INTERNATIONAL ENERGY AGENCY
energy conservation in buildings and
community systems programme

8th AIVC Conference

Ventilation Technology Research and Application

Supplement to Proceedings

Air Infiltration and Ventilation Centre
Old Bracknell Lane West, Bracknell,
Berkshire RG12 4AH, Great Britain.

This report is part of the work of the IEA Energy Conservation in Buildings & Community Systems Programme.

Annex V Air Infiltration and Ventilation Centre

Document AIC-PROC-8-S-87
ISBN 0 946075 34 4

Participants in this task:

Belgium, Canada, Denmark, Federal Republic of Germany, Finland, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and United States of America.

Distribution: Unrestricted

Additional copies of this report may be obtained from:

The Air Infiltration and Ventilation Centre,
Old Bracknell Lane West,
Bracknell, Berkshire
RG12 4AH, Great Britain.

8th AIVC Conference

Ventilation Technology Research and Application

(held at Park Hotel St. Leonhard,
Überlingen, Federal Republic of Germany
21 – 24 September 1987)

Supplement to Proceedings

CONTENTS (i)

Additional Papers:

Additional Posters:

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, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the United States of America.

Introduction

This document is a supplement to the AIVC's 8th Conference Proceedings, AIC-PROC-8-87. It contains 10 additional papers and five additional posters which were presented at the Conference, together with a discussion record based on written questions and answers prepared by conference participants and authors.

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

PAPER S.1

VENTILATION TECHNOLOGY - AIMS OF FEDERAL MINISTRY FOR RESEARCH AND TECHNOLOGY IN RESEARCH AND APPLICATION

KEYNOTE ADDRESS

DR H HLAWICZKA

Federal Ministry for Research and Technology
(BMFT)
Federal Republic of Germany

Mr Chairman, ladies and gentlemen,

On behalf of the Federal Ministry of Research and Technology (BMFT), it is a pleasure for me to welcome you as the participants of the 8th Air Infiltration and Ventilation Centre Conference here in Ueberlingen, the German Riviera of the Bodensee, at one of the most beautiful and scenic spots in Germany. The sun is shining bright and clear and it seems to me, that after having funded solar energy research during the last 10 years, the sun has now opened the fund to sponsor myself.

We are very proud to have the privilege to host the well renowned AIVC Conference this year. During the next 4 days researchers from 12 OECD countries will again find a forum to present their research activities, to discuss their research results, to exchange their points of view and to get a first hand view of what their colleagues are working on.

May I offer my Ministry's very best wishes for the success of this conference, as well as for the AIVC Steering Committee's meeting and the meetings of the working groups, which follow up this conference.

Introduction

The Federal Republic of Germany (FRG) joined the International Energy Agency's (IEA) Annex V "Air Infiltration and Ventilation Centre" (AIVC) activity in December 1985 as the twelfth participant. We consider this step consistent with our energy R&D policy, ie, to find new ways and new solutions for practical application by stimulating and supporting relevant