilation efficiency (for a period of time) [-]
$\boldsymbol{\epsilon}_{\mathbf{m}}$	Mean ventilation efficiency (matrix) [-]
ϵ_0	Overall multizone ventilation efficiency [-]
$\boldsymbol{\eta}$	Distribution efficiency (matrix) [-]
η_0	Overall distribution efficiency [-]
S	Instantaneous (tracer) source strength [h^{-1}]
$\mathbf{S}$	Multizone (matrix) source strength [h^{-1}]
σ_ϵ	Scatter in the multizone efficiency [-]
t	Time [h]
τ_e	Instantaneous turn over time [h]
$\boldsymbol{\tau}_{\mathbf{e}}$	Multizone (matrix) turn over time [h]
Δt	Discrete time step [h]
V_0	Total volume of the building [m^3]
$\mathbf{V}$	(Diagonal) room volume (matrix) [m^3]
$\bar{X}$	*Overbar:* The time average of the instantaneous quantity X

INTRODUCTION

In the last few years the need for a simple and accurate way of measuring the average ventilation rates of large numbers of dwellings has increased. This growing demand has spurred the development of low-cost, long-term monitors that use an emitter, to provide a constant source of a tracer gas throughout the period of measurement and a sampler to provide a time-averaged measurement of the tracer concentration. Any system that incorporates constant emission of tracer gas with a time-averaged concentration measurement, regardless of its physical details, falls into the category of a *passive ventilation measurement technique.*

Several different variations of this technique exist, but the most popular and generalizable system appears to be AIMS — the Average Infiltration Monitoring System. This system, which uses a tube filled with Perfluorocarbon Tracer (PFT) as an emitter and a diffusion-limited charcoal-like adsorber as a sampler, is the one to which most of the scientific[1], professional[2], and trade[3] refers. Although most studies reflect a fairly good understanding of the technique in highly controlled environments, large studies such as the Residential Standards Demonstration Program (RSDP) of the Bonneville Power Administration (BPA) are getting systematic differences, between the PFT and calculations based on leakage measurements, on the order of 50%[4]—a phenomenon that researches do not understand.

It is the intent of this report to discuss some of the measurement errors associated with the generic technique— specifically, to quantify the errors caused by variations occurring in ventilation during the measurement period. We believe that much of the systematic underprediction seen in the measurements obtained by these passive techniques, may be caused by this type of error.

BACKGROUND

In most small commercial buildings and virtually all residential buildings, unintentional air infiltration, or natural ventilation is the dominant mechanism for supplying fresh (i.e., outdoor) air. The rate of infiltration is caused by the interaction between the building's leakage characteristics and the external driving forces caused by the weather. Thus, infiltration varies from building to building, from climate to climate, and from hour to hour. On an annual basis, the average weather-driving forces in North America vary by a factor of three [5] and vary considerably more over shorter periods of time. The tightness of the building envelope, expressed in terms of the effective leakage area per unit of floor area, has been shown to vary over one order of magnitude [6]. Even within a single building, measured infiltration rates have a standard deviation that is typically half the size of its annual mean.

When estimating energy loads related to ventilation, the quantity of interest is the amount of energy required to condition the incoming air. In this situation, ventilation plays the same role as heat conductance because in both calculations its product with the inside-outside temperature difference yields the energy loss; because the infiltration depends on the temperature difference, however, the relationship is nonlinear. On the other hand, when estimating the ventilation component that contributes to indoor air quality, it is the effective dilution of pollutants rather than the average ventilation which is the important quantity to determine.

Many mathematical models exist for predicting infiltration. They range in complexity from single-zone methods useful for houses to complex network models common to large commercial or multifamily buildings. The *Air Infiltration and Ventilation Centre* in England has prepared a guide for selecting the appropriate model [7]. In the sections to follow, we will refer to the model, AIRMOV, which is the ventilation and air movement model incorporated in the Thermal Analysis Research Program (TARP) developed by the National Bureau of Standards (NBS) [8] for simulating ventilation on an hourly basis.

Any time a simulation model is used to draw generalizable conclusions, the assumptions it uses are open to criticism; the NBS programs are no exception. It should be noted, however, that we are using these programs only to generate *typical* infiltration-rate profiles. The absolute values of air flows are factored out and only variations and percentage differences are finally reported. In other words, the conclusions we present are independent of the simulation program used.

VENTILATION EFFICIENCY

Of the many methods used for predicting ventilation rates, virtually all involve measuring the dilution of a tracer gas by the ventilation air[9-11]; these techniques are essentially independent of the specific tracer used[12]. With the exception of the passive technique most tracer techniques take multiple air samples in a time not longer than it takes for the air in the room to be exchanged with outdoor air (i.e. the turn-over time). Thus, these techniques actually measure the *instantaneous* ventilation; to get an average ventilation value the instantaneous measurements much be repeated many times over the period of interest. Any technique, including the passive technique, that averages the concentration of tracer gas over a long period of time will not be able to measure the average ventilation over that period of time accurately—except in the case of unvarying ventilation rates.

One of our earlier studies[13] showed systematic underpredictions* in average ventilation, because the tracer under study and ventilation are not linearly related. However, when estimating pollutant exposures of constant source strength, the ventilation measured from an average concentration *is* the *effective* ventilation. For this earlier work, we used the *mass conservation equation*,

$$\dot{C}(t) + A(t)C(t) = S(t) \tag{1}$$

to derive a characteristic *turn over time*, τ_e,

$$\tau_e(t) \equiv \int_{-\infty}^{t} e^{\int_{t'}^{t} A(t'')dt''} dt' \tag{2}$$

that couples the concentration of a tracer (or pollutant) to its source strength (assuming a relatively steady term):

$$C(t) = \tau_e(t)\, S(t)$$

* Fundamentally, this underprediction is caused by the fact that the ventilation and concentration are inversely related and that the average of the inverse is not the inverse of the average.

This turn over time is the characteristic time for the tracer concentration to approach steady state and has been defined similarly by Sandberg [14,15].

We can define the *ventilation efficiency*, ϵ, this way — so as to allow the mean concentration to be related to the mean source strength and ventilation—

$$\epsilon(t) \equiv \frac{1}{A(t)\tau_e(t)} \tag{3.1}$$

and the *mean-ventilation efficiency* for a period of time as

$$\epsilon_m \equiv \frac{1}{\overline{A}\,\overline{\tau_e}} \tag{3.2}$$

The average concentration of a pollutant or tracer can thus be related to the average ventilation rate and the average emission rate through the mean-ventilation efficiency:

$$\overline{C} = \frac{\overline{S}}{\epsilon_m \overline{A}} \tag{4}$$

(It should be kept in mind that the ventilation efficiency represents a *temporal* efficiency and considers only the time variation of the ventilation, not the local inefficiencies associated with the imperfect mixing of contaminants with incoming air.)

It is in this expression that a systematic error can creep into the passive ventilation measurement. For example, $\overline{S}$ represents the known emission rate of the tracer, $\overline{C}$ is its measured average concentration, and $\overline{A}$ is the quantity of interest—the average ventilation rate; if the ventilation rate varies over the measurement period, ϵ_m will, in general, be less than unity. Given that the usual goal is to measure the average ventilation and that ventilation efficiency is unknown, the difference between actual and effective ventilation represents a systematic error or *bias* in the measurement technique. For indoor air quality measurements, however, we might prefer to know the product $\epsilon_m \overline{A}$, which is the *effective* ventilation rate, and in this case the passive technique gives us exactly what we want.

MULTIZONE VENTILATION EFFICIENCY

The analysis above was based on the assumption that the building could be treated as a single, well-mixed zone. Very often, however, it is necessary to assess the ventilation in a multizone building. Just as spatial efficiency concepts can be expanded to multiple zones [16], so can temporal efficiency concepts. Each of the quantities in the defining relations become matrices reflecting the multizone configuration of the building. The continuity equation becomes the following:

$$\dot{\mathbf{C}}(t) + \mathbf{A}(t) \cdot \mathbf{C}(t) = \mathbf{S}(t) \tag{5}$$

where:

A has a row and column for each zone and

C and **S** have a row for each zone and a column for each species of tracer.

The multizone ventilation-rate matrix, A, has positive diagonal elements that, when suitably volume weighted, represent the total air flow in and out of that zone to all other zones and the outside; the off-diagonal elements are the negative of the flow from one zone to another. Note that there can be flow both from zone i to zone j as well as from zone j

to zone i. The sum of a row or column yields the flow to or from the outside (which is not explicitly treated as a zone), and the sum of all elements yields the total ventilation of the building.

The tracer concentration is related to its source strength through matrix multiplication,

$$\mathbf{C}(t) = \tau_{\mathbf{e}}(t) \cdot \mathbf{S}(t)$$

where we have solved* the multizone continuity equation to get an expression for the multizone *turn over time* :

$$\tau_{\mathbf{e}}(t) \equiv \int_{-\infty}^{t} e^{\int_{t'}^{t} \mathbf{A}(t'')dt''} dt' \tag{6}$$

We can similarly define the *ventilation efficiency matrices as*

$$\epsilon \equiv \left(\mathbf{A} \cdot \tau_{\mathbf{e}}\right)^{-1} \tag{7.1}$$

$$\epsilon_{\mathbf{m}} \equiv \left(\overline{\mathbf{A}} \cdot \overline{\tau_{\mathbf{e}}}\right)^{-1} \tag{7.2}$$

to yield the expression,

$$\overline{\mathbf{C}} = \left(\epsilon_{\mathbf{m}} \cdot \overline{\mathbf{A}}\right)^{-1} \cdot \overline{\mathbf{S}} \tag{8}$$

The ventilation efficiency matrix serves the same function in a multizone environment that the ventilation efficiency served in the single-zone situation but is more difficult to interpret because, it splits and (through its off-diagonal terms) mixes flows from different chambers. Although this matrix is the full descriptor of the efficiency, it may be more useful to have a scalar quantity to use as an overall indicator of the ventilation efficiency in multizone situations. The *overall multizone ventilation efficiency*, ϵ_0, serves this function:

$$\epsilon_0 \equiv \frac{\sum \mathbf{V} \cdot \epsilon_{\mathbf{m}} \cdot \overline{\mathbf{A}}}{\sum \mathbf{V} \cdot \overline{\mathbf{A}}} \tag{9}$$

(where the sum is over all elements of the resulting matrices).

For the multizone case then, this efficiency, ϵ_0, is directly analogous to the single-zone efficiency, ϵ_m. However, because the multizone case is represented by a matrix of efficiency values, we can estimate the variation of the individual elements of the efficiency by taking the root mean square value of the difference between the efficiency matrix and unity:

$$\sigma_\epsilon \equiv RMS\left\{\mathbf{I} - \epsilon_{\mathbf{m}}\right\} \tag{10}$$

where RMS indicates the root mean square sum over all elements in the matrix.

* The matrix differential equation is not generally soluble in closed form; this expression for the turn over time is true only if the ventilation matrix commutes with its derivative. We can, however, use this expression whenever the derivative is small compared to the ventilation or by breaking it into segments in which the ventilation rate can be assumed constant. (The exponential of a matrix is defined through its Taylor series expansion.)

DISTRIBUTION EFFICIENCY

Another important concept which becomes an important factor in multizone environments is that of *distribution efficiency*—that is, the amount of a tracer or pollutant in one zone compared to a perfectly mixed single-zone. This factor involves both spatial and temporal *efficiencies* and is crucial in determining how concentrations from a single source can vary within a building. The distribution efficiency* is defined to be the ratio of the concentration of a gas in a zone to the concentration that would have occurred had the entire building been a single well-mixed zone; it is a matrix. From our definitions of turn over time it is a straight forward task to write down the expression for distribution efficiency:

$$\eta = \frac{V_o}{\tau_e} \tau_{\mathbf{e}} \cdot \mathbf{V}^{-1} \tag{11}$$

The turn-over time in the denominator, τ_e, is the turn-over time for the building calculated as a whole. The inverse volume term enters the equation because we have assumed that there is an equal amount of tracer gas injected into each zone yielding an S-matrix that is proportional to the inverse volume.

The average value of the elements of this matrix, which we designate by η_0, represents the average concentration of the tracer gas in the building assuming equal emission from each zone. Without active control of or advance knowledge about the ventilation in a multizone environment, the best one can do with a single tracer gas is to inject and sample in each zone to get a distribution efficiency of η_0. Even when cruder strategies are used, the distribution matrix can often be used to evaluate the magnitude of the inefficiencies so created.

The average value of a *column* of the distribution matrix is the distribution efficiency for the zone-averaged concentration given emission into a single-zone. The Root Mean-Square (RMS) deviation of this average (from η_0) is a measure of the error associated with using a single emitter and multiple samplers. Similarly the average value of a *row* of the matrix is the distribution efficiency obtained when emitting into all zones and sampling in a given zone; and the RMS deviation of this average (from η_0) is a measure of the error associated with using multiple emitters and a single sampler.

The RMS deviation of all elements of the matrix from η_0 represents the distribution error associated with making a measurement using single sampler randomly placed and a single random placed emitter. Although this may be closest to the sampling strategy used in single family homes—which are often considered as a single zone even though they may have strong multizone character—the sampler is not normally placed in the same zone as the injector. It would be useful, therefore, to separate the distribution efficiency into two groups of sampling in the same or different zones as emitting. Because each subset need not have the same mean distribution efficiency, the average for these two situations is separately recalculated the average for these two situations.

* The distribution efficiency can be greater than unity. Some authors prefer to make a distinction between "efficiency" and "effectiveness" based on whether or not the quantity is constrained to be between zero and unity. Since this distinction is not relevant here, the cleaner term "efficiency" is used in this report.

APPLICATION TO THE PASSIVE TECHNIQUE

The efficiency techniques described above can be directly applied to the passive ventilation measurement technique. If the building can be treated as a single, well-mixed zone, a single tracer gas emitter and a single sampler can be used to estimate the average ventilation rate. This rate would be in error by the difference between the actual ventilation efficiency and the assumed ventilation efficiency (i.e., unity). If the building is broken into a set of internally well-mixed zones that exchange air with one another, then a multizone technique must be employed using one unique tracer gas and one sampler for each zone to get a concentration matrix (zones by gases) from which the average ventilation matrix can be estimated. Again this matrix will be in error by the difference between the efficiency and actual ventilation matrix.

The value of an effective ventilation or distribution efficiency matrix will depend upon the specifics of the problem including the weather, the building type, and the building environment. Because of the large number of factors and the numerical complexities involved in a calculation, the most practical method of demonstrating the variations in the passive technique is to simulate the ventilation behavior for some typical cases. Typical hourly weather data[17-19] was used to calculate the ventilation efficiencies for the six cities of Chicago, Illinois, Edmonton, Alberta Canada, Los Angeles, California, Miami Florida, Seattle, Washington, and Washington, District of Columbia. These data combined with two typical single-family floor plans and the AIRMOV program [8] to generate all of the hourly air flows for an entire year. These twelve sets of data were then used to generate the single-zone and multizone ventilation efficiencies and distribution efficiencies for the four seasons (denoted by the four quarters of the calendar year). The results of these 48 datasets are presented in Table 1.

Two house types were chosen for this simulation: single-story and two-story. In both cases external envelope (wall) leakages totaling approximately 900 cm^2 were assumed so as to achieve typical natural air change rates in the range of 0.3 to 1.0 ach. More specifically, the houses were patterned after typical North American house types: the *Ranch* house, (single-story) and the *Colonial* house, (two-story). A short description of each follows:

The **Ranch house** is a single-story slab-on-grade house broken into five zones (two bed/bath zones, two living zones, and a hall). All of the zones are connected to other zones by open doorways except for one bedroom which connects only to the hall by a closed doorway.

The **Colonial house** is a two-story house with central stairwell and full basement. It was assumed that each level was a well-mixed zone. (This assumption is justified *a posteriori* by looking at the mixing of a single story with open doors connecting the zones.) Approximately 400, 300, and 200 cm^2 of leakage area were assumed for the top floor, main floor, and basement, respectively. A central open stairwell connects the top and main levels and a closed door connects the main level to the basement.

In both examples one of the internal doorways was assumed to be closed and all of the others were open. These doorways represent the only leakage paths (i.e. connections) between the different zones. If short term tests are made on houses, the internal doors are usually opened; in the passive technique, however, the doors are operated normally by the occupants and it is quite likely that one or more will be closed for much of the

TABLE 1a: OVERALL VENTILATION RATES AND EFFICIENCIES for a Ranch House

City	Season	Ventilation Rate $\bar{A}$ $[h^{-1}]$	Single-Zone Efficiency ϵ_m [%]	Multizone Efficiency ϵ_0 [%]	Multizone Error σ_ϵ [%]
Chicago	Winter	0.922	75.5	75.8	14.6
	Spring	0.772	72.3	74.0	14.7
	Summer	0.616	70.7	71.3	14.9
	Fall	0.844	75.6	75.9	13.2
Edmonton	Winter	0.812	81.2	81.3	8.9
	Spring	0.660	69.4	69.1	13.0
	Summer	0.556	70.5	70.0	12.5
	Fall	0.688	77.8	77.4	9.2
Los Angeles	Winter	0.610	68.2	67.6	21.1
	Spring	0.644	74.2	72.4	21.1
	Summer	0.576	74.8	72.6	21.1
	Fall	0.471	76.3	75.1	17.8
Miami	Winter	0.646	74.1	74.4	13.5
	Spring	0.538	77.0	77.4	12.5
	Summer	0.449	81.8	81.3	11.1
	Fall	0.728	77.9	79.1	11.2
Seattle	Winter	0.803	72.9	73.7	16.6
	Spring	0.669	80.7	81.4	12.8
	Summer	0.564	80.4	81.4	12.5
	Fall	0.789	71.2	71.7	14.3
Washington, D.C.	Winter	0.907	75.2	76.2	12.7
	Spring	0.738	77.5	78.3	11.9
	Summer	0.530	80.9	81.5	11.5
	Fall	0.623	70.9	71.4	12.0

measurement period. Sensitivity tests showed only a mild effect of closing a door on the overall ventilation efficiencies, but a large percentage effect on the interzonal flows and associated distribution efficiencies.

The ventilation rate in Table 1 is the overall ventilation rate produced by the simulation. The single-zone ventilation efficiency (ϵ_m) is the ratio of the air change rate that the passive technique would have measured to the actual air change rate, assuming a single-zone building having the same air flows through the envelope as in a multizone building. The next column, ϵ_0, is the ratio of the overall air change rate that a multitracer passive technique would have measured to the actual air change rate.

The last column in Table 1, σ_ϵ, is a measure of the uncertainty of an individual multizone term (i.e., the ventilation between one zone and another) caused by the temporal variation in ventilation. It should be noted that this uncertainty represents a *mixing* of the actual ventilation terms and that the error, therefore, cannot be interpreted as a

TABLE 1b: OVERALL VENTILATION RATES AND EFFICIENCIES for a Colonial House

City	*Season*	*Ventilation Rate* $\bar{A}$ $[h^{-1}]$	*Single-Zone Efficiency* ϵ_m [%]	*Multizone Efficiency* ϵ_0 [%]	*Multizone Error* σ_ϵ [%]
Chicago	Winter	0.807	78.4	84.6	9.5
	Spring	0.678	75.2	82.8	11.6
	Summer	0.537	72.6	78.8	15.1
	Fall	0.722	77.3	85.6	9.8
Edmonton	Winter	0.674	84.6	92.9	6.7
	Spring	0.552	73.7	80.3	12.6
	Summer	0.471	73.3	79.7	13.5
	Fall	0.565	80.9	88.6	9.1
Los Angeles	Winter	0.543	73.3	76.1	12.5
	Spring	0.562	75.6	77.6	11.9
	Summer	0.499	76.6	78.5	11.4
	Fall	0.422	79.9	83.0	9.3
Miami	Winter	0.557	75.9	83.7	12.6
	Spring	0.464	77.9	82.7	13.6
	Summer	0.406	85.2	88.0	9.2
	Fall	0.633	77.7	83.7	11.8
Seattle	Winter	0.666	74.2	81.3	15.7
	Spring	0.551	81.2	88.7	11.5
	Summer	0.470	82.9	89.5	9.5
	Fall	0.646	73.3	80.7	15.6
Washington, D.C.	Winter	0.763	77.6	85.5	12.0
	Spring	0.628	79.4	87.5	10.2
	Summer	0.457	83.1	89.8	10.2
	Fall	0.524	74.5	81.4	12.4

percentage of an individual measured interzone flow but rather it should be considered as a percentage of the total flow to or from those zones. The error expressed as a percentage of the actual flow between two zones will be quite large for low flows and may be infinite since the measured flows are almost always non-zero while the actual flows may be zero (e.g., if the flow is unidirectional between two zones there would be a zero entry in the matrix).

Table 1 expresses the ventilation efficiencies and ventilation efficiency errors for a multizone building where one unique tracer gas is used for each zone. In most field situations only a single tracer is employed although there may be multiple injection and sampling points. Because the distribution efficiency relates the concentration so measured to what one would have measured had the building been a single, well-mixed zone, it is the indicator of choice for understanding errors due to the use of a single (passive) tracer in a multizone environment.

TABLE 2a: DISTRIBUTION EFFICIENCY AND ERRORS
for a Ranch House

City	Season	*Distrib Eff.* η_0 *[%]*	*Uncertainties for* *I All S One [%]*	*I One S All [%]*	*I One S One [%]*	*Eff.±Uncer. Inject One* *S Same [%]*	*S Diff. [%]*
Chicago	Winter	104.5	16.1	12.5	74.7	216.3±65.0	76.6±44.9
	Spring	102.6	12.2	11.5	68.7	202.1±65.8	77.7±41.5
	Summer	103.7	13.5	11.8	69.0	198.0±62.9	80.2±46.7
	Fall	105.3	22.7	10.4	71.9	209.7±54.2	79.2±48.1
Edmonton	Winter	107.2	28.6	11.9	75.2	215.5±48.5	80.1±53.0
	Spring	106.2	21.8	10.9	69.8	201.4±53.1	82.4±50.6
	Summer	106.2	19.3	11.5	67.4	196.1±53.0	83.7±49.4
	Fall	107.2	28.8	10.3	71.9	206.4±45.5	82.4±53.5
Los Angeles	Winter	104.2	11.0	10.4	70.3	200.7±69.6	80.2±45.4
	Spring	108.7	24.5	11.5	68.9	202.6±44.5	85.2±51.8
	Summer	109.3	22.7	12.6	68.1	200.7±45.4	86.5±51.7
	Fall	104.9	10.2	10.9	68.8	197.0±68.3	81.8±45.8
Miami	Winter	103.4	8.2	12.7	74.8	206.7±78.7	77.6±45.9
	Spring	101.9	4.9	13.7	71.9	198.9±76.3	77.7±45.4
	Summer	102.2	5.1	12.5	75.2	200.8±84.4	77.5±47.5
	Fall	99.8	12.9	14.7	78.2	208.1±93.8	72.7±42.0
Seattle	Winter	103.9	17.5	10.5	70.8	206.4±58.8	78.3±46.0
	Spring	104.2	20.3	9.2	67.4	200.3±53.0	80.1±45.7
	Summer	103.2	12.4	9.9	65.8	195.9±63.3	80.1±41.6
	Fall	104.7	17.2	11.8	72.4	208.0±60.3	78.8±48.0
Washington	Winter	103.9	16.3	12.3	72.7	212.3±62.5	76.9±44.3
	Spring	105.1	16.6	13.2	69.8	205.2±58.0	80.1±46.0
	Summer	104.1	12.2	12.9	67.4	196.6±61.5	80.9±45.3
	Fall	103.5	16.2	8.6	66.5	196.0±60.0	80.5±44.2

Table 2 summarizes the distribution efficiencies for the same set of conditions assumed in Table 1. The distribution efficiency, η_0, represents the ratio of the average concentration one would measure if emitters and samplers were in all chambers to the equivalent single-zone (i.e., well-mixed) situation. In addition to this bias, an extra amount of uncertainty will be associated with strategies that do not involve injecting and sampling in all zones. The next three fields of the table indicate the extra uncertainties associated with the non-ideal mixing of a single tracer gas, based on such sampling strategies: the "*I All/S One*" column gives the additional random error associated with the strategy of injecting in all zones and then making a single measurement tracer gas of concentration; the "*I One/S All*" column gives the additional random error associated with the strategy of injecting in a single zone and then averaging the concentrations from all of the zones; the "*I One/S One*" column gives the additional random error associated with the strategy of injecting in a single zone and sampling in a single zone.

TABLE 2b: DISTRIBUTION EFFICIENCY AND ERRORS for a Colonial House

City	Season	*Distrib Eff.* η_0 *[%]*	*Uncertainties for* *I All S One* *[%]*	*I One S All* *[%]*	*I One S One* *[%]*	*Eff.±Uncer. Inject One* *S Same* *[%]*	*S Diff.* *[%]*
Chicago	Winter	114.2	49.0	71.7	161.	275.3±192.4	33.7±30.9
	Spring	112.1	51.7	56.6	158.	280.8±179.8	27.9±19.2
	Summer	111.0	52.3	47.7	154.	279.9±167.3	26.6±18.4
	Fall	114.5	51.4	66.7	164.	283.5±192.4	30.0±22.8
Edmonton	Winter	117.8	49.8	80.7	164.	276.3±203.5	38.6±33.5
	Spring	116.5	54.0	73.0	168.	283.6±203.5	32.9±27.8
	Summer	115.6	54.5	67.0	165.	283.9±196.7	31.5±24.3
	Fall	117.6	49.3	79.8	163.	276.0±201.5	38.5±33.2
Los Angeles	Winter	114.3	48.6	66.1	160.	281.4±184.0	30.8±31.3
	Spring	115.5	48.6	57.1	164.	297.8±174.6	24.4±24.4
	Summer	115.3	50.6	50.6	166.	303.3±169.8	21.3±20.9
	Fall	114.1	49.2	62.5	160.	283.3±180.7	29.5±29.1
Miami	Winter	111.1	53.2	52.8	160.	283.5±178.5	24.9±19.7
	Spring	108.1	46.7	36.3	142.	271.1±140.7	26.6±21.5
	Summer	107.4	57.1	40.1	142.	258.4±156.0	31.9±34.6
	Fall	109.6	48.0	46.6	153.	280.3±161.0	24.3±21.2
Seattle	Winter	112.9	44.5	65.2	154.	272.8±177.7	33.0±25.3
	Spring	113.4	50.2	59.8	161.	285.6±182.7	27.3±20.2
	Summer	113.5	52.6	58.0	163.	287.8±184.3	26.4±22.3
	Fall	113.8	47.2	67.8	158.	275.0±186.0	33.2±25.9
Washington	Winter	114.9	51.6	69.9	165.	281.2±196.9	31.8±26.7
	Spring	113.1	55.5	56.2	163.	285.3±186.4	27.1±19.1
	Summer	110.4	53.6	42.7	150.	274.7±161.6	28.2±21.5
	Fall	116.4	54.7	71.4	167.	283.1±202.9	33.1±26.2

The last two columns of Table 2 are an expansion on the single injection/single sample strategy. Although this strategy may be used often, the sampled zone is not normally the same as the injected zone. The middle three columns of Table 2 are all uncertainties around the same mean distribution efficiency (η_0). When the sampled zone is the same as the injected zone, the mean distribution efficiency is generally going to be higher than the η_0 and, conversely, when the sampled zone and the injected zone are different then it will be lower. Therefore, the distribution efficiency and its uncertainty have been recalculated for these two cases and results are given in the last two columns: "*S Same*" indicates that the sampling has taken place in the same zone as the injection (i.e., the diagonal element of distribution efficiency matrix); and "*S Diff*" indicates that the sampling has taken place in a zone other than the injection zone (i.e., off diagonal).

DISCUSSION

Passive ventilation measurement techniques tend to underestimate the average ventilation of even a well-mixed (i.e., single-zone) building if the ventilation varies over time. For the two building types and six climates investigated, the seasonal ventilation tended to be low by from 15% to 35% (See ϵ_m column of Table 1.) Earlier modeling of a specific two-zone environment suggests a similar size effect[20]. Although the size of this underprediction is affected by weather, construction details, duration of measurement period, absolute ventilation rate, etc. (see ref. 13), the trend toward significantly low measurement is clear.

Although this low bias may have a significant impact on the ventilation rate used for such purposes as calculating energy load, it has no impact on the ventilation rate used to determine the indoor pollutant exposure caused by constant sources. That is, the *effective ventilation rate* measured by the passive technique is the appropriate ventilation rate to couple a pollutant source strength to the average concentration in the building. The ventilation efficiency is the ratio of this effective ventilation to the average ventilation and is a direct measure of the bias in the passive ventilation measurement technique.

In a multizone building the situation is qualitatively similar but quantitatively more complex. There are two additional ways that the passive technique can be used in a multizone building: in full multigas, multizone mode, or in a single-gas mode. The former allows all interzonal flows to be estimated whereas the latter is intended to get only the overall ventilation of the building.

The simplest comparison one can make between a single-zone and multizone building is in the ventilation efficiency (ϵ_m, ϵ_0 respectively). For the ranch-style house these two numbers are very close. This closeness indicates that for a house with relatively good communication between zones, the overall ventilation efficiency measured with multiple tracer gasses yields the same result as if additional internal mixing were induced (i.e., as if the building were made effectively single zone).

The agreement between the two overall ventilation efficiencies is not so close for the colonial-style house. Although the individual zones may have large openings between them, the presence of the stack effect tends to make the airflows go in a single direction; therefore, the communication is not as good as that in a single-story building. It should be noted that while the single-zone efficiencies for the two building types are approximately the same, the multizone ventilation efficiency for the colonial-style house is higher. In short, it is an advantage to use multiple tracer gases in multistory buildings.

If multiple tracer gases are used, interzonal airflows can be calculated by the passive technique. From this analysis the uncertainty of any of these values, σ_ϵ, is 10% to 20% of the value of the zone is total. Thus, even for moderate interzonal flows the value of those flows may be off by a large amount. The passive method can accurately determine only the largest flow from any zone; at best only qualitative indications of other air flows can be gleaned from this technique.

In general, the information gained by using multiple tracers will not be worth the effort required; accordingly, it is important to understand the errors induced by using a single tracer gas in a multizone environment. That is, the distribution efficiency must be taken into account. (Note that all of the following arguments are valid whether the ventilation rate is stationary or time-varying.)

The overall distribution efficiency, η_0, is an estimate of the bias involved in estimating the overall ventilation efficiency from single tracer-gas information. Specifically, it is the ratio of the average concentration obtained by injecting into every zone to the concentration obtained when injecting into a single, well-mixed zone. For the ranch-style house the average concentration is 0-5% higher than that associated with the equivalent single-zone building and for the colonial-style house the concentration is 8-18% higher. These values parallel the ratio of the overall multizone ventilation efficiency to the single-zone ventilation efficiency and are similarly caused.

If a less than ideal injection/sampling pattern is used, there will be a large uncertainty in the result in addition to the bias mentioned in the paragraph above. For the ranch-style house there will be an extra 10-25% uncertainty in the estimated tracer concentration (and hence ventilation), if either the sampling or injecting is not done in every zone. The analogous figures are much higher for the colonial-style house (i.e., 40-80%) because of the poor communication from one story to the next.

If injection and sampling are done in a single zone only, both the biases and uncertainties become unacceptably large. In cases where experimental design prohibits using many samplers or injectors in a building, additional mixing must be provided to increase the communication between zones. The fan from a typical central HVAC system can supply more than enough mixing to convert a multizone building into a single-zone building, and, as long as the fan does not induce any extra infiltration, one design strategy is to run the fan continuously during the experiment.

CONCLUSIONS

Ease of use does offer a clear advantage to the passive ventilation measurement technique. Unfortunately, its simplicity is gained at the expense of some accuracy. The theoretical description of the phenomenon and the results in Tables 1 and 2 have been used to draw the following conclusions about these errors and the appropriateness of the technique.

- *The passive technique underpredicts the average ventilation.* Time-varying ventilation causes the (temporal) ventilation efficiency to be less than unity for the averaging times associated with the passive ventilation measurement technique. The examples presented indicate a seasonal underprediction in the range of 20-30%.
- *The passive technique is appropriate for indoor air quality measurements.* The effective ventilation measured by the passive technique can be used directly to estimate the average concentration of any pollutant of (known) constant source strength.
- *Multiple injectors and samplers should be used.* Mixing of tracer gases throughout the test space is critical. Without good tracer distribution, the uncertainty in the results could easily be 100% in a multizone building. Even with good injector/sampler coverage there will be a bias on the order of 10%. If possible, internal mixing should be added.
- *Multiple tracer gases for unidirectional flow.* In some buildings the internal air flow tends to flow continuously in one direction (e.g., stack-dominated buildings or houses in heavy prevailing winds). The use of a different tracer gas in each zone will improve the estimate of the average ventilation, as in the example of the colonial-

style house, where the underprediction was cut by one third.

- *Interzonal airflows are unreliable.* Multiple tracer gases ostensibly allow the estimation of average interzonal airflows. The uncertainties on all but the largest flows are sufficient to make these estimates quantitatively useless. As noted above, however, these values may be useful in predicting the average concentration level in one zone due to a pollutant source in another zone.

These conclusions are based on simulation runs on two housing types in six climates. Although such calculations cannot be considered exhaustive, they do span the typical range of conditions found in single-family homes. These simulations lay the groundwork for both future theoretical and experimental research.

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Discussion

P Charlesworth (UK)
Do you have any knowledge of the PFT technique being compared with "air change rate" as evaluated from DC pressurization tests?

M Sherman (USA)
There are several such intercomparisons currently being performed in North America. The results will probably be published soon.

P Collet (Denmark)
Is it possible to use the PFT method by mailing the site equipment to householders and having it returned in the same way to be analysed in the laboratory?

The PFT method shows a small negative bias when used in unoccupied buildings. Would the bias be greater or less in occupied buildings?

M Sherman (USA)
No. The adequate deployment of PFTs requires the skill of a trained technician. Therefore the results from "Mailshot" PFT tests would be unreliable.

The bias in PFT measurements increases with the variation of air change rate. Since, in general, occupants increase the variation in air change rate, occupied flats would exhibit larger biases.

R Dietz ventilation (USA)
1) What is the time constant for calculating the change due to a step change in ventilation and how does the standard deviation in the calculated flows vary with that time constant?

2) Will you provide your estimated errors on the Hibbert apartment flow rates?

M Sherman (USA)
1) The time constant is a user-defined quantity. Increasing it yields a smoother result by damping out fluctuations but delays response to a step change. Our default value is half an hour.

2) This data will be a focus of analysis in the months ahead and we expect to write a report upon the completion of the analysis.

AIR INFILTRATION AND VENTILATION CENTRE
MEASUREMENT TECHNIQUES WORKSHOP 1988

Køge, Denmark
21-23 March 1988

APPENDIX 1

INSTRUCTIONS :
BROOKHAVEN AIR INFILTRATION MEASUREMENT SYSTEM

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Brookhaven National Laboratory
USA

INSTRUCTIONS
BROOKHAVEN AIR INFILTRATION MEASUREMENT SYSTEM

by
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Revised: November 13, 1986

The BNL/AIMS (Air Infiltration Measurement System) employs a passive miniature perfluorocarbon tracer (PFT) source and a passive sampler (CATS - capillary adsorption tube sampler) to determine a time averaged indoor tracer concentration, the reciprocal of which times the source rate is approximately equal to the average infiltration rate. Sampling periods can be as short as 2 hrs and as long as several months. Comparisons of this technique with simultaneous measurements by SF_6 decay, SF_6 steady-state, automated SF_6 decay, and blower door techniques, have shown the BNL-AIMS to be simpler, more reliable, and more consistent from one measurement to the next.

By using multiple types of tracers, i.e., a different type of PFT in each zone or floor of a building, detailed information on the rates of air exfiltration and infiltration from each zone as well as the rates of mixing between zones can be determined. This information is essential for realistic assessment of the distribution and fate of indoor contaminants and for accurate predictions of energy savings resulting from weatherization.

The PFT sources are shipped separately from the samplers. Each source shell is engraved with a code, the first number of which identifies it as one of the 4 available PFT types, i.e., type 1,2,3 (or TC), or 8. The sources are usually deployed one per every 500 ft^2 (46.5 m^2) of living area. Typically, in a single story ranch-type home, two sources are placed in the living room - dining room - kitchen area (as per the attached diagrams) and one in each of the bedrooms.The same type of source should be used if the floor is to be treated as a single zone. If the house has a basement, a different PFT type should be used since it is a separate but attached zone. For an open (unfinished) basement, one or two sources may be used; if it is divided into rooms, 2 sources should be used. Ignoring the basement by not including any sources and samplers or using sources of the same type as the main floor, can result in errors in the determination of the living space ventilation rate.

Alternatively, the main floor of a ranch-type home can be divided into two zones, the family zone (living room - dining room - kitchen) and the bedroom zone (the bedrooms, bathroom, and hall), each tagged with the appropriate number of PFT sources but of different types. With a basement, the house then becomes a 3-zone study.

In a two story home, two sources of one type are deployed on the main floor (e.g., the living room and family or dining area) and one of a second type in each bedroom upstairs. If the living area is to be treated as a single zone, then only two sources of one type should be deployed on the main floor. The stack effect will provide an essentially equal concentration upstairs without sources; the concentration should, however, be measured upstairs as well as on the main floor. During these tests, the doors to all rooms should remain open with the exception of the basement doorway which should be closed if that is its normal position.

The sources are used as received; they are always emitting tracer, there is nothing to open or uncover, and they may be placed in any orientation. Generally, a PFT source is placed within 0.5- to 1.5-meters of the floor and no closer than 1-m to an outside wall. For example, it can be taped onto the leg of a table or end table or even on a lower portion of a hanging chandelier. Since the source is sensitive to temperature, it should not be placed within a meter of a heating or cooling source, in direct sunlight or other drafty location such as a window, nor at a location where air would carry the PFT vapors outside or to another zone before they had mixed uniformly within the zone where they were placed. Since heated air rises and cooled air sinks, the PFT location should be at a vertical location not too far above or below the temperature measurement/control elevation and not be placed above a warm air source (e.g., a lamp or the top of a refrigerator) nor below a cooled air source (e.g., an air conditioner vent or a window sill). The average temperature of the source must be recorded on the data sheet, which is attached. Note: The daily average room temperature is usually adequate for this purpose, even in the case of one or more daily temperature set-back cycles.

The choice of PFT source types with zone location is important in multizone structures. Because of the stack effect in all houses, a source placed on the second floor will have a very low concentration in the basement. To improve the precision of its measurement in the basement, the second floor-tracer selected should be one with the highest emission rate and the highest detectability, i.e., the earliest eluting tracer on the gas chromatograph (GC) column. Thus the choice for the second floor tracer in a 3-zone study is either Type 1 or Type 8*. The same reasoning extended to the other floors dictates that Type 2 be used on the first floor and Type 3 in the basement. The use of Type 1 in one zone and Type 8 in another zone in a 3-zone building should be avoided because those two tracers elute very close to each other and are therefore difficult to quantify without using special GC conditions. In stacked 4-zone structures, when both Types 1 and 8 must be used, the correct choice for the uppermost zone is Type 1, followed by Type 8 in the next lower zone, Type 2 in the next, and Type 3 in the lowest zone (see below).

The passive samplers (CATS) are also shipped under separate cover. Please remember: DO NOT STORE THE SOURCES AND THE SAMPLERS IN THE SAME LOCATION. The sources and samplers should definitely not be shipped in the same container and, ideally, not even shipped on the same day. For example, if transported in the same car or truck, there is a possibility of contamination. During field deployment, the samplers can be placed in the engine compartment of a vehicle (effectively outside) while the sources are maintained within the vehicle passenger compartment or trunk. To this end it is generally wise for 1 or 2 passive samplers to remain as controls, that is, to remain unopened, for each series of home infiltration measurements.

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*Tracer Codes:

Type	Abreviation and Name	Deployment in Bldg. Zone Locations: 3-Zone Study	Deployment in Bldg. Zone Locations: 4-Zone Study
1	PDCB-perfluorodimethylcyclobutane	—	Highest
8	PMCP-perfluoromethylcyclopentane	Highest	Next to highest
2	PMCH-perfluoromethylcyclohexane	Middle	Next to lowest
3	PDCH-perfluorodimethylcyclohexane	Lowest	Lowest

One or two samplers are usually deployed in each zone of the home with the same location restrictions as the sources and at least 1 to 2 meters from any PFT source or source of air not representative of the room air (e.g., air from outside or another zone). Thus, the samplers are usually placed near another inside wall location (but at least 2 cm from any wall) and not in a flowing air stream without a shelter (such as an envelope or box). In the bedroom zone of a ranch house or 2-story house, it is prudent to sample in the master bedroom plus one other bedroom; this provides a better average for that zone. In the family zone, two samplers located as per the two-story diagram give an average concentration which is better than just placing one sampler as per the one story diagram.

The samplers are not temperature sensitive, but extremes should be avoided. They can be placed on a table or taped to the leg of a chair or table in any orientation. The samplers have a rubber cap on each end. To initiate sampling, only one cap must be removed (the one near the numbered end). The sampler number, location, and time and date sampling commenced must be recorded.

At the end of the designated sampling period (e.g., one day, one week, one month, etc.), cap the sampler and record the time and date sampling ceased. If provided, return the CATS in the 30-capacity trays, arranged by home and by zone according to the data sheet to fascilitate record keeping and analysis. A strip of masking tape on the foam tray below the row of CATS can be conveniently marked to identify the CATS associated with a particular home or measurement period.

Also record other information as called for on the attached data sheet. The volume of each zone of the house should be obtained from inside dimension measurements or estimated from outside lengths and widths, subtracting 1 foot (0.3 m) from each, but using inside ceiling heights. A separate data sheet should be used for each home; please make copies from the attached sheet.

Return sources and samplers to different buildings. PFT sources are returned to Arlene Waltz , BNL, Bldg. 527, and samplers to Robert W. Goodrich, BNL, Bldg. 426.

IMPORTANT INFORMATION:

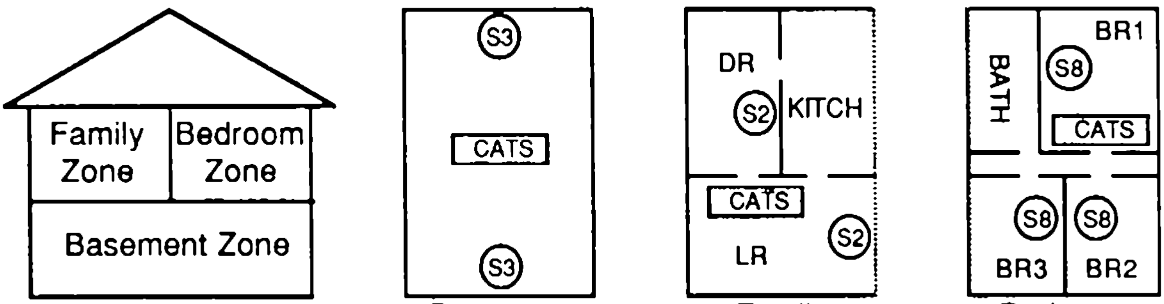
- ALL PFT sources, CATS passive samplers, and 30-capacity trays must be returned at the conclusion of your use. A charge of $5 per CATS or tray and $10 per PFT source will be billed for each item not returned or lost.
- All PFT sources must be returned, sorted by type, with all of one type in one container or envelope to Arlene Waltz , Bldg. 527. All types may be shipped in the same package, but not with the samplers.
- All CATS must be sorted by home and by zone as indicated above and returned in the trays provided to Robert W. Goodrich, BNL, Bldg. 426. If not, the samplers will be returned to you for compliance.
- Individual data sheets of the attached format must be completed for each home and sent with the samplers to Bldg. 426. You may use your own sheets for your field use, but then you must transcribe the information onto our sheets. We will return data sheets that do not comply, which will delay analysis and reporting of results.

DEPLOYMENT OF PFT SOURCES AND SAMPLERS

As a reminder, the PFT sources are temperature sensitive and should not be placed on or near an object that is at a significantly different temperature than the average temperature in the zone. An ideal spot is near (but not on) an inside wall so that the tracer can be mixed and distributed uniformily throughout the zone before leaving in any of the outgoing air.

The samplers should be placed closer to the center of the measurement zone and should sample the greatest open volume of air possible. If multiple samplers are used for a given zone, then the samplers should be distributed so that they sample approximately equal volumes within the zone. The samplers are not temperature sensitive, but are affected by high air velocities such as in front of a forced air vent or in a duct; shielding can prevent such effects.

One-Story, Ranch Style House with a Basement



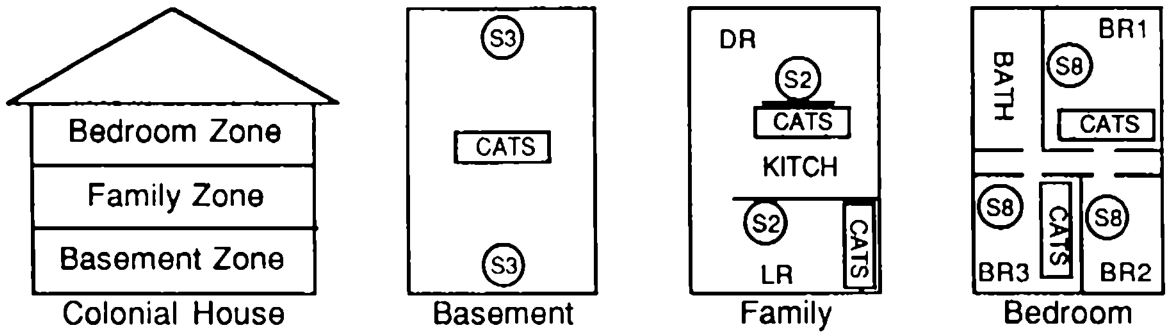
Ranch House   Basement   Family   Bedroom

<u>Basement Zone</u>
Sources - Place two PFT type 3 sources on opposite ends of the basement. If an obstruction exists, place a source on either side of the obstruction.
Sampler - Place the CATS in the center of the basement or within the largest open area.

<u>Family Zone</u>
Sources - Place two PFT type 2 sources within the two largest rooms.
Sampler - Place a CATS in the largest room.

<u>Bedroom Zone</u>
Sources - Place one PFT type 8 source in <u>each</u> bedroom.
Sampler - Place a CATS in the largest bedroom in the zone.

Two-Story, Colonial Style House with a Basement



<u>Basement Zone</u>
Sources - Follow directions for ranch house.
Sampler - Follow directions for ranch house.

<u>Family Zone</u>
Sources - Place two PFT type 2 sources in the rooms at opposite ends of the zone.
Samplers - Place two CATS in the two largest rooms in this zone, towards the center, but away from each other and the sources.

<u>Bedroom Zone</u>
Sources - Follow directions for ranch house.
Samplers - Place two CATS in the two largest bedrooms within this zone.

House Description
____ 1 story
____ 2 story
____ w/basement
____ split level
____ w/fireplace
____ w/woodstove

Project Title ______________________

House ID: ____________ # of Zones: ____

Start Date: / / Start Time: : am pm (Circle one)

Stop Date: / / Stop Time: : am pm

Zone #: _____ Zone ID: __________ # of Sources: _____ Source Code: ___

Avg. Temp. (^oF): _______ (^oC): _______ Volume (ft^3): _______ (m^3): _______ # of CATS: _______

CATS ID	Room	Item Placed On	Source Location: Room	Source Location: Item Placed On

Zone #: _____ Zone ID: __________ # of Sources: _____ Source Code: ___

Avg. Temp. (^oF): _______ (^oC): _______ Volume (ft^3): _______ (m^3): _______ # of CATS: _______

CATS ID	Room	Item Placed On	Source Location: Room	Source Location: Item Placed On

Zone #: _____ Zone ID: __________ # of Sources: _____ Source Code: ___

Avg. Temp. (^oF): _______ (^oC): _______ Volume (ft^3): _______ (m^3): _______ # of CATS: _______

CATS ID	Room	Item Placed On	Source Location: Room	Source Location: Item Placed On

Zone #: _____ Zone ID: __________ # of Sources: _____ Source Code: ___

Avg. Temp. (^oF): _______ (^oC): _______ Volume (ft^3): _______ (m^3): _______ # of CATS: _______

CATS ID	Room	Item Placed On	Source Location: Room	Source Location: Item Placed On

AIR INFILTRATION AND VENTILATION CENTRE
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APPENDIX 2

EVALUATION OF THE PERFLUOROCARBON TRACER TECHNIQUE FOR DETERMINING INFILTRATION RATES IN RESIDENCES

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Evaluation of the Perfluorocarbon Tracer Technique for Determining Infiltration Rates in Residences

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■ A simple passive perfluorocarbon tracer (PFT) technique, for determining air infiltration rates into homes and buildings, was evaluated in a well-defined environmental chamber under experimental conditions of (1) constant temperature and ventilation rate, (2) constant temperature but variable ventilation rate, and (3) variable temperature but constant ventilation rate. Two PFT sources of known emission rate and temperature dependence produced chamber concentrations of 100–300 nL/m^3 (parts per trillion). The average relative standard deviation for sampling and analysis of 16 paired samplers in experiment 1 was ±1.9 ± 1.0%, and there was negligible consequence of sampler orientation. For a 3-fold variation in ventilation rates (experiment 2), the passive samplers accurately measured the average chamber tracer concentration, but the PFT-determined ventilation rate had a 10% negative bias. Temperature cycling differences of as much as 8 °C were accommodated to provide essentially no bias in the PFT-determined ventilation rate. The PFT technique is applicable to the expected range of conditions in homes and buildings.

Introduction

Efforts to reduce energy consumption in residences have led to the construction of energy efficient homes and the undertaking of residential weatherization programs which, in turn, have raised concerns about the quality of indoor air. The reduction of air infiltration rates in residences is an effective way to conserve energy by reducing heating and air conditioning demands. Reductions in infiltration rates, however, could result in the occurrence of air contaminants indoors at concentrations that may result in human exposures in excess of health- and comfort-related standards. The determination of infiltration rates in residences is necessary in order to assess the effectiveness of weatherization programs and to develop and evaluate models for infiltration and assessment of indoor air contaminant levels. This paper presents an evaluation of a new tracer system for determining infiltration rates.

The only direct measure of air infiltration in residences under normal occupancy conditions is by the tracer gas technique, which is applied to assessing infiltration rates in two ways. The first method is generally referred to as the tracer gas decay method (*1, 2*) and the second is referred to as the steady-state tracer gas method (*3–5*).

Considering a residence as a well-mixed single chamber and letting C = concentration of tracer in chamber (nL/m^3), V = volume of chamber (m^3), S' = source strength of tracer (nL/h), $S = S'/V$ (nL/hm^3), R_E = rate of air exfiltration or leakage (m^3/h), and $n = R_E/V$ or number of air changes per hour (ach) (h^{-1}), a mass balance around the chamber gives

$$dc/dt = S - nC \quad (1)$$

Integrating from C_0 at $t = 0$ to C_t, the tracer concentration at time t, gives

$$C_t = \frac{S}{n} + \left(C_0 - \frac{S}{n}\right)e^{-nt} \quad (2)$$

For the tracer decay approach, in which a small amount of tracer is well-mixed into the chamber and the source is turned off ($S = 0$), eq 2 becomes

$$C_t = C_0 e^{-nt} \quad (3)$$

and hence

$$\ln C_t = \ln C_0 - nt \quad (4)$$

When the natural logarithm of the tracer concentration vs. time is plotted, the air changes per unit time, n, is obtained as the negative of the slope as shown by eq 4. In practice, the tracer gas concentration in the space is measured as a function of time via either continuous monitors or a series of grab samples transported to a laboratory for subsequent analysis. This method has employed a number of gases as tracers (SF_6, CH_4, N_2O, CO_2, CO, C_2H_6, He, etc.) which have been evaluated in a number of studies (*6–8*). The tracer gas decay method provides a short-term measurement of air exfiltration rates, usually on the order of a few hours.

The steady-state tracer gas method uses SF_6 or a perfluorocarbon tracer gas. The tracer gas is emitted into the space at a constant rate either via a mechanical or microprocessor system (*3, 5, 9*) or via a liquid permeation source (*4*). The tracer gas is allowed to come to steady-state conditions in the space and then is sampled in the space either continuously, periodically with a sequential sampling system into a collection media such as syringes or bags, or passively using adsorption tube samplers. The latter two collection methods require subsequent laboratory analysis. At steady state ($dC/dt = 0$), eq 1 becomes

$$n = \frac{S}{C} = \frac{S'}{VC} \quad (5)$$

The number of air changes per hour, n, is simply the known tracer source rate divided by the volume of the house and the measured steady-state average tracer concentration.

One steady-state tracer gas method for assessing air-exchange rates, developed at Brookhaven National Laboratory and called the Brookhaven National Laboratory Air Infiltration Measurement System (BNL/AIMS) (*10*), is being extensively employed in large field studies of indoor air quality and impact of weatherization (*11–14*). The BNL/AIMS method consists of miniature perfluorocarbon tracer (PFT) sources and miniature passive capillary adsorption tube samplers (CATS). The sources and samplers are about the size of a cigarette. The PFT sources use one of four perfluorocarbon compounds: perfluorodimethylcyclohexane (PDCH); perfluoromethylcyclohexane (PMCH); perfluoromethylcyclopentane (PMCP); perfluorodimethylcyclobutane (PDCB). Vapors from the perfluorocarbon liquid in the PFT sources permeate through an elastomeric plug crimped into one end. The PFT sources emit the tracer gas at a constant rate for 2–7 years. The emission rate, however, does vary with temperature (*15*). The emission rates are determined gravimetrically.

The CATS device is a passive sampler utilizing about 50 mg of type XE-347 Ambersorb as the collection media. After sampling, the collected tracer gas is thermally desorbed into a gas chromatograph for determination of the PFT concentration. One type of PFT source can be used for a single-compartment model, while up to a four-compartment model (air-exchange rates between the space and outdoors as well as between compartments or rooms in the space) can be evaluated by using four different types of PFT sources, one type per compartment. This method is typically used to obtain integrated air-exchange rates over periods of 1 day to several weeks or months. Use of a programmable sampler with sampling pump will allow for multiple short-term (<1 h) sample collections for determinations of air exchange rates on a short-term basis. The small size of the sources and samplers, their passive nature (e.g., no pumps), wide range of sampling times (from hours to weeks or months), ease of analysis, and relative low cost have made the BNL/AIMS ideally suited to large-scale field studies of infiltration rates in residences and large buildings (*16*).

This paper presents the results of experiments conducted in an environmental chamber to evaluate the BNL/AIMS system for determining air-exchange rates. The accuracy of the BNL/AIMS system by comparison with CO_2 tracer decay, the impact of orientation of the CATS samplers with respect to flow direction, and the impact of variations in infiltration rate and temperature are evaluated under conditions of near ideal air mixing in the chamber.

Methods

Environmental Chamber. Figure 1 presents a schematic view of the environmental chamber with associated control equipment. The box on the right, actually a cross-sectional schematic of the 34-m^3 chamber itself, displays within it the range of operating conditions. All ductwork and internal surfaces were constructed of aluminum. The floor, 11 m^2, consisted of uniformly perforated aluminum sheets overlaid with an aluminum grating. The perforated floor served as an air diffuser. Air entered the chamber via a plenum beneath the floor and flowed upward through the performations to the ceiling. The design allowed a volume flow of up to 2000 cfm (1 m^3/s) with low linear velocity and very rapid mixing. The volume flow (recirculation rate) could be varied from 400 to 2000 cfm (0.2–1.0 m^3/s) which corresponded to 20–100 air changes per hour (ach) and a vertical velocity of 0.02–0.09 m/s. A variable percentage of the recirculated air could comprise fresh ventilation air. The fresh air brought into the chamber could be varied from 0 to 400 cfm (0–0.2 m^3/s) which corresponded to 0–20 ach of fresh air. The chamber possessed excellent temperature and humidity control. Air cleaning could be accomplished by diverting the recirculated air through an electronic air cleaner or granular filter media. At no time during these experiments were the air cleaning capabilities of the chamber utilized.

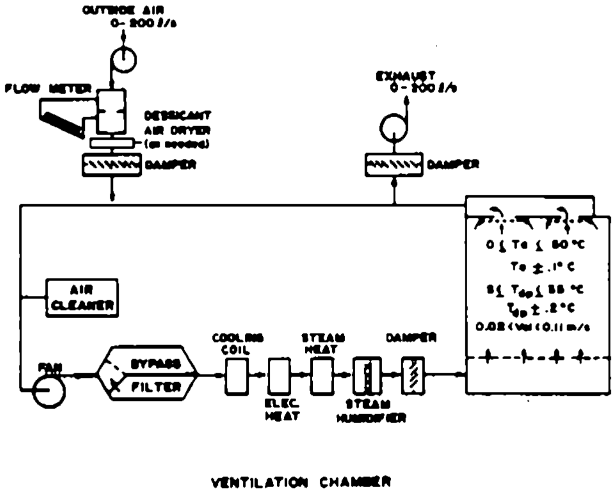

Figure 1. Schematic view of environmental chamber and control equipment. Arrows in box at right portray the flow of air from the plenum beneath the floor to the return ducts in the ceiling.

BNL/AIMS. The PFT sources and CATS were supplied by the Department of Applied Science, Brookhaven National Laboratory (BNL). Analysis of the passive samplers and emission rate determinations of the PFT sources were done by BNL. In this set of experiments, two perfluorodimethylcyclobutane (PDCB) PFT sources were used. The emission rates of these PFT sources were determined gravimetrically at a stabilized temperature of 25 °C. The PFT sources were shipped via mail to the chamber facility laboratory where they were stored at 23 °C for over 2 weeks prior to their use. The average PFT source strengths were adjusted to the 23 °C base temperature at which the experiments took place according to the following formula (*15*):

$$S'_t = S'_{25}e^{-4000(1/T-1/298)} \tag{6}$$

where S'_t = PFT source strength at the average base temperature (t, °C) in nL/h, S'_{25} = PFT source strength at 25 °C (determined gravimetrically as 5688 ± 120 nL/h), and T = average base temperature (t, °C) in kelvin at which the PFT source is used. For short-term (less than 48 h) temperature changes, the exponential constant was found to be half that for long-term (greater than 10 days) changes (*15*). Thus, when the temperature of the chamber was varied for short-term changes

$$S'_t = S'_{23}e^{-2000(1/T-1/296)} \tag{7}$$

where S'_t = PFT source strength at chamber temperatures in nL/h, S_{23} = PFT source strength at 23 °C base temperature (from eq 6) in nL/h, and T = chamber temperature in K.

The CATS were delivered to this laboratory by hand and stored in a separate building prior to and after use in order to minimize contamination. Two unopened but deployed CATS were included as controls in this set of experiments. After use, the CATS were returned to BNL for analysis by gas chromatography. BNL was blind as to the placement of the passive samplers and chamber conditions for each experiment. A detailed description of the BNL/AIMS method can be found elsewhere (*10, 15*).

CO_2 Decays. Ventilation rates (n) throughout these experiments were determined by the tracer gas decay method using CO_2 as the tracer gas. At regular intervals during each experiment CO_2 was injected into the chamber until the concentration in the chamber reached 1%. The gas was then shut off and the decay of CO_2 recorded

Table I. Average Measured PDCB Concentrations for Paired CATS vs. Sampler Orientation and Chamber Location [Experiment 1: av ach_{CO_2} = 0.601 ± 0.011 h^{-1}, S = 152.8 ± 4.3 nL/(h•m^3) at 23 °C]

passive sampler orientation to flow	average PDCB concn of paired samplers ± SD,[a] nL/m^3 (%),[b] at chamber location A	B	C	D	CATS orientation average
1 (perpendicular)	246.3 ± 3.4 (1.4)	243.3 ± 3.0 (1.2)	237.7 ± 3.0 (1.2)	244.1 ± 8.3 (3.4)	242.9 ± 5.0 (2.1)
2 (away)	231.3 ± 1.4 (0.6)	240.0 ± 2.2 (0.9)	235.3 ± 1.4 (0.6)		235.5 ± 4.1 (1.7)
3 (into)	244.9 ± 3.0 (1.2)	237.9 ± 5.3 (2.2)	234.6 ± 9.9 (4.2)		241.5 ± 4.6 (1.9)[c]
4 (shielded)	234.6 ± 6.2 (2.7)	235.5 ± 6.0 (2.5)	241.4 ± 5.6 (2.3)		237.1 ± 5.7 (2.4)
5 (perpendicular)	241.7 ± 2.9 (1.2)	244.5 ± 5.3 (2.2)	246.9 ± 6.3 (2.6)		244.4 ± 4.5 (1.9)
average	239.8 ± 6.8 (2.8)	240.2 ± 4.9 (2.0)	239.2 ± 6.6 (2.7)[c]	244.1 ± 8.3 (3.4)	240.4 ± 5.7 (2.4)[c,d]

[a] The average of 16 paired standard deviations was 4.6 ± 2.4 nL/m^3 (1.9 ± 1.0%) with a range of 1.4–9.9 (0.6–4.2%) and a median of 5.3 (2.2%). [b] Quantities in parentheses are the percent relative standard deviations. [c] One concentration excluded from location C (orientation 3) in computation of the overall averages. [d] Calculated overall average PDCB concentration was 254.2 ± 12.8 (5.0%).

continuously on a Beckman LB-2 infrared CO_2 analyzer. Background CO_2 levels were also recorded. The CO_2 analyzer was calibrated before and after each experiment with NBS traceable gases. For each decay, background levels were subtracted. The natural logarithms of 11 concentrations per decay (5-min intervals) were plotted vs. time, and a least-squares linear regression was used to obtain the slope and hence ventilation rate (eq 4).

Experiments. Three experiments were conducted to evaluate the BNL/AIMS infiltration measurement method under controlled conditions in the environmental chamber, as outlined in Figure 2. The two PFT sources used throughout all experiments were placed in the center of the chamber 1.9 m above the floor. This ensured that the PDCB tracer gas was well mixed in the recirculation loop before exposure to the samplers. Although the PFT sources were stored at 23 °C before use, they were allowed to equilibrate at a temperature of 23 °C for 3 days in the chamber before the experiments began in order to ensure that a steady-state concentration of the PDCB tracer gas was achieved in the chamber under the conditions of an air recirculation rate of 60 ach and a fresh air ventilation rate of about 0.6 ach.

(a) Experiment 1. The impact of CATS orientation during sample collection and accuracy of the BNL/AIMS method at a known and constant ventilation rate were evaluated in the first experiment. A constant temperature of 23 °C, an air recirculation rate of 60 ach, and a fresh air rate of about 0.6 ach were maintained throughout the experiment. The CATS samplers were placed on four chairs, equidistantly spaced in the chamber. The five positions of the CATS samplers placed on each chair are shown in Figure 2. The open end (only *one* end during sampling) was facing up in position 2, down in position 3, and off the back of the chair in position 5. All samples were taken in duplicate. One of the chairs (location D) had CATS in position 1 only, for a total of 32 CATS samples in the chamber. Hour-long CO_2 decays were obtained at six equally spaced times during the course of this 44-h experiment.

(b) Experiment 2. The accuracy of the BNL/AIMS method in measuring the average ventilation rate over a period of time where the ventilation rate was varied in discrete steps was evaluated in this experiment. A constant temperature of 23 °C was maintained throughout the run while the ventilation rate was varied in a series of 11 steps among three levels of about 0.60, 1.29, and 1.64 ach. The chamber was well-mixed (recirculation rate greater than 60 ach) and duplicate CATS samples only for position 1 were obtained on all four chairs (eight CATS samples). A total of twenty 1-h CO_2 decays (one after each new ventilation rate was set and, generally, a duplicate run later)

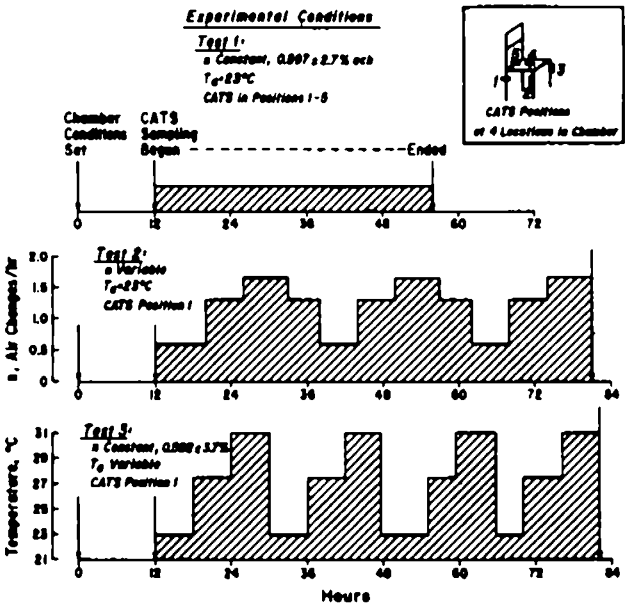

Figure 2. Experimental conditions in the environmental chamber for each of three tests for evaluating the BNL/AIMS method for determining ventilation rates. CO_2 decays performed throughout each of the three experiments served as the basis for comparison.

were obtained for this 69-h experiment.

(c) Experiment 3. The impact of varying temperature on the PFT source emission rate in determining ventilation rates was evaluated in this experiment. After the initial equilibration period at 23 °C, the temperature was cycled among three temperature settings (23, 27, and 31 °C) for a total of 12 steps as shown in Figure 2. The ventilation rate was constant at about 0.6 ach and the recirculation rate at 60 ach during this 72-h experiment. The standard temperature correction factor (eq 6) was applied to the PDCB PFT sources in calculating the emission rate at 23 °C and the short-term correction (eq 7) for the 27 and 31 °C rates. Sixteen hour-long CO_2 decays were obtained, one after each temperature change and an occasional repeat. Duplicate CATS samples were obtained in position 1 for all four chairs (eight CATS samples).

Results

Experiment 1. The average measured concentrations, standard deviations, and relative standard deviations of the 16 paired samplers are shown in Table I, arranged according to sampler orientation and location within the chamber. The average of the 16 paired standard deviations was 4.6 ± 2.4 nL/m^3 which, for an overall average concentration of 240.4 ± 5.7 nL/m^3, corresponded to an av-

Table II. Comparison of BNL/AIMS Measured vs. Calculated PDCB Concentrations

experiment	conditions	no. of changes	average PDCB concn, nL/m³ measured[a]	average PDCB concn, nL/m³ calculated[b]	measd/calcd
1	constant temp, constant ach	0	240.4 ± 5.7	254.2 ± 12.8	0.946 ± 0.074
2	constant temp, variable ach	11	139.3 ± 2.5	149.2 ± 7.7	0.934 ± 0.068
3	variable temp, constant ach	12	290.5 ± 8.0	280.9 ± 19.3	1.034 ± 0.107

[a] Measured concentrations were determined with CATS. [b] Calculated concentrations were obtained either from eq 5 (experiment 1) or from eq 9 (experiments 2 and 3), time-weighted over each measurement period.

erage relative standard deviation of 1.9 ± 1.0% with a range of 0.6–4.2% and a median of 2.2%. Thus, the expected precision of duplicate samplers, ±2%, demonstrates that there is no need to perform duplicate sampling during actual field use, since the sampling rates, handling, and analytical procedures for the CATS are consistent and reproducible.

All 32 sampler analyses results are shown in Figure 3, where they are plotted vs. both sampler orientation and chamber location. Also included are the means (crosses) and standard deviations (bars) for all samplers in each orientation and location as well as the overall average and standard deviation for 31 samplers (one result at orientation 3 and location C, which had a value of 227.6 nL/m³, was statistically low and was excluded from all averaging).

Figure 3 clearly shows that the averages of the 10 samplers in each of the three chamber locations (A–C) were statistically identical. In fact, excluding location D because there were only two samplers, the maximum difference between the three averages was only 0.4%, indicating that the chamber concentration was uniformly identical at all locations.

Figure 3 does show that sampler orientation did affect the average sampling rate. Positions 1 and 5 both exposed the samplers at right angles to the chamber flow; their averages were identical within 0.7% and about 1.3% above the overall mean. Position 3, CATS facing into the direction of flow, had an average that was 0.5% above the overall average. The lowest mean concentrations were for positions 2 (facing away from the direction of flow) and 4 (shielded by the chair seat), probably because those positions prevent turbulence at the sampling end. Those means were 2.0 and 1.4% below the overall mean. As shown in the figure, only position 2 was statistically different (more than 1 standard deviation) from the overall average.

The average chamber ventilation rate, n, based on five of the six CO_2 decay measurements was 0.601 ± 0.011 h^{-1}. The tracer source strength, S', based on gravimetric measurements at 25 °C was 5688 ± 120 nL/h. Substituting into eq 6 gave S'_{23} = 5195 ± 145 nL/h, and dividing by the chamber volume (V = 34 m³) gave S = 152.8 ± 4.3 nL/(h·m³). The PDCB concentration can then be calculated from eq 5:

$$C = \frac{S}{n} = \frac{152.8 \pm 4.3}{0.601 \pm 0.011} = 254.2 \pm 12.8 \text{ nL/m}^3$$

which, as shown in Table II, is identical within the standard deviation of the average of the measured concentrations.

Experiment 2. Unlike experiment 1, which was conducted at steady-state conditions of constant temperature and ventilation rate, experiments 2 and 3 were performed over multiple periods in which the temperature and ventilation rate were constant during each period, but at least one of the two was changed from the previous period. The tracer concentration at any time, t, during the period is

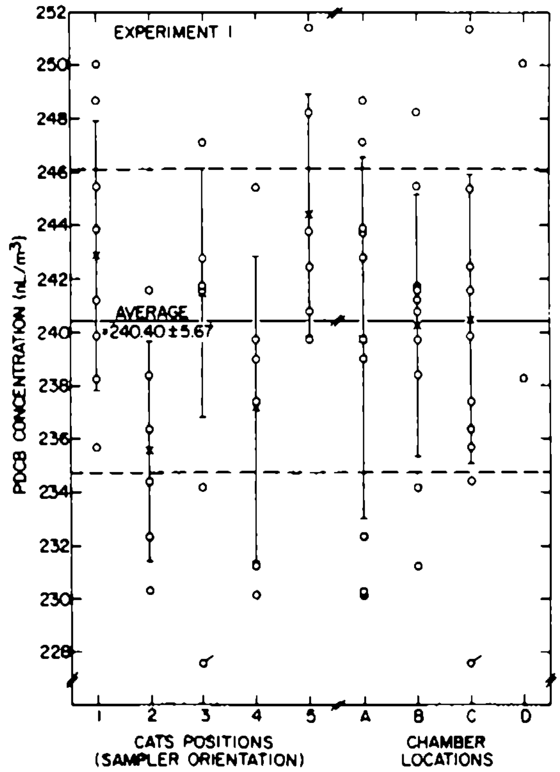

Figure 3. PDCB concentrations (O), averages (X), and standard deviations (—) for 16 paired CATS vs. sampler orientation (position 1, 90° from into the wind; position 2, 180°; position 3, 0°; position 4, shielded; position 5, 90°) and chamber location.

given by eq 2 where C_0 is the concentration at the end of the previous period.

The average concentration during each period is given by

$$\bar{C} = \frac{1}{\tau}\int_0^{\tau} C_t \, dt \qquad (8)$$

Substituting eq 2 into eq 8 and integrating give

$$\bar{C} = \frac{S}{n} - \left(\frac{C_0 - S/n}{n\tau}\right)(e^{-n\tau} - 1) \qquad (9)$$

where τ = the duration of each period (h).

The ach (n) and duration (τ) for each period of experiment 2 (constant temperature and variable ach) are given in Table III and were used in eq 2 and 9 to compute the concentration as a function of time and the average concentration for each period as shown in Figure 4 (top). The series of exponential curves, when integrated over each period, gave the average concentrations listed in Table III; the calculated overall average concentration for the 69-h period was 149.2 ± 7.7 nL/m³.

Table IV lists the measured concentrations obtained with the eight CATS. The relative standard deviation of

Table III. Conditions and Calculated Results for Variable Infiltration Rate Experiment [Experiment 2: S = 152.8 ± 4.3 nL/(h•m³) at 23 °C]

period	average ach_{CO_2} ± SD, h^{-1} (%)[a]	time of period, h: duration	time of period, h: from–to	calcd av PDCB[b] concn, nL/m³
1	0.608 ± 0.004 (0.7)	8	0–8	251.3 ± 8.8
2	1.306 ± 0.069 (5.3)	6	8–14	134.1 ± 10.8
3	1.627	7	14–21	95.9 ± 6.2
4	1.312 ± 0.062 (4.7)	5	21–26	113.0 ± 8.5
5	0.599 ± 0.014 (2.4)	6	26–32	217.6 ± 11.4
6	1.298 ± 0.046 (3.5)	6	32–38	134.9 ± 9.0
7	1.623 ± 0.021 (1.3)	7	38–45	96.2 ± 4.3
8	1.263 ± 0.014 (1.1)	5	45–50	116.7 ± 4.7
9	0.567	6	50–56	227.3 ± 8.6
10	1.273 ± 0.001 (0.1)	6	56–62	138.9 ± 4.6
11	1.624 ± 0.070 (4.3)	7	62–69	96.4 ± 6.8
av[c]	1.190 ± 0.033 (2.8)			149.2 ± 7.7(5.1%)

[a] Average of two measurements per period with standard deviation and percent relative standard deviation in parentheses. [b] Calculated from eq 9 including the error in S and ach_{CO_2} (n). [c] Time-weighted average.

Table IV. Measured PDCB Concentrations for Variable Infiltration Rate Experiment (Experiment 2: Calculated Time-Weighted Average PDCB Concentration = 149.2 ± 7.7 nL/m³)

chamber location	CATS sampler	PDCB concn, nL/m³: measured	PDCB concn, nL/m³: average ± SD (%)[a]
A	5621	142.2	142.0 ± 0.3 (0.2)
	5391	141.8	
B	5366	139.2	139.1 ± 0.2 (0.1)
	5655	138.9	
C	5332	131.4	133.4 ± 2.8 (2.1)
	5627	135.4	
D	4682	140.4	138.8 ± 2.3 (1.7)
	5379	137.1	
av[b]		139.3 ± 2.5 (1.8)	

[a] Average of two measurements with standard deviation and percent relative standard deviation in parentheses. [b] CATS 5332 not included in overall average.

the four sets of duplicate measurements ranged from 0.1 to 2.1%, similar to the experiment 1 paired results. The overall average PDCB concentration was 139.3 ± 2.5 nL/m³ which, as shown in Table II, agrees with the calculated concentration for experiment 2 within the standard deviation of each determination.

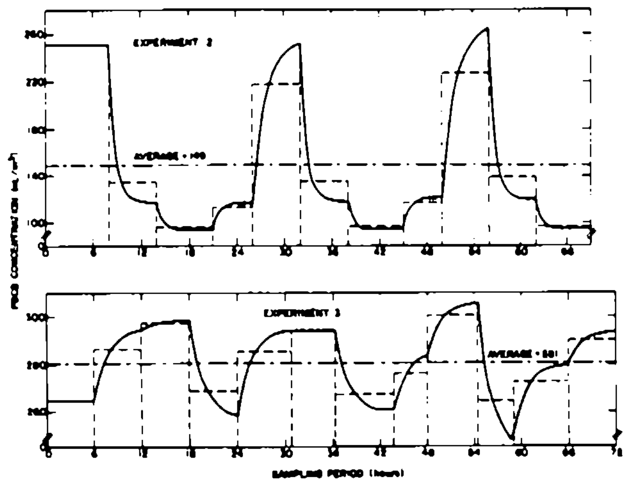

Figure 4. Calculated PDCB concentrations vs. sampling time: (top panel) effect of 11 step changes in ventilation rate; (bottom panel) effect of 12 temperature step changes (between 23 and 31 °C) and minor ventilation rate changes.

Experiment 3. The chamber temperature and its effect on the PDCB source strength term (S), the ach (n), and the duration (τ) for each period of this variable temperature experiment are given in Table V and were used in eq

Table V. Conditions and Calculated Results for Variable Temperature Experiment [Experiment 3: S = 152.8 ± 4.3 at 23 °C, 167.2 ± 5.8 at 27 °C, 182.5 ± 7.5 nL/(h•m³) at 31 °C][a]

period	chamber temp, °C	av ach_{CO_2} ± SD h^{-1} [b]	time of period, h: duration	time of period, h: from–to	calcd av PDCB[c] concn, nL/m³
1	23.0	0.577 ± 0.009	6	0–6	264.8 ± 11.8
2	27.0	0.566	6	6–12	286.7 ± 18.3
3	31.0	0.611	6	12–18	297.5 ± 22.3
4	23.0	0.593 ± 0.018	6	18–24	268.8 ± 17.9
5	27.0	0.567	6.75	24–30.75	285.7 ± 19.6
6	31.0	0.621	5.5	30.75–36.25	293.9 ± 22.0
7	23.0	0.588 ± 0.018	7.5	36.25 ± 43.75	267.5 ± 17.5
8	27.0	0.585	4.25	43.75–48	276.4 ± 18.4
9	31.0	0.596	6.5	48–54.5	300.5 ± 22.5
10	23.0	0.626	4.5	54.5–59	264.7 ± 18.5
11	27.0	0.597	7	59–66	272.5 ± 18.6
12	31.0	0.621 ± 0.026	6	66–72	290.1 ± 23.7
av[d]	27.0	0.595 ± 0.022			280.9 ± 19.3

[a] The time-weighted average S was 167.5 ± 5.9 nL/(h·m³). [b] A standard deviation of ±0.02 h^{-1} was assumed for the single measurement periods. [c] Calculated from eq 9 including the error in S and ach_{CO_2} (n). [d] Time-weighted average.

Table VI. Measured PDCB Concentrations for Variable Temperature Experiment (Experiment 3: Calculated Time-Weighted Average PDCB Concentration = 280.9 ± 19.3 nL/m³)

chamber location	sampler	PDCB concn, nL/m³ measured	PDCB concn, nL/m³ av ± SD (%)[a]
A	5461	312.5	296.9 ± 22.1 (7.4)
	4678	281.3	
B	5251	292.4	298.6 ± 8.7 (2.9)
	5361	304.7	
C	5513	281.5	287.2 ± 8.1 (2.8)
	5641	293.0	
D	5476	292.4	290.3 ± 3.0 (1.0)
	5551	288.2	
controls	5656	0.33	
	5297	0.28	
average[b]		290.5 ± 8.0 (2.8)	

[a] Average of two measurements with standard deviation and percent relative standard deviation in parentheses. [b] CATS 5461 (location A) and controls not included in average.

2 and 9 to compute the PDCB concentration vs. time and the average for each of the 12 periods as shown in Figure 4 (bottom) and listed in Table V; the time-weighted overall calculated average concentration was 280.9 ± 19.3 nL/m³ for the 72-h experiment.

Table VI lists the measured concentrations obtained with the eight CATS plus the levels from the two controls which were never opened; the controls showed levels of about 0.1% of the sampled values. The relative standard deviations of three pairs (locations B–D) ranged from 1.0 to 2.9%, similar to that of experiment 1; location A had a high difference for the CATS pair (±7.4%). Excluding the high value from the overall average gave a measured concentration of 290.5 ± 8.0 nL/m³ which, as shown in Table II, agreed with the calculated average for experiment 3 and was well within the standard deviation of each determination.

Discussion

As summarized in Table II, for each of the these experiments (constant temperature and ventilation rate, constant temperature but variable ventilation, and constant ventilation but variable temperature), the ratio of the PDCB concentration measured by the CATS samplers divided by the calculated concentration determined from CO_2 decay measured ventilation rates and known PDCB source strengths was equal to 1 within the standard deviation associated with some of the errors. Thus, the passive sampling method does give an accurate measure of the average concentration that existed during a measurement period.

The agreement was even more within the error bounds than indicated in Table II because certain errors in the measurement technology were not included such as the error associated with the absolute sampling rate of the CATS (±2%) and the uncertainty in the gas calibration standards (±2%).

Experiment 1. The chamber recirculation rate in each experiment was 60 ach, equivalent to an upward air velocity of 0.052 m/s. Typical between-zone air-exchange rates can be as large as 200 m³/h (*10*). Assuming that CATS are sampling the air in a room near a doorway, that there are four doors per zone, and that the cross-sectional area for flow is about one-fourth the area of a doorway (i.e., about 0.4 m³), the maximum anticipated velocity in a home is of the order of 0.04 m/s, comparable to the chamber velocity. Some actual horizontal velocity measurements in a home showed levels from 0.05 to 0.2 m/s (*17*) in the more turbulent regime within 0.5 m of the ceiling.

The effect of wind speed and orientation into the wind was studied for a passive NO_2 sampler (*18*). From their data, the rate of sampling relative to still air for different orientations was correlated with wind speed and then used to calculate the effect at the chamber velocity of 0.052 m/s. As shown in Table VII, the agreement of the Palmes measurements with those from this study was very good and consistent, with the largest effect occurring at 90° to the wind, the next lowest effect at 0° (facing into the wind), and the least effect at 180° (facing away from the wind). It can be seen that the maximum bias in the sampling rate at velocities expected in homes and buildings is less than 2–3% and can be ignored. In fact, by placing the sampler on a flat surface within the room, any local wind effects can be blocked.

The ventilation rate computed by the BNL/AIMS technique using the computed source strength [S = 152.8 ± 4.3 nL/(h·m³)] and CATS average measured concentration (240.4 ± 5.7 nL/m³) is given by eq 5 as

$$n = \frac{S}{C} = \frac{152.8 \pm 4.3}{240.4 \pm 5.7} = 0.636 \pm 0.034 \text{ h}^{-1}$$

in agreement with the CO_2-decay average value of 0.601 ± 0.011 h⁻¹. Thus, under constant ventilation rate and constant temperature conditions, there was no bias in the determination of the average ventilation rate with the BNL/AIMS approach.

Experiment 2. As shown in Figure 4 (top), the widely varying ventilation rate caused significant swings in the calculated PDCB chamber concentration vs. time. But, as expected, the CATS measured concentration of 139.3 ± 2.5 nL/m³ was in agreement with the calculated average value of 149.2 ± 7.7 nL/m³.

Although the passive samplers are capable of determining the correct average tracer concentration over a measurement period, it has been shown that the reciprocal of an average concentration, $\bar{C}$, the quantity measured, is close to but not identical with the average of reciprocal concentrations. For example, for conditions of constant temperature (S is constant) but multiple equal-duration

Table VII. Effect of Air Velocity and Direction on Passive Samplers (Experiment 1)

CATS orientation	angle from into wind	av PDCB concn, nL/m³	PDCB concn relative to still air: from this study[a]	PDCB concn relative to still air: calcd from Palmes measurements[b]
1	90°	242.86 ± 5.04	1.024 ± 0.047	1.014 ± 0.038
2	180°	235.54 ± 4.09	0.993 ± 0.042	0.976 ± 0.010
3	0°	241.46 ± 4.65	1.018 ± 0.045	1.004 ± 0.027
4	shielded	237.14 ± 5.68		
5	90°	244.37 ± 4.53	1.030 ± 0.045	1.014 ± 0.038

[a] The CATS shielded by the chair was assumed to be in still air. [b] Calculated from linear regression fit of data collected for wind velocity from 0.5 to 2.6 m/s (*18*) for the chamber velocity of 0.052 m/s.

periods (m) of different ventilation rates (i.e., different $\bar{C}_k$), eq 5 becomes

$$n = S\frac{1}{m}\sum_{k=1}^{m}\frac{1}{\bar{C}_k} \approx \frac{S}{\bar{C}} \qquad (10)$$

Substituting the explicit values of S and $\bar{C}$ from Table III gives

$$n \approx \frac{152.8 \pm 4.3}{149.2 \pm 7.7} \text{ or } 1.02 \pm 0.09 \text{ h}^{-1}$$

However, Table III shows that the actual time-weighted average ventilation rate was 1.19 ± 0.03 h^{-1}. Thus, for a measurement period in which the ventilation rate varied about 2.7-fold on a cyclical basis, there was an explicit underestimate of the true average ventilation rate by about 14%.

Such periodic variation can occur in actual building measurements on a diurnal basis because the ventilation driving force, the inside–outside temperature difference, increases at night and decreases during the day; a 1.5–2-fold variation on a daily basis is not unreasonable. However, the cycle in experiment 2 as shown in Figure 4 (top) is biased somewhat by the constant rate in the first period (0–8 h). By looking at periods 2–9 inclusive in Table III, which includes exactly two complete up–down cycles, the average concentration would have been 141.2 ± 7.9 nL/m^3 corresponding to an apparent ventilation rate of 1.08 ± 0.10 h^{-1}, and the true average ventilation rate would have been 1.21 ± 0.04 h^{-1}, for a rate underestimate of less than 11%. Thus, for measurement periods of several days or longer, it can be expected that the BNL/AIMS approach may underestimate the true ventilation rate by about 3–6%, a tolerable bias for this convenient technique.

Experiment 3. Figure 4 (bottom) showed that the 8 °C swing in chamber temperatures from 23 to 31 °C and down again caused less than a 1.2-fold variation in the concentration, and again, as shown in Table II, the CATS-measured concentration of 290.5 ± 8.0 nL/m^3 was in agreement with the expected concentration of 280.9 ± 19.3 nL/m^3.

Since both the source strength, S, and the PDCB concentration, C, are different for each period, for multiple equal-duration periods (m), eq 5 becomes

$$n = \frac{1}{k}\sum_{k=1}^{m}\frac{S_k}{C_k} \approx \frac{1}{\bar{C}}\frac{1}{k}\sum_{k=1}^{m}S_k \approx \frac{S}{\bar{C}} \qquad (11)$$

The reciprocal concentration term can be more accurately factored out in the case of the temperature cycling because the magnitude of the concentration swings is much less and more accurately represented by an average value than was the case for experiment 2.

The time-weighted averages of source strength and concentration were 167.5 ± 5.9 nL/(h·m^3) and 280.9 ± 19.3 nL/m^3, respectively (cf. Table V). Substituting in eq 11 gives

$$n = \frac{167.5 \pm 5.9}{280.9 \pm 19.3} \text{ or } 0.596 \pm 0.067 \text{ h}^{-1}$$

which is essentially identical with the measured average ventilation rate of 0.595 ± 0.022 h^{-1}. Thus, the BNL/AIMS technique is not biased to any significant extent if the appropriate temperature for the source is known.

For these chamber experiments, the base temperature was 23 °C, the value at which the sources were conditioned before the experiment began. The source strengths for the two other temperatures, 27 and 31 °C, were computed from eq 7 because these were short-term temperature adjustments; the total duration of the experiment was only 3 days.

If these measurements had been conducted over a 2-week or longer period, then the average source strength could have been estimated from the time-weighted average source temperature and used in eq 6; this would be the procedure for a ventilation rate determination in a home, where the time-weight average thermostat setting would be used as the average base temperature. Assuming long-term equilibration at the chamber base temperature of 27 °C, eq 6 becomes

$$S'_{27} = \frac{5688 \pm 120}{34}e^{-4000(1/300-1/296)} = 182.9 \text{ nL/(h·m}^3\text{)}$$

which, divided by the average concentration, gives

$$n = \frac{182.9}{280.9} = 0.651 \text{ h}^{-1}$$

This is about 9.4% higher than the true ventilation rate of 0.595 h^{-1} because the sources had not equilibrated at the experiment 3 base temperature of 27 °C in the 3-day period.

One can reverse the procedure and use the measured ventilation rate and average PDCB concentration from Tables V and VI, respectively, to compute the source strength and hence the estimated average chamber temperature. From eq 5

$$S_t = nC = (0.595 \pm 0.022)(290.5 \pm 8.0) = 172.8 \pm 11.3 \text{ nL/(h·m}^3\text{)}$$

Equation 6 becomes

$$172.8 \pm 11.3 = \frac{5688 \pm 120}{34}e^{-(4000\pm300)(1/T-1/298)}$$

or $T = 298.9 \pm 2.2$ K (25.7 ± 2.2 °C). This average chamber temperature of 25.7 °C is, as expected, above the preexperiment base temperature of 23 °C and below the long-term time-weighted chamber temperature of 27 °C, confirming the applicability of the BNL/AIMS approach in variable temperature scenarios.

Conclusions

The relative standard deviation of multiple paired passive samplers is $\pm1.9 \pm 1.0$%, indicating that the reproducibility in the manufacture, handling, and analysis of the CATS is sufficiently good to preclude the necessity of duplicate sampling in field experiments.

For the low air movement velocities in homes (<0.2 m/s, away from any forced air vents), the effect of sampler orientation is not consequential on the sampling rate, having less than a 2–3% positive bias in the worst case.

Under conditions of widely varying concentrations, the passive sampler accurately measures the correct time-weighted average tracer concentration. However, because the determination of ventilation ratios requires the determination of the average reciprocal tracer concentration rather than the reciprocal of the average tracer concentration, which is the item measured by the passive sampler, there is an estimated negative bias in the ventilation rate determination of about 3–6%, a tolerable bias for this convenient technique.

By use of a time-weighted average temperature for determining the estimated source strength, room temperature fluctuations or intentional cycling differences of as much as 8 °C (14 °F) can be accounted for in order to produce essentially no bias in the determination of ventilation rates.

Acknowledgments

Appreciation is expressed to Bob Wieser for the manufacture and calibration of the PFT sources and passive samplers, to Bob Goodrich and Ed Cote for the analytical determination, and to Ted D'Ottavio for suggestions with the modeling.

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AIR INFILTRATION AND VENTILATION CENTRE
MEASUREMENT TECHNIQUES WORKSHOP 1988

Køge, Denmark
21-23 March 1988

APPENDIX 3

EXAMPLE OUTPUT FROM BROOKHAVEN AIR INFILTRATION MEASUREMENT SYSTEM

General Description of the BNL/AIMS Output Format
June 1986

Revised: April 8, 1987

The top portion of the BNL/AIMS sheet shows the project title, the house name, the start and stop times and dates for sampling, the date analyzed, and the final date that computations were made.

The rates section gives the overall infiltration rate (m^3/h) for all zones and the air change rate (h^{-1}) by dividing by the total volume. Next is given, for each zone, the zone location, source information (gravimetric calibration rate at 25°C, quantity, and total emission rate adjusted for temperature, assuming an enthalpy of 6.8 kcal/mole), and exfiltration and infiltration rates with their standard deviations (SDs), followed by the zone to zone air flow rates and SDs. The total flow in or out of each zone, sometimes a useful quantity, is also given.

Note: All gaseous volumes, i.e., those for air flow rates and perfluorocarbon tracer (PFT) source rates, are reported at conditions of 25°C and 1 atm. When comparing results with those from other techniques, consideration must be given to the conditions under which those results are being reported. For example, tracer decay volumetric rates are reported for the conditions at the site (i.e., the indoor temperature and the prevailing barometric pressure).

The analysis section gives for each zone the volume, source type, and average tracer concentration with SDs, only for those used in the computations. Below is the individual CATS analyses by zone with the calibration correction factors. The PFT concentrations of those used in the computations are reported first, by zone, and then those for other PFTs found. Note that even though separate calibration curves are used for the mt-, mc-, and total m PDCH, the sum of mt and mc is generally very close to the m PDCH.

The notes section mentions the SDs assigned to the source rates and volumes; conditions or results that should not exist are flagged by printing in capital letters.

The current number codes of the tracers are:

PFT Code	PFT	Isomers Reported
1	PDCB	
2	PMCH	
3	m PDCH	mt PDCH and mc PDCH
4	o PDCH	oc PDCH and ot PDCH
5	p PDCH	pc PDCH and pt PDCH
6	PTCH	1 PTCH and 2 PTCH
8	PMCP	

Although these are 7 PFT source types currently available, chromatographic analysis limitations restrict certain combinations. In addition, the software is not yet available for the computation of more than 5 zones.

BNL-AIMS 15:25:06 03-03-1988

PROJECT: PRINCETON START: 14:40 (02-24-1988) FILE: 6916A
HOUSE:HI8B3 STOP: 20:25 (02-24-1988) ANALYZED: 02-29-1988

******************** RATES ********************

OVERALL INFILTRATION RATE = 980.3 ± 82.3(m^3/h)
OVERALL AIR EXCHANGE RATE = 1.846 ± 0.163(1/h)

ZONE	ZONE LOCATION	SOURCE RATE @25C (nL/m)	QTY	@T (nL/h)	EXFILTRATION RATE (m^3/h)	SD	INFILTRATION RATE (m^3/h)	SD	ACH (/h)	SD
1	LDK-BSMNT	10.7	8	4228	143.5	28.1	141.9	18.1	1.279	0.175
2	BDBTH-BSMT	5.9	8	2553	61.4	18.6	21.1	7.9	0.358	0.136
3	STOR.BSMT	23.2	8	11360	223.5	41.8	254.5	43.7	1.674	0.299
4	APT 1B	6.6	4	1248	551.9	71.1	562.8	71.5	2.693	0.368

ZONE-ZONE	RATE	± SD (m^3/h)	ZONE-ZONE	RATE	± SD (m^3/h)
1 - 2	89.4	15.8	2 - 1	68.0	13.0
1 - 3	4.9	3.8	3 - 1	17.4	4.9
1 - 4	-0.1	1.5	4 - 1	10.4	2.7
2 - 3	13.8	4.6	3 - 2	32.9	7.8
2 - 4	0.8	2.2	4 - 2	0.7	1.2
3 - 4	0.4	0.5	4 - 3	1.0	1.1

TOTAL FLOW IN OR OUT

ZONE	RATE	± SD (m^3/h)	ACH	± SD(/h)	ZONE	RATE	± SD (m^3/h)	ACH	± SD(/h)
1	237.7	30.0	2.141	0.291	2	144.1	22.4	2.442	0.399
3	274.2	47.0	1.804	0.322	4	563.9	71.6	2.698	0.368

******************** ANALYSIS ********************

AVG.TRACER CONC. (pL/L) ± SD

ZONE	VOL m^3	SOURCE TYPE	ptPDCH	T-PTCH	PMCH	ocPDCH
1	111	ptPDCH	21.81 ± 1.28	6.37 ± 0.45	7.12 ± 0.39	0.12 ± 0.02
2	59	T-PTCH	13.78 ± 0.51	21.95 ± 2.08	14.07 ± 1.05	0.09 ± 0.01
3	152	PMCH	1.09 ± 0.18	1.22 ± 0.22	42.27 ± 5.77	0.01 ± 0.01
4	209	ocPDCH	0.02 ± 0.02	0.03 ± 0.07	0.05 ± 0.01	2.21 ± 0.17

CONCENTRATION(pL/L)

	CATS#	ptPDCH	T-PTCH	PMCH	ocPDCH	PDCB	omPDCH	opPDCH	mPDCH	PMCP			
1	6492	20.89	5.76	6.82	0.10	0.00	0.00	23.32	20.70	8.75	0.00	0.00	
1	3525	23.67	6.74	7.71	0.14	0.00	1.21	25.19	23.70	9.69	0.00	0.00	
1	8908	21.66	6.84	7.32	0.11	0.00	0.00	21.38	19.01	9.82	0.00	0.00	
1	4593	26.59	6.11	6.79	0.14	0.00	0.00	29.64	26.20	9.10	0.00	0.00	DELETED 1,
1	736	21.03	6.40	6.96	0.12	0.00	0.00	20.80	18.50	10.19	0.00	0.00	
2	2384	14.83	22.83	14.71	0.08	0.00	0.00	16.19	14.47	20.58	0.00	0.00	
2	8325	13.86	22.29	15.52	0.09	0.00	0.00	15.92	14.23	27.35	0.00	0.00	
2	8721	13.87	18.82	12.90	0.09	0.00	0.00	16.05	14.35	17.87	0.00	0.00	
2	9348	12.79	20.05	12.86	0.08	0.00	0.00	13.05	11.72	17.85	0.00	0.00	
2	1542	13.87	23.71	14.03	0.10	0.00	0.00	16.13	14.41	19.26	0.00	0.00	
2	3323	14.27	24.00	14.39	0.11	0.00	0.00	16.47	14.72	20.56	0.00	0.00	
3	6362	1.02	1.10	36.57	0.01	0.00	0.00	1.28	1.16	53.76	0.00	0.00	
3	10791	1.00	1.12	49.92	0.01	0.00	0.00	1.30	1.19	74.94	0.00	0.00	
3	10996	0.97	1.12	43.18	0.02	0.00	0.00	1.02	0.93	63.30	0.00	0.00	
3	1597	1.35	1.56	39.41	0.03	0.00	0.00	1.42	1.29	58.04	0.00	0.00	
4	2995	0.00	0.00	0.06	2.24	0.00	0.00	0.28	0.26	0.21	0.00	0.00	
4	3814	0.02	0.00	0.06	2.20	0.00	0.00	0.28	0.25	0.11	0.00	0.00	
4	9766	1.55	1.37	1.70	3.18	0.00	0.00	0.00	0.00	8.57	0.00	0.00	DELETED
4	4341	0.00	0.00	0.05	1.93	0.00	0.00	0.31	0.29	0.24	0.00	0.00	
4	10423	0.03	0.15	0.06	2.36	0.00	0.00	0.36	0.33	0.16	0.00	0.00	
4	5685	0.03	0.00	0.03	2.33	0.00	2.23	0.37	2.76	0.07	0.00	0.00	
4	4296	0.00	0.06	0.00	0.01	0.00	0.00	0.01	0.01	0.04	0.00	0.00	DELETED

C.F.:	PDCB	PMCP	PMCH	ocPDCH	ptPDCH	mPDCH	PTCH	COEFFICIENTS FILE
	0.84	0.84	0.99	0.98	0.98	0.98	0.98	6A160

******************** NOTES ********************

All gas volumes are reported at 25 C. and 1 atm.
The standard deviation in the source strength has been set at 10 %.
The standard deviation in the volume measurement has been set at 5 %.
The overall normalized condition number (K(C)/N^1.5)= 0.656
K(DC)/N = 1.312
Zonal condition numbers are:

ZONE	1	2	3	4
Condition Number	1.515	1.548	1.090	1.002

STANDARD DEVIATION OF ptPDCH IN ZONE 4 IS GREATER THAN 25 %
STANDARD DEVIATION OF T-PTCH IN ZONE 4 IS GREATER THAN 25 %
STANDARD DEVIATION OF ocPDCH IN ZONE 3 IS GREATER THAN 25 %
RATE14 IS NEGATIVE

MEASUREMENT TECHNIQUES

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ABSTRACT
After discussing briefly the principles of natural ventilation, goes on to describe tracer gas techniques, air movement measurements, and various model techniques including analogues. Advantages and disadvantages of each method are indicated, and their suitability for particular applications.
KEYWORDS
air change rate, natural ventilation, tracer gas, modelling, instrumentation,

NO 418 Airtightness - measurement and measurement methods
Matningar och matmetoder for lufttathet
AUTHOR Kronvall J.
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ABSTRACT Describes methods of measuring the air tightness of whole buildings. Outlines three tracer gas methods; constant concentration; decreasing concentration and constant emission. Describes pressurisation method. Describes measuring equipment and test procedure and discusses calculation of ventilation rate and error magnitudes. Gives brief summary of measured results and an appendix contains a print-out of data on the air tightness of houses.
KEYWORDS
air infiltration, tracer gas, pressurization, instrumentation,

NO 1862 Documenting air movements and infiltration in multicell buildings using various tracer-gas techniques.
AUTHOR
Harrje D T, Dutt G S, Bohac D L, et al.
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Preprint. ASHRAE Transactions 1985, Vol 91, Pt 2. HI-85-40 No 3. 15p. 11 figs, 18 refs. DATE 00:00:1985 in English AIC 1267
ABSTRACT
Tracer gas techniques for measuring airflows in buildings fall into three categories - dilution, constant injection, and constant concentration. Dilution of a single tracer works well in buildings with a single zone and also in some two-zone buildings. Multiple tracer gas measurements, necessary to characterize flows among more zones, are best conducted using the constant injection approach. The constant concentration method uses a single tracer gas to determine the air flow rates from the outside into each of as many as ten building zones. The paper outlines the different tracer techniques for making airflow measurements in multicell buildings and describes the operation of a constant concentration system. This system measures tracer gas concentration in different zones and injects

accordingly to maintain a constant concentration in each zone. The system was tested in a single zone structure and successfully applied to a small three-zone house. Sensitivity analyses and calibration procedures described in this paper define the capabilities and limitations of this technique. Although this method does not fully characterize all interzone airflows in the building, it can be useful in analyzing the energy balance of multizone buildings. Additionally, these measurements can be used to evaluate the dilution of indoor air pollutants and the ventilation efficiency of buildings.
KEYWORDS
multi-chamber, tracer gas, measurement technique, decay rate, constant concentration, constant emission, air movement, air infiltration

NO 2216 Tracer gases as a ventilation tool: methods and instrumentation. AUTHOR
Farant J P, McKinnon D L, McKenna T A
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Ventilation '85. (Chemical Engineering Monographs 24). Edited by H D Goodfellow. Amsterdam, Elsevier, 1986. p263-274. 4 figs, 5 tabs, 3 refs. DATE 00:00:1986 in English AIC bk, AIC 1815
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Tracer gas techniques, used for routine ventilation checks or trouble shooting are outlined with emphasis on their applicability in a variety of situations. These include methods of determining volumetric flow rates in closed conduits and finding ventilation rates at work stations. Other uses of tracer gases are also dealt with. Investigations have been performed on the use of occupant generated carbon dioxide (CO2) as an indicator of ventilation rates. Results comparing the simultaneous decay of CO2 and sulphur hexafluoride (SF6) are presented showing the former to be a potentially useful ventilation tool. Presently, tracer gas studies are limited by available sampling and analytical equipment. Recent developments in the technology used for tracer gas testing and the research being performed on sampling and analytical techniques are outlined. Several different sampling methods are considered ranging from passive to pump operated bag sampling. SF6 has received wide acceptance as a tracer gas. However, investigations have shown that while it has most of the desirable tracer gas characteristics, it also has some shortcomings. The physical, chemical, a and toxicological properties of alternative gases were reviewed for this reason and their relative usefulness as tracer gases is presented.
KEYWORDS
tracer gas, carbon dioxide, sulphur hexafluoride

NO 2277 A review of tracer gas techniques for measureing airflows in buildings.
AUTHOR
Lagus P, Persily A K
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ASHRAE Trans, 1985, Vol 91 Part 2B, H1-85-22 No 1, p1075-1087. 8 figs, 2 tabs, 38 refs. DATE 00:00:1985 in English AIC 1645
ABSTRACT
This paper describes tracer gas measuring techniques that have been used to characterize ventilation and air infiltration in buildings, with an emphasis on recent developments and applications in large industrial and commercial structures. Fundamentals and applications are presented for both single and multiple tracer gas methods. In addition to techniques suitable for detailed characterization of building airflows, procedures and equipment appropriate to surveying large numbers of buildings are also discussed. Illustrative examples of

the various measuring techniques as well as discussion of their advantages and disadvantages are provided. A detailed bibliography is also included to facilitate a more thorough examination of the topics discussed.
KEYWORDS
tracer gas, measurement technique, air flow, industrial building, office building, pressurisation

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Ventilation has a considerable influence on both the indoor air quality and energy consumption of buildings. Three parameters can be identified which are of key importance in the assessment of ventilation behaviour: air change rate, interzonal air flows, air leakage characteristics. This paper describes measurement techniques which enable these parameters to be evaluated. The list of techniques presented is not exhaustive and the descriptions given are not particularly detailed. The main aim of this report is to illustrate the spectrum of techniques which are currently available for the quantification of ventilation and air leakage.
KEYWORDS
measurement technique, air leakage

TRACER GAS TECHNIQUES

Constant Concentration Method

NO 1513 Application of the constant concentration technique for ventilation measurement to large buildings.
AUTHOR
Etheridge D W.
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SERC Workshop on Ventilation, Coventry Polytechnic, 25-26 October 1984, 16pp, 6 figs. DATE 13:08:1984 in English Rev. version BSERT, Vol 6, No 3, 1985. p129-133 AIC 962
ABSTRACT
The British Gas 'Autovent' system utilises the constant concentration technique and was developed for measuring ventilation rates in dwellings. It has recently been used in two large open-plan buildings, a school nursery and a factory unit, and the opportunity was taken to carry out special tests to assess its validity in such buildings. The reason why these tests were needed, the nature of the tests and the results obtained form the main content of the paper. The evidence from the tests strongly indicates that the system is suitable. This evidence is supported by the ventilation measurements themselves, examples of which are presented.
KEYWORDS
school, factory, ventilation, constant concentration, measurement technique

NO 1752 Research on fresh-air change rate: 1. occupants' influence on air-change.
AUTHOR
Kvisgaard B, Collet P F, Kure J.
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2nd. ed. Copenhagen, Denmark: Building Technology, Technological Institute of Copenhagen, 1985. 233p. 168 figs, 41 tabs, 14 refs. DATE 00:12:1984 in English AIC bk ABSTRACT
Knowledge of the air change in dwellings under conditions of use is a prerequisite for the calculation of energy consumption and for evaluation of a dwelling's indoor climate. Air change was measured in a total of 25 occupied dwellings over an aggregate period of 205 days, using the constant concentration tracer gas method. Results showed that the occupants exert a very considerable influence on the total air change in the dwelling. The air change rate for occupied dwellings is, on average, 3-4 times greater than the air change rate in sealed buildings (with air-escape valves, doors, windows and ventilation systems closed). The average air change rate for the sealed dwellings is 0.19 ach. Although the average air change rate for occupied dwellings is higher than the recommended rate, some 20% of dwellings have an extremely low air change rate. Mechanically ventilated dwellings tend to have a higher air change rate than naturally ventilated dwellings. Air-escape valves with apertures of 30 cm2 per room were not found to provide the requisite air change rate for sealed dwellings.
KEYWORDS
air change rate, occupancy effects, measurement technique, tracer gas, constant concentration

NO 1816 Continuous air renewal measurements in an occupied solar office building.
AUTHOR
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Paper presented at CLIMA 2000, Copenhagen, August 1985. Rapport No. 85-01-03. Ecole Polytechnique Federale de Lausanne. 5p. 4 figs, 12 refs. DATE 00:08:1985 in English AIC 1187
ABSTRACT
A Compact Equipment for Air Renewal Survey (CESAR) has been developed by the Ecole Polytechnique Federale de Lausanne. The device has been designed for simultaneous analysis of up to 10 different inhabited rooms over extended periods of time (days or weeks). The constant concentration tracer gas technique was used for the first survey done in the South rooms of the LESO building. Mean outdoor to room flow rates of between 1 and 40 m3/h were found. The mean building to room air flow was found to be 5 m3/h for rooms with only one communicating door with the rest of the building. A second survey, performed a year later in 1984/85, showed an increase in building to room air flows within the range of 11 to 45%, due to occupancy effects.
KEYWORDS
air change rate, measurement technique, tracer gas, multi-chamber, constant concentration, air movement, office

NO 2076 The use of a constant concentration tracer gas system to measure ventilation in buildings.

AUTHOR

Bohac D L

BIBINF

PU/CEES Report No 205, February 1986. 292p. 81 figs, 17 tabs, 45 refs DATE 00:02:1986 in English AIC 1451

ABSTRACT

A constant concentration tracer gas system was designed and constructed to continuously measure the air infiltration rate in as many as ten zones of a building. The portable, microcomputer controlled system injects a metered amount of tracer gas into each zone so that the concentration of the gas is held at the same target level in all the zones. With the concentration kept at the target level, the air infiltration rate of a zone is approximately equal to the tracer injection rate into the zone divided by the target concentration. The system was field tested for 11 days in an unoccupied single family house. Analysis of the data indicate that the system is generally reliable. The startup time and control of the system was as good as, or superior to, that achieved by other constant concentration tracer gas systems. The measured air infiltration rates were reasonable and appear to respond to both wind and stack effects. In addition, large differences in the infiltration in separate zones of the house were able to be measured even when there was a high degree of interzone mixing.

KEYWORDS

house, tracer gas, constant concentration, measurement technique, multi-chamber, sulphur hexafluoride

NO 2745 The use of modified constant concentration techniques to measure infiltration and interzone air flow rates.

AUTHOR

Bohac D L, Harrje D T

BIBINF

8th AIVC Conference, 'Ventilation Technology - Research and Application', Ueberlingen, Federal Republic of Germany, 21-24 September, 1987, Supplement to Proceedings, p129-152, 9 figs, 5 tabs, 12 refs.

DATE 00:00:1987 in English AIC 2315

ABSTRACT

The constant concentration tracer gas (CCTG) technique is typically used to measure air infiltration rates in multizone buildings. The measurements are performed by injecting metered amounts of a tracer gas into each zone so as to keep all the zones at a target concentration. One drawback to this method is that no information is gained about the level of interzone flow rates in the building. Modified constant concentration techniques are described which allow selected infiltration and interzone air flow rates to be estimated. These techniques differ from the typical operation in that there are certain zones where no tracer gas is injected. One approach, described as discontinued injection, is useful for measuring interzone flow rates between two sections of a building when the air flow rates are relatively constant. The tracer gas injection in one of the sections is stopped at a certain point in time, but the concentration measurements are continued. The increase of tracer gas injection in the other section and the drop in concentration in the "starved" section are used to estimate the air flow rates between the sections. Field measurements using the modified CCTG methods are presented for experiments in single family amd multifamily buildings. The results are compared to those obtained by passive, multiple tracer gas tests.

KEYWORDS

constant concentration, infiltration rate, air flow, tracer gas, measurement

NO 1253 Ventilation measurements in large buildings.
AUTHOR
Freeman J. Gale R. Lilly J.P.
BIBINF
4th AIC Conference "Air infiltration reduction in existing buildings" Switzerland, 26-28 September 1983 p.5.1-5.14 6 figs. 2 refs. DATE 26:09:1983 in English AIC 2071
ABSTRACT
Compares and contrasts different methods of ventilation measurement in large buildings. Conventional methods of using tracer gas to measure ventilation rates in large volumes are cumbersome and expensive. These constant concentration and decay measurements require artificial mixing, complex monitoring equipment and large installation costs. By using discrete injection sampling units, long term samples of tracer gas be collected with the minimum of capital and installation costs. Samples collected represent the mean local equilibrium tracer gas concentrations. Finds the method to be a useful measure of ventilation rate but increasing problems are found with increase of measured volume requiring greater attention to thorough mixing of the atmosphere and injection sample bag positioning.
KEYWORDS
tracer gas, measurement technique, constant emission,

NO 1653 A modified tracer gas infiltration method for use in a residential indoor air quality/weatherization study.
AUTHOR
Totzke D. et al.
BIBINF
Indoor Air. Vol 5. Buildings, Ventilation and Thermal Climate. Edited by B Berglund, T Lindvall, J Sundell. Swedish Council for Building Research, 1984. 459-464, 8 refs. DATE 00:00:1984 in English AIC bk
ABSTRACT
As part of a study to evaluate the effects of home weatherization on indoor air quality, a tracer gas method to determine infiltration rates was developed by modifying existing methods to meet several project constraints. A method was needed that did not involve occupant participation, required only a small amount of time from the field investigators, and had to be fabricated from rugged, low cost materials that could be easily transported. The method developed is based on the continuous release of pure sulfur hexafluoride (SF6) from a cylinder and the transfer of indoor air to a storage bag. The collection bags were analyzed for SF6 concentration by gas chromatography using an electron capture detector. The concentration of SF6 along with tracer release rates and house volume measurements were used to calculate an air exchange rate for each home studied. Fifty homes were evaluated several times each using this method under varying weather conditions before and after energy conservation improvements were performed.
KEYWORDS
tracer gas, sulphur hexafluoride, retrofit, constant emission, sample bag, chromatograph, measurement technique

NO 1657 Indoor air pollution evaluation by tracer gas technique.
AUTHOR
Hampl V.
BIBINF
Indoor Air. Vol 5. Buildings, Ventilation and Thermal Climate. Edited by B Berglund, T Lindvall, J Sundell. Swedish Council for Building Research, 1984. 505-510, 2 figs, 1 tab, 5 refs. DATE 00:00:1984 in English AIC bk, AIC 1807
ABSTRACT
A tracer gas technique has been used for evaluation and characterization of air flow pattern of contaminants penetrating into buildings. As a tracer, sulfur hexafluoride (SF6) was used and detected by a gas chromatograph equipped with an electron capture detector. SF6 was released at suspected points of contaminant origin at a constant flow rate and was detected quantitatively in the room or laboratory of concern. A dilution factor concept was established which can be used to estimate room contaminant levels and to calculate the level of contaminant in a laboratory hood exhaust system which will result in any given level in the make-up air system or room supply system. In all cases, the tracer gas method was successful and proved to be an effective method for the characterization and the investigation of the contaminant flow pattern. The sensitivity of the SF6 gas detection, the low toxicity, and the specificity of the tracer make this procedure a very useful tool for this type of study.
KEYWORDS
tracer gas, sulphur hexafluoride, constant emission, measurement technique

NO 2536 Microcomputer-aided measurement of air change rates.
AUTHOR
Heidt F D, Werner H
BIBINF
Energy Bldgs, Vol 9, 1986, p313-320, 8 figs, 10 refs.
DATE 00:00:1986 in English AIC 2042
ABSTRACT
Air change rates are measured by a non-dispersive one-beam IR gas analyser using the decay and constant-emission methods with nitrous oxide as tracer gas. Disturbing influences due to H2O and CO2 are low. The analyzer is coupled via a RS-232-C interface to a microcomputer, which is programmed to service the following functions: (1) calibration, (2) preparation and control of measurements, (3) recording, displaying and storing of data, (4) evaluation of results, and (5) error analysis. The implemented programs provide an instant access to results. The whole equipment is installed in compact form on a mobile rack. Measurements have been taken in a university laboratory to examine air change rates with (1) closed door and window, (2) open door only, and (3) tilted window only. Typical results are given and show where the decay method or the constant-emission method is more appropriate.
KEYWORDS
computer, measurement, air change rate, decay rate, constant emission, tracer gas, nitrous oxide, door, window, instruments

NO 1732 Detailed description and performance of a passive perfluorocarbon tracer system for building ventilation and air exchange measurements.
AUTHOR
Dietz R N, Goodrich R W, Cote E A, et al.
BIBINF
Paper presented at the Symposium on Measured Air Leakage Performance of Buildings, American Society for Testing and Materials, Philadelpia, Pennsylvania, April 2-3, 1984. Upton, New York, USA:Brookhaven National Laboratory, Dept of Applied Science, February 1985. 104p. 15 figs, 23 tabs, 26 refs. DATE 00:02:1985 in English AIC 1085
ABSTRACT
The manufacturing procedures and performance of a building air infiltration kit consisting of miniature passive perfluorocarbon tracer permeation sources and passive adsorption tube samplers are described. Having four PFT-types available, homes and buildings with up to four separate zones can be fully evaluated under steady state conditions for the air infiltration and exfiltration rates from each zone as well as the air exchange rates between zones using this inexpensive and non-obtrusive field kit. Complete details on deployment in homes and on gas chromatographic analysis of the passive samplers are presented. Examples of total air changes per hour results in several studies showed average values between 0.25 to 0.64 h-1. A generalized correlation was used to characterize the leakiness of eleven homes in the US and Canada, showing ACH dependency only on inside-outside temperature difference, wind speed to the 1.5 power, and a subjective terrain factor: the approach has application in evaluating weatherization performance.
Details of multizone measurements in four homes provided insight into the role of attics, crawl-spaces, and basements on the indoor air quality and weatherization needs for the living zone.
KEYWORDS
air infiltration, tracer gas, perfluorocarbon, passive sampling, multi-chamber, measurement technique, air change rate, air quality, attic, basement,

NO 2278 Evaluation of the perfluorcarbon tracer technique for determining infiltration rates in residences.
AUTHOR
Leaderer B P, Schaap L, Dietz R N
BIBINF
Environ Sci Technol, Vol 19, No 12, 1985. p1225-1232. 4 figs, 7 tabs, 18 refs. DATE 00:12:1985 in English AIC 1646
ABSTRACT
Describes the evaluation of a new simple passive perfluorocarbon tracer technique for determining air infiltration rates into houses and buildings. The authors explain the methods used and present and discuss their results.
KEYWORDS
tracer gas, house, residential building

NO 2825 Influence of airflow on the performance of perfluorocarbon tracer techniques for measuring ventilation rates.
AUTHOR
Vercammen M, Leaderer B P, Dietz R N

BIBINF
in: Indoor Air '87, Proceedings of 4th International Conference on Indoor Air Quality and Climate, Berlin (West), 17-21 August 1987. Vol 3 Institute of Water, Soil and Air Hygiene, 1987, p 388-392, 3 figs. 3 refs.
DATE 00:00:1987 in English AIC 2395
ABSTRACT
The perfluorocarbon tracer technique (PFT) is being extensively used for determining air infiltration rates in residences and office buildings. The method has been evaluated in chamber studies for effects of temperature, variable ventilation rates and orientation of the passive capillary collectors in low air velocities (<.2m/s) typical of residences. This paper presents the results of chamber studies designed to evaluate the PFT method under conditions of constant temperature and high air velocities (0.8 to 6.4 m/s). The efficiency of the passive capillary collectors was evaluated as a function of air velocity and orientation in the flow. Two different enclosures for the collectors, designed to minimize the air velocity effects, were also evaluated. The results indicate that air velocities above 0.8 m/s and collector orientation affect the efficiency of the collectors. Enclosing the collector and orienting it 180o to the flow minimizes effect.
KEYWORDS
air flow, perfluorocarbon, tracer gas, ventilation rate

Decay Rate Method

NO 1272 Evaluation of evacuated glass tubes for sampling of SF6/Air mixture for air exchange measurements.
AUTHOR
Tamura G.T. Evans R.G.
BIBINF
ASHRAE Jnl. vol.25 no.10 p.40-43 3 figs. 2 tabs. 4 refs. DATE 01:10:1983 in English AIC 802
ABSTRACT
Grab sampling of a tracer gas/air mixture in conjunction with the tracer gas decay technique is a convenient method for conducting a survey of air infiltration rates in homes. Examines such a method, using SF6 as the tracer gas and storing the concentration in evacuated glass tubes.
KEYWORDS
tracer gas, decay rate, measurement technique, sulphur hexafluoride,

NO 1356 Parameters affecting air infiltration and air tightness in 31 east Tennessee homes.
AUTHOR
Gammage R.B. Hawthorne A.R. White D.A.
BIBINF
Preprint ASTM Symposium on measured air leakage performance of buildings Philadelphia USA April 2-3 1984 13 pp. 2 tabs. DATE 02:04:1984 in English AIC 870
ABSTRACT
A major pathway for loss of conditioned air in east Tennessee homes with externally located HVAC systems is leakage in the ductwork. The effect on infiltration rates, as measured by Freon-12 tracer gas dilution, becomes marked if the central duct fan is operating. Duct fan on and duct fan off

measurements of the rate of air exchange gave mean values of 0.41 and 0.78 ach respectively in a total of 31 homes. Specific leakage areas measured using a pressurization technique are affected to a lesser extent by inclusion of the ductwork volume within the total volume of the house being pressurized. A subset of 7 of the study homes were measured using this technique - the average increment in the specific leakage area was 15%.
KEYWORDS
mechanical ventilation, air leakage, pressurization, component leakage, tracer gas, decay rate, fan, duct,

NO 1386 The measurement of air infiltration in large single cell industrial buildings.
AUTHOR
Waters J.R. Simons M.W.
BIBINF
Preprint ASTM Symposium on measured air leakage performance of buildings Philadelphia USA April 2-3 1984 23pp. 7 figs. 4 tabs. DATE 02:04:1984 in English AIC 890
ABSTRACT
Carries out measurements of the air infiltration rate of 3 large single cell buildings using the tracer dilution method. The purpose is to determine whether or not there are any special difficulties in using the tracer dilution method in this type of building, prior to emabarking on a more substantial measurement program. Uses nitrous oxide and sulphur hexafluoride as tracers. Finds both to be satisfactory, but concludes that SF6 in conjunction with a portable gas chromatograph performs more reliably when used for on-site measurements.
KEYWORDS
tracer gas, decay rate, sulphur hexafluoride, nitrous oxide, air infiltration,

NO 1895 Strategy for measuring infiltration rates in large, multicelled and naturally ventilated buildings using a single tracer gas.
AUTHOR
Perera M D A E S, Walker R R
BIBINF
Building Services Engineering Research & Technology, 1985, Vol 6, No 2, p82-88. 5 figs, 5 tabs, 7 refs. DATE 00:00:1985 in English AIC 1313
ABSTRACT
Large, multicelled and naturally ventilated buildings pose many inherent problems for the measurement of overall infiltration rates using tracer gases. Considering a single tracer gas decay technique, the most obvious problems are: (a) local variations in infiltration, (b) imperfect internal mixing of the air, and (c) practical difficulties in distributing (ie, seeding) the tracer gas and subsequently obtaining air samples. This paper proposes a relatively simple technique which avoids these problems and which, if successful, makes a breakthrough in the measurement of infiltration rates in large and complex buildings. By considering a multicell model, it is shown that it can be sufficient to seed part of a building with a single tracer gas in order to measure the overall infiltration rate to a good approximation.
KEYWORDS
measurement technique, multi-chamber, tracer gas, decay rate, mathematical modelling

NO 1944 Rapid thermal calibration of houses.
AUTHOR
Everett R
BIBINF
Milton Keynes, UK:Energy Research Group, Open University,1985. ERG 055. 200p. figs, tabs, 6 refs. DATE 00:08:1985 in English AIC bk
ABSTRACT
Presents a detailed description of the measurement technique and apparatus used to measure the air change rate in the Spencer St and Linford low-energy houses in Milton Keynes, UK. An automatic air infiltration rig using nitrous oxide tracer gas constant decay was used. Air leakage was also measured by pressurization for the Linford houses and some from the neighbouring Pennyland project.
KEYWORDS
air change rate, air leakage, measurement technique, automatic equipment, nitrous oxide, tracer gas, decay rate, pressurization

NO 2594 The use of detector tubes with carbon dioxide as a tracer gas.
AUTHOR
Sandberg M, Sundberg J
BIBINF
AIR, Vol 8, No 3, May 1987, p6-7, 2 figs, 1 tab, 2 refs.
DATE 00:05:1987 in English AIC 2114
ABSTRACT
Tracer gas concentrations are often analysed by using infrared spectroscopy. Infrared gas analysers have a fast response time and are accurate. Howener, this type of instrumentation is relatively expensive and can only be used for this type of measurement. A cheaper alternative is therefore preferred. Normally there is a trade-off between cost and accuracy. Detector tubes are inexpensive and are available for many gases, among them CO2. They are packed with a selective solid absorbent which gives a colour reaction with the gas in question. The higher the concentration of gas which enters the tube the further the coloured region extends down the packing. The tubes have approximate calibration markings which show the concentration of the gas.
This article reports a method of measuring the ventilation air flow rate using a tracer decay technique in occupied houses with CO2 as a tracer gas. The metabolic CO2 from people is taken into account. The accuracy of the method has been explored through various tests.
KEYWORDS
tracer gas, carbon dioxide, instrumentation, ventilation rate, decay rate, residential building, measurement technique

Multiple Tracer Gas Methods

NO 1258 Ventilation rates and inter cell air flow rates in a naturally ventilated office building.
AUTHOR
Perera M.D.A.E.S. Walker R.R. Oglesby O.D.
BIBINF
4th AIVC Conference "Air infiltration reduction in existing buildings" Switzerland, 26-28 September 1983 p.12.1-12.13 5 figs. 5 refs. DATE 26:09:1983 in English AIC 1757

ABSTRACT
Determines ventilation rates and intercell flow rates in naturally ventilated office building using multiple tracer gases. Subdivides the building into 3 zones and seeds each zone individually with a different tracer gas. Monitors the time histories of the concentrations of all gases in each zone using non-dispersive infra red gas analysers. Calculates air flow rates from experimental data. Uses an in-house computer program which predicts the dispersion of a tracer gas in a multi-zoned environment, to compare the predicted time histories of concentrations with those obtained experimentally.
KEYWORDS
air flow, multi-chamber, modelling, tracer gas, office building,

NO 1731 Application of perfluorocarbon tracers to multizone air flow measurements in mechanically and naturally ventilated buildings.
AUTHOR
Dietz R N, Goodrich R W, Cote E A, et al.
BIBINF
Upton, New York, USA:Brookhaven National Laboratory, Dept of Applied Science, August 1984. BNL 35249. 23p. 7 figs, 7 tabs, 10 refs. DATE 00:08:1984 in English AIC 1084
ABSTRACT
The Brookhaven air infiltration measurement system (BNL/AIMS) uses a family of four passive perfluorocarbon tracer sources and miniature passive adsorbent samplers to inexpensively but very effectively tag individual zones within multizone buildings with uniquely discernible tracer vapours. The concentrations measured with the passive samplers allow the air infiltration and exfiltration rates from each zone to be computed as well as the air exchange rates between zones. Two naturally ventilated buildings, a 2-zone (3056 m3) jailhouse and a 4-zone (1028 m3) apartment building were tested: the former showed a 2.5 to 1 ratio in the fresh air rates into the zones. Two mechanically ventilated buildings, each of 3-zones, were also tested. The 3-storey (each floor was a zone) library (5840 m3) was shown to have 10 times more fresh air entering the first floor than the second (1.33 h-1 compared to 0.15 h-1). The 16-storey office building (142,500 m3) had 4 times as much fresh air in one zone compared to a side-by-side identical zone (1.07 h-1 versus 0.25 h-1). The performance of BNL/AIMS in certifying HVAC systems is demonstrated.
KEYWORDS
tracer gas, perfluorocarbon, measurement technique, multi-chamber, air flow, natural ventilation, mechanical ventilation

NO 1843 Automation, extension and use of the PCL multi-tracer gas technique for measuring interzonal air flows in buildings.
AUTHOR
Littler J, Martin C, Prior J
BIBINF
Final Report on SERC Grant GR/C/63427. RIB/1985/718. January 1985. 26p. 14 figs, 8 refs. DATE 00:01:1985 in English AIC 1219
ABSTRACT
Describes the development of an automated air sampling equipment to measure air infiltration and interzonal air flows. A new matrix analysis method has

been developed to calculate single zone infiltration and interzonal air flow rates from measured data. A number of multi-zone experiments have been carried out in the PCL solar heated house at Peterborough, and several single zone infiltration rate measurement experiments have been carried out in a wide variety of buildings. A grab-tube method has been developed for assessing air change rates.
KEYWORDS
tracer gas, multi-chamber, passive sampling, passive solar house, measurement technique, automatic equipment

NO 1992 The measurement of airflows using a rapid response tracer gas technique.
AUTHOR
Irwin C, Edwards R E, Howarth A T
BIBINF
Building Services Engineering Research and Technology, 1985, Vol 6 No 4, p146-152. 7 figs, 1 tab, 7 refs. DATE 00:00:1985 in English AIC 1410
ABSTRACT
The multiple tracer gas technique of I'Anson et al. has been improved, in order to increase the rate at which samples can be taken. Using parallel gas chromatographic separation columns and an electron capture detector, it is now possible to take an air/tracer gas sample every thirty seconds in the case of a two-zone ventilation and air movement test. Rapid sampling enables a new, simplified analysis of the air movement between two connected zones to be employed. This analysis derives ventilation rates and intercell airflows simultaneously. A specimen set of results for two cell ventilation/air movement is given.
KEYWORDS
tracer gas, measurement technique, decay rate, air change rate, air movement, multi-chamber

NO 2645 The measurement of air movements between four interconnected cells by a multiple tracer gas decay technique.
AUTHOR
Edwards R E, Irwin C
BIBINF
Roomvent 87, proceedings, Stockholm 10-12 June 1987, 16p, 9 figs, 2 tabs, 10 refs.
DATE 00:06:1987 in English AIC 2207
ABSTRACT
This paper describes the development and application of a multiple tracer gas decay technique for the measurement of the ventilation rates in, and the air movements between, four interconnected cells. The measurement equipment used is a refinement of the existing UMIST parallel separation column portable gas chromatograph. By the use of the parallel electron capture detectors, it is possible to measure the concentrations of four tracer gases in four cells, within sufficiently short a time interval for an air movement calculation procedure, based on the previous procedures used for two and three cells, to be used successfully: this procedure is summarised in this paper. A typical set of results is presented, in order to demonstrate a situation in which the technique could be applied to complex air movements within the building envelope. The possible extension of the technique to five or more cells is also briefly discussed.
KEYWORDS
measurement technique, air movement, tracer gas, decay rate

Intercomparison of Tracer Gases

NO 200 An intercomparison of tracer gases used for air infiltration measurements.
AUTHOR
Grimsrud D.T. Sherman M.H. Janssen J.E. Pearman A.N. Harrje D.T.
BIBINF
Lawrence Berkeley Laboratory. University of California paper LBL-8394 2 figs -ASHRAE trans. 1980. vol 86 no 1. DATE 19:04:1979 in English AIC 18.
ABSTRACT
Reviews ideal characteristics of a tracer gas and gives literature review of the subject. Reports tests made on a house in California giving a direct intercomparison between common tracer gases used to measure air infiltration rates in buildings. Results indicate that air exchange rates measured using sulphur hexafluoride are slightly larger than those measured using methane or nitrous oxide. The ratio of air change rates measured using sulphur hexafluoride to air change rates measured concurrently using a lighter tracer gas was found to be 1.10 +- 0.10
KEYWORDS
tracer gas, air change rate, sulphur hexafluoride, methane nitrous oxide,

NO 1005 The effect of tracer gas on the accuracy of air change measurements in buildings.
AUTHOR
Shaw C.Y.
BIBINF
Preprint for ASHRAE Atlantic Meeting January 23-27 1983 30pp. 10 figs. 5 tabs. 6 refs. DATE 23:01:1983 in English AIC 606
ABSTRACT
Compares the air change rates measured using the decay method with several different tracer gases. Tracer gas measurements were conducted in a tightly sealed room where constant air leakage rates were maintained using an exhaust fan. Tracer gases investigated were CH_4, CO, CO_2, N_2O and SF_6. Agreement between tracer gas measurements and measured flow rates of the exhaust fan was very good for CH_4, CO and N_2O. The agreement was also satisfactory for CO_2 and SF_6, but the scatter in tracer gas data was much greater then it was for the other three gases.
KEYWORDS
tracer gas, decay rate, methane, carbon monoxide, carbon dioxide, nitrous oxide, sulphur hexafluoride,

Intercomparison of Tracer Gas Methods

NO 1954 A comparison of the perfluorocarbon and tracer gas decay methods for assessing infiltration.
AUTHOR
Schaap L, Leaderer B P, Renes S, et al.
BIBINF
Proceedings of the CLIMA 2000 World Congress on Heating, Ventilating and Air-Conditioning, Copenhagen, 25-30 August 1985. Edited by P Fanger. Vol 2 Building Design and Performance. p19-24. 1 fig, 1 tab, 3 refs. DATE 00:08:1985 in English AIC 1377

ABSTRACT
The passive perfluorocarbon tracer (PFT) technique for determining air infiltration rates into homes and buildings was evaluated in an environmental chamber. The impact of sampler orientation at a constant ventilation rate and a constant temperature, of variable ventilation rate at a constant temperature, and of variable temperature at a constant ventilation rate were evaluated in three experiments. The average relative standard deviation of 16 paired samplers deployed in experiment 1 was plus or minus 1.9% plus or minus 1.0% indicating good reproducibility of the passive sampling rate and sample analysis. No impact of sampler orientation with respect to low air velocities (less than 0.2 m/s) present in houses is expected. The passive samplers accurately measured the average tracer concentration as compared with calculations based on the known source strength (CO2 decays) and the measured ventilation rate under conditions of a 3-fold variation in ventilation rates (experiment 2). Temperature cycling differences of 8 deg. C (experiment 3) did not produce a bias in the PFT determined ventilation rate. The PFT technique is applicable to the expected range of conditions in homes and buildings.
KEYWORDS
perfluorocarbon, environmental chamber, decay rate, passive sampling

NO 2367 Predicting a time-varying flow rate using the constant concentration and decay technique.

AUTHOR
Sandberg M

BIBINF
Ashrae Trans, Vol 93 Part 1, 4 figs, 1 tab, 3 refs.
DATE 00:00:1986 in English AIC 1754

ABSTRACT
This study deals with the accuracy of different tracer gas techniques for predicting the mean flow rate of a time-varying airflow rate, as occurs in naturally ventilated houses. A theoretical analysis of the accuracy is first presented. Experiments were conducted in a test house ventilated by natural ventilation. The methods explored were the constant concentration method and the decay method. The airflow rate in the duct connected to the house was continuously recorded by the constant tracer gas flow technique. The oscillations in flow rates that occurred were of a high frequency nature, which should not affect the accuracy. Incomplete mixing of both tracer gas and air seems to be the greatest source of error, even in cases with a time-varying ventilation airflow rate.

KEYWORDS
tracer gas, air flow, natural ventilation

NO 2738 Field study comparisons of constant concentration and PFT infiltration measurements.

AUTHOR
Bohac D L, Harrje D T, Horner G S

BIBINF
8th AIVC Conference, 'Ventilation Technology - Research and Application', Ueberlingen, Federal Republic of Germany, 21-24 September, 1987, Supplement to Proceedings, p47-62, 9 figs, 10 refs. DATE 00:00:1987 in English AIC 2308

ABSTRACT
The accuracy of tracer gas measurements of building air infiltration rates has been a widely discussed topic. One question that has often come up at past AIVC conferences is the ability of passive methods, such as the

Perfluorocarbon Tracer (PFT) method, to accurately measure fluctuation air flow rates. A series of field studies is being conducted to compare the air infiltration measurements of the constant concentration tracer gas (CCTG) and PFT methods and provide recommendation for their proper implementation in the field. The field studies include side-by-side measurements of multi-zone air infiltration rates using the CCTG and PFT methods. The results are reported from two tests in an unoccupied single-family house and eight tests in an occupied house. Test periods varied from one to three weeks. The measurements from the unoccupied house showed that there were no major discrepancies between the two methods. The PFT measurements in the occupied house were consistently lower than those by the CCTG method. Warm weather periods with substantial, periodic airing resulted in the PFT method producing underprediction errors greater than 30%. During the cold weather periods when the fluctuation in the infiltration rate was due to weather changes and a small amount of airing, the underprediction error ranged from 5 to 29%.
KEYWORDS
constant concentration, perfluorocarbon, tracer gas measurements

PRESSURIZATION TECHNIQUES

DC Pressurization-Building Components

NO 1105 Measurement of local airtightness in buildings.
AUTHOR
Siilonen V.
BIBINF
Technical Research Centre of Finland Research Note 125 July 1982 12 pp. 4 figs. 1 tab. DATE 01:07:1983 in English AIC 676
ABSTRACT
Decribes the "collector chamber" method, where a room or whole building is pressurised and the air leaking through the target areas is collected with a pressure compensated chamber to a measurement device.
KEYWORDS
component leakage, instrumentation, measurement technique,

NO 1423 Ventilation in small functional buildings - measurements of air leakage of interior walls
Ventilatie in kleine utilitaire gebouwen metingen aan luchtlekken van binnewanden
AUTHOR
Phaff J C., de Gids W F.
BIBINF
IMG-TNO Report C522, September 1983, 81pp, 55 figs, 23 tabs. DATE 01:09:1983, in Dutch, AICR NL10.
ABSTRACT
This is the second part of a study on natural ventilation in functional buildings. Reports the results of 23 measurements on a number of partitions, internal walls and one brick built internal wall. Measurements were made in 4 buildings. For the largest leakages measured in these 4 buildings, a strong influence was observed on the ventilation of neighbouring rooms. The opening of a window in a room has notable consequences on the ventilation and air flow in the other rooms. The measured air leakages ranged from 0038 to 0.068 m2 for a wall and .0131 -.0529 m2 for a room.
KEYWORDS
component leakage, brick wall, air flow, open window

NO 1662 The value of pressure testing to establish the viability of retrofit procedures for a high rise building.
AUTHOR
Ward I C.
BIBINF
Energy and Buildings, January 1984, Vol 6, No 1, 93-94, 2 figs, 1 tab, 1 ref.
DATE 00:01:1984 in English AIC 1031.
ABSTRACT
Presents the results of air leakage tests on the windows of the Arts Tower at Sheffield University. The results quoted show the ranges into which infiltration coefficients fall. Relates pay-back periods for weatherstripping to height above ground level. Tabulates mean values of leakage coefficient and flow exponent for defective and non-defective sealant and compares with values suggested in CIBS Guide.
KEYWORDS
window, high rise building, component leakage, sealant, weatherstripping

NO 1739 Air leakage tests on polyethylene membrane installed in a wood frame wall.
AUTHOR
Shaw C Y.
BIBINF
Ottawa: National Research Council Canada, 1985. Building Research Note No 225. 26p. 19 figs, 1 tab. DATE 00:01:1985 in English AIC 1112
ABSTRACT
This report presents the results of air leakage tests on polyethylene membranes installed in a frame wall. The results would be useful in evaluating the methods commonly used for installing such a component. They can be summarized as follows: 1, a 6 mil polyethylene membrane was stiffer than a 4 mil membrane and had a greater air leakage rate through the joint, 2, the best method for installing a wall joint was to have the two sheets of polyethylene overlapped by about 400 mm, with the edges stapled to two vertical studs, 3, the spline system was too difficult to apply, especially at the corners, 4, taping and caulking the joint did not produce an air-tight joint, and 5, a new technique is needed to fasten the edges of the polyethylene sheet to the window frame and hold the edges in place.
KEYWORDS
wood frame, vapour barrier, component leakage, joint, pressurization

NO 2628 Balanced fan depressurization method for measuring component and overall air leakage in single and multi family dwellings.
AUTHOR
Reardon J T, Kim A K, Shaw C Y
BIBINF
Preprint, Ashrae Trans, Vol 93, Part 2, No 3062, 1987, 15p, 8 figs, 3 tabs, 6 refs.
DATE 00:00:1987 in English AIC 2162
ABSTRACT
The balanced fan depressurization technique has been applied to measure air leakage characteristics of row houses and individual house stories. Controlled field tests on two detached, two-storey houses with full basements were

carried out to verify the consistency of the method. The technique was then used to measure the air leakage rates of three row house units and the storeys of two other houses. The results were presented and discussed.
KEYWORDS
fan depressurization, component leakage, air leakage, multi family building, house, terraced house

NO 2708 Air leakage measurements on full-scale construction.
AUTHOR
Baker P, Valentine G
BIBINF
Bldg Serv Eng Res Tech, 8(1987), p69-71, 5 figs, 5 refs.
DATE 00:00:1987 in English AIC 2279
ABSTRACT
A technique for identifying and measuring air leakage through the fabric of buildings is presented. The leakage characteristics of a few selected full-scale building details are illustrated. The data derive from both laboratory and real-world buildings, and indicate the importance of design detailing and construction of junctions to control air leakage.
KEYWORDS
air leakage, thermography, measurement technique

NO 2722 The validation and application of a portable pressurisation test facility for the measurement of the flow characteristics of background leakage areas.
AUTHOR
Baker P H, Sharples S, Ward I C
BIBINF
in: Third International Congress on Building Energy Management, III Ventilation, air movement and air quality: field measurement and energy auditing, held in Lausanne, Switzerland, September 28- October 2, 1987, p277-284, 7 figs, 9 refs.
DATE 00:09:1987 in English AIC 2293
ABSTRACT
The use of the pressurisation system, which is capable of direct localised measurement can greatly aid the identification and quantification of individual background leakage areas. The test uses the guarded pressure box principle to measure the air flow through a specified target under pressurisation. The whole room or house is pressurised using a blower door and a measurement box, pressurised by an auxillary fan, is placed over the target. The latter fan, if adjusted to maintain a zero pressure difference, between the measurement box and the room, compensates for any disturbance of the leakage flow due to the presence of the measurement box and the connected volume flow meter. The resultant flow, is the leakage due only to the target area at the pressure difference, maintained across the building envelope.
KEYWORDS
validation, pressurization testing, leakage area, air flow, blower door

NO 1260 Airtightness of residential buildings in Japan.
AUTHOR
Murakami S. Yoshino H.
BIBINF
4th AIVC Conference "Air infiltration reduction in existing buildings" Switzerland, 26-28 September 1983 p.15.1-15.20 11 figs. 3 tabs. 37 refs. DATE 26:09:1983 in English AIC 1758
ABSTRACT
Measures the airtightness of various types of 25 residential units (9 detached houses and 16 apartments) using the fan pressurization technique. Shows the relationship between the pressure difference across the building envelope and the volumetric flow rate of air as well as the ratio of the effective leakage area of one building element to the total leakage area. Compares the airtightness of various types of houses in different countries using the value of the effective leakage area per floor a at a pressure difference of 10 Pa. Considers the important points in the design of ventilation systems for an airtight house.
KEYWORDS
residential building, pressurization, air leakage, tight house,

NO 1276 Air leakage in industrial buildings - preliminary results.
AUTHOR
Lundin L.
BIBINF
4th AIC Conference "Air infiltration reduction in existing buildings" Switzerland, 26-28 September 1983 p.6.1-6.8 5 figs. 1 ref. DATE 26:09:1983 in English AIC 2012
ABSTRACT
Describes pressurization tests conducted by the National Testing Institute on 3 large industrial buildings. Sets out equipment and methods used including a tracer gas method to calculate air flow through the fan rather than the usual measuring duct. Gives construction and volume details of buildings measured.
KEYWORDS
industrial building, air leakage, pressurization, fan, tracer gas, instrumentation, measurement technique,

NO 1355 Air flow calibration of building pressurization devices.
AUTHOR
Persily A.K.
BIBINF
Preprint ASTM Symposium on measured air leakage performance of buildings Philadelphia USA April 2-3 1984 = NBSIR 84-2849 30pp. 7 figs. 4 tabs. 23 refs. DATE 02:04:1984 and 5th AIC Conference 'The implementation and effectiveness of air infiltration standards in buildings' Reno, Nevada, 1-4 October 1984, pp21.1-21.18 in English AIC 869
ABSTRACT
Describes a calibration technique to relate the air flow rate through a blower door to the fan speed and pressure difference across the door. To obtain an accurate and well-documented calibration of pressurization devices, a facility was designed and constructed at the US National Bureau of Standards. This

accurately determines the flow rate through the fan as a function of fan speed, air density and pressure difference across the fan. Describes the calibration facility, presents the results of the calibration of one blower door, and discusses the effect of the form of the calibration equation on the accuracy of the air flow rate determination.
KEYWORDS
fan, blower door, pressurization, air flow,

NO 1414 Airtightness, pressure differences and indoor climate in the experimental building Kasarminkatu 24.
AUTHOR
Saarnio P.
BIBINF
Proc.CIB Workshop on indoor air quality and energy conservation Helsinki June 1983 ESPOO Report B3 p.V.1-V.15 10 figs. 1 tab. 1 ref. DATE 01:06:1983 in English AIC
ABSTRACT
Reports on pressure tests carried out on the Kasarminkatu 24 building (a museum of architecture) in Helsinki. The fans in the building were used to measure airtightness of the building envelope, and the tightness of windows and doors was measured separately by the guarded box method. The tightness of the building envelope was good (2 ach at 50 Pa). 70% of total air leakage came through the wooden roof structure, and only 5-10% through the window structure. Three alternative mechanical ventilation systems were also studied in the same building to assess their impact on indoor climate.
KEYWORDS
pressurization, museum, air tightness, mechanical ventilation, air quality,

NO 1431 Air tightness tests on 200 new houses across Canada. Summary of results
AUTHOR
Sulatisky M.
BIBINF
Canada Buildings Energy Technology Transfer Program publication no.84.01, 1984, 51pp, 6 figs, 34 tabs, 6 refs. DATE 01:01:1984, in English, AICR CA12
ABSTRACT
A database on the airtightness performance of houses built according to current construction practices (1980 to 82) was established, province by province, across Canada. Airtightness tests were conducted using the fan-depressurisation method and the results were compared by province, builder, house style, type of vapour barrier and house size. The survey shows considerable variation in the leakiness of the houses when the results are compared by province. Less variation in airtightness exists when the houses are compared by builders, house style and house size on a provincial basis. The results suggest that builders in Canada should have little difficulty in constructing houses with a 50% improvement in the level of airtightness at little extra cost. This involves enclosing electrical outlets and fixtures in polyelthylene and caulking the header joist connection. Sources of error in air tightness surveys are discussed.
KEYWORDS
house, pressurization, air leakage,, air tightness, caulking, vapour barrier, residential, building

NO 1665 Preliminary survey of air tightness levels in New Zealand houses.
AUTHOR
Bassett M.
BIBINF
Transactions of the Institution of Professional Engineers of New Zealand, July 1984, Vol 2, No 2/EMCh, 53-61, 9 figs, 22 refs. DATE 00:07:1984 in English
AIC 1034
ABSTRACT
Air tightness results for 40 New Zealand timber frame houses of varying age and construction detail are given. The steady pressure method was used at 6-9 indoor-outdoor pressure differences in the range 10-150 Pa. The data is presented in four ways: 1. air changes per hour at 50 Pa, 2. the coefficient and exponent of a generalized leakage function, 3. the leakage rate per unit shell area at 50 Pa, and 4. the equivalent leakage area at 50 Pa. Houses in the 0-5 and 6-20 year age groups were not significantly different in terms of air tightness. The greater than 20 year age group were less tight. Air leakage around openable doors and windows made up 17% of the total envelope leakage in houses less than 5 years old and 23% in older houses. The air tightness test has only limited application in locating leakage openings for weatherstripping because of the number of leaks.
KEYWORDS
air leakage, component leakage, air tightness, pressurization, door, window

NO 1873 Fan pressurization of buildings: standards, calibration, and field experience.
AUTHOR
Gadsby K J, Harrje D T
BIBINF
Preprint. ASHRAE Transactions 1985, Vol 91 Pt 2. HI-85-03 No 1. 10p. 6 figs, 1 tab, 24 refs. DATE 00:00:1985 in English AIC 1278
ABSTRACT
The fan pressurization method has been widely used by groups working with building retrofits and with new construction to evaluate the air tightness of building envelopes. To ensure uniformity in the testing method ASTM Standard E779-81 was developed. This standard is reviewed with commentary on practical aspects of its application. Calibration of the fan pressurization systems, often referred to as blower doors, is also discussed, pointing out where calibration difficulties have arisen and the implications on field inspections. Use of fan pressurization together with infrared scanning is one of the best methods to pin-point air leakage sites in building envelopes. The applications of such methods in a variety of buildings are discussed in order to demonstrate the utility of the methods in the evaluation of building tightness, including seasonal variations, effectiveness of envelope sealing, and the location of problem areas in the building envelope.
KEYWORDS
pressurization, measurement technique, standard

NO 2251 Air leakage and fan pressurization measurements in selected naval housing.
AUTHOR
Lagus P L, King J C

BIBINF
Measured air leakage in buildings. A symposium on performance of building constructions, Philadelphia, 2-3 April 1984. ASTM Special Technical Publication 904. Edited by H R Trechsel and P L Lagus. ASTM 1986. p5-16. 4 figs, 6 tabs, 9 refs. DATE 00:00:1986 in English AIC bk
ABSTRACT
Data from detailed tracer concentration decay and induced pressurization measurements were obtained in tests of duplex and row apartments at Norfolk, Virginia and Pensacola, Florida to accurately determine air leakage characteristics of selected naval housing. Local meteorological information also was collected to facilitate comparison of predicted versus measured air leakage rates. For the Norfolk data, the 4-Pa leakage areas inferred from pressurization±depressurization measurements are uniformly lower than those calculated from the measured tracer dilution air leakage rate via the Sherman air leakage model. Considerable tracer dilution testing was performed on a single unit of duplex housing at Pensacola. Air leakage testing within rooms of this unit disclosed a uniformly low air leakage rate. The data also illustrated the directional nature of air leakage in a duplex. Of particular additional interest were two measurements taken over a 24-h period utilizing a single tracer injection followed by monitoring of dilution decay. Samples were taken by the container method and analyzed.
KEYWORDS
fan pressurization, air leakage, sulphur hexafluoride, leakage area

NO 2257 Pressurization testing of federal buildings.
AUTHOR
Persily A K, Grot R A
BIBINF
Measured air leakage of buildings. A symposium on performance of building constructions, Philadelphia 2-3 April 1984. ASTM Special Technical Publication 904. Edited by H R Trechsel and P L Lagus. ASTM 1986. p184-200. 3 figs. 5 tabs. 21 refs. DATE 00:00:1986 in English AIC bk, AIC 2026
ABSTRACT
Seven federal buildings ranging in size from 1900 to 48000 m2 of floor area were pressure tested to determine the airtightness of the building envelopes. These tests are part of a larger project to evaluate the thermal integrity of the envelopes of federal buildings. The buildings were pressurized using the air-handling equipment in the buildings and a constant-injection, tracer gas technique to measure the airflow through the fans. In addition, selected windows in some of these buildings were pressure tested separately to determine the airtightness of individual components. The results of the whole building and component pressurization tests are presented and discussed. In addition, the component pressurization test results are used to estimate the contribution of the windows to the total building air leakage. The results of the building pressurization tests are compared empirically to measured infiltration rates on the same buildings. The large building infiltration model developed by Shaw and Tamura of the National Research Council of Canada is applied to the buildings to predict air infiltration rates induced by weather.
KEYWORDS
air leakage, air tightness, component pressurization, large building, pressurization testing

NO 2409 Measuring air leakage.
AUTHOR
Uglow C
BIBINF
Building Services, Vol 8, No 2, February 1986, p59, 2 figs, 6 refs.
DATE 00:02:1986 in English AIC 1879
ABSTRACT
Describes a simple fan pressurisation technique being used at BRE to study the air leakage characteristics of dwellings.
KEYWORDS
pressurization technique, air leakage, residential building

NO 2412 Air permeability of some Australian houses.
AUTHOR
Biggs K L, Bennie I, Michell D
BIBINF
Bldg Environ, Vol 21, No 2, p89-96, 1986, 4 figs, 1 tab, 13 refs.
DATE 00:00:1986 in English AIC 1882
ABSTRACT
The paper reports the first air permeability measurements carried out on Australian houses. Permeability was measured by the fan pressurization method. Comparison is made with results obtained in other countries. Variation between types of houses is discussed on the basis of measured leakage of components in an experimental building. Methods of predicting the permeability of houses are considered and an empirical approach is adopted. The cost effectiveness of housetightening measures in discussed.
KEYWORDS
permeability, residential building, fan pressurization method, retrofit.

AC Pressurization

NO 479 Air leakage in a building at low pressures using an alternating pressure source.
AUTHOR
Grimsrud D.T. Sherman M.H.. Sonderegger R.C.
BIBINF
Proceedings XXI International Congress for Building Services Engineering 17-18 April 1980 DATE 17:04:1980 in English AIC 193
ABSTRACT
Reports low-pressure measurements of the leakage function of a building using an alternating (AC) pressure source with variable frequency and displacement. Synchronous detection of the indoor pressure signal created by the source eliminates the noise due to fluctuations caused by the wind. Finds good agreement between AC and DC leakage results in pressure regions where the results can be compared. The low-pressure values made with the AC source suggest that the air flow is dominated by orifice flow effects down to pressures less than one Pascal.
KEYWORDS
pressurization, alternating pressure, air infiltration

NO 1872 AC pressurization: a technique for measuring leakage area in residential buildings.

AUTHOR

Modera M P, Sherman M H

BIBINF

Preprint. ASHRAE Transactions 1985, Vol 91 Pt 2. HI-85-03 No 3. 12p. 4 figs, 2 tabs, 20 refs. DATE 00:00:1985 in English AIC 1277

ABSTRACT

This report presents a new technique for measuring the leakage area of residential buildings. This technique, called AC pressurization, is designed to overcome most of the shortcomings of fan pressurization, the conventional technique for measuring leakage area. The fan pressurization technique (often performed using a blower door) has several known deficiencies: 1, the pressures it exerts on the building envelope are significantly higher than those experienced under natural conditions, thereby requiring extrapolation outside of the measurement range to calculate the leakage area, 2, it cannot make real-time leakage area measurements, and 3, the large volumes of air displaced by the fan can cause inconveniences such as large indoor temperature changes. AC pressurization, which induces sinusoidal pressure differences across the building envelope, can make real-time leakage measurements at low pressures without inducing large flows through the building envelope. The AC pressurization apparatus and analytical technique, as well as the laboratory measurements that determined the specifications for the field device are described herein. Field measurements of leakage area obtained with the prototype AC pressurization device are compared with those obtained by fan pressurization tests of six single family residences.

KEYWORDS

alternating pressure, measurement technique

NO 2640 Low frequency measurement of leakage in enclosures.

AUTHOR

Sherman M, Modera M

BIBINF

LBL, Applied Science Div, University of California, March 1986, 10p, 2 figs, 10 refs.

DATE 00:03:1986 in English AIC 2202

ABSTRACT

A wide variety of enclosed structures either require or cannot entirely prevent leakage from their interior space to the outside. Existing methods for measuring such leakage have important disadvantages. We have developed a device and technique that permits leakage areas to be measured from within or without the enclosure without causing unacceptable disturbance. The apparatus uses low-frequency (1 Hz) acoustic monopoles to generate an internal pressure signal which is then analyzed syncronously to provide a measurement of leakage area. We have successfully applied this technique to measuring air tightness in residential houses, and believe it can be easily adapted for use in field, laboratory, or classroom applications. We are currently evaluating why the values we obtained were, on average, 14% lower than those obtained through conventional methods and we are investigating the apparent inability of the device, as presently designed, to measure large leaks.

KEYWORDS

air leakage, measurement technique, sound, leakage area

QUALITATIVE TECHNIQUES

Thermographic Leak Detection

NO 375 Thermography. Testing of the thermal insulation and airtightness of buildings.
AUTHOR
Petterson B. Axen B. BIBINF
Swedish Council for Building Research D5. 227p. 20tabs 128 figs 21 refs. DATE 01:01:1980 in English AICR SE10
ABSTRACT
Discusses in general terms energy consumption and energy requirements and the testing and checking of buildings. Gives principles of thermography and discusses the influence of various parameters on the thermography of buildings. Gives rules for interpretation of thermograms and use of comparative thermograms. Gives examples of comparative thermograms for common defects in insulation and airtightness, and actual cases where certain constructions and components were examined. Shows effectiveness of improvements made to remedy certain types of defects in insulation and air tightness. Reports results of a general survey to find systematic defects in insulation and airtightness. Recommends preparations to be made before measurement and indicates a suitable procedure for the thermography of buildings. Gives a brief history of the application of thermography to buildings.
KEYWORDS
thermography, air leakage, insulation,

NO 1573 Infrared detection of leaks.
Infrarood detectie van lekken.
AUTHOR
Schurer K.
BIBINF
Koeltechniek, May 1983, Vol 76, No 5, p96-98, 1 fig, 5 refs. DATE 00:05:1983 in Dutch AIC 976
ABSTRACT
Distinguishes two categories of leaks in buildings for cold storage. Thermal leaks through parts of the construction with poor thermal insulation and air leaks through openings in the walls allowing a more or less free flow of air. Outlines principles of infrared radiation and thermography. Discusses applications for both types of leaks. Under the conditions of high emissivity of the surface to be studied, and absence of local heating or cooling (sun, wind, rain), thermography is an effective method for the detection of thermal leaks and a powerful tool for localizing air leaks.
KEYWORDS
thermography, air leakage, wall, commercial building

NO 2686 Appliance of infrared-thermography in examining air leakage of buildings.
AUTHOR
Adam O C G, Hendriks L W J L

BIBINF
8th AIVC conference, ' Ventilation Technology - Research and Application', 21-24 September 1987, Ueberlingen, West Germany, AIVC 1987, p5.1-5.18, 6 figs, 3 tabs.
DATE 00:09:1987 in English AIC 2257
ABSTRACT
Sections include: measuring procedure air tightness of facades; evaluation of measuring air tightness in practice; infrared thermography; thermographical research in air tightness, ability to detect air tightness deficiencies with thermography; ability to quantify air leakage; architectural analysis of air tightness deficiencies; recommendations.
KEYWORDS
thermography, air leakage, measurement technique, air tightness

Acoustic Leak Detection

NO 683 Listening for air leaks - How to spot infiltration with your ears.
AUTHOR
Bolon P.
BIBINF
Popular Science February 1981 p38,40 DATE 01:02:1981 in English AIC 332
ABSTRACT
Describes use of an acoustic method developed by Keast to detect air leaks. A loud source of sound is placed inside the building and a microphone, stethoscope, rubber hose or sound meter is used to detect places where an increase in sound indicates air leakage. Finds method is effective in detecting simple leaks but will not spot complex paths through walls.
KEYWORDS
sound, air leakage, house,

Air Flow Visualisation

NO 2630 Test ventilation with smoke, bubbles and balloons.
AUTHOR
Pickering P L, Cucchiara A L, et al
BIBINF
Preprint. Ashrae Trans, Vol 93, Part 2, NT-87-01-3, 1987, 9p, 6 figs, 6 refs. DATE 00:00:87 in English AIC 2164
ABSTRACT
The behaviour of smoke, bubbles, and helium-filled balloons was videotaped to demonstrate the mixing of air in the plutonium chemistry laboratories of a plutonium facility. The air distribution patterns, as indicated by each method, were compared. Helium filled balloons proved more useful than bubbles or smoke in the visualization of airflow patterns. The replay of various segments of the videotape proved useful in evaluating the different techniques and in identifying air flow trends responsible for air mixing.
KEYWORDS
air flow, measurement technique, smoke

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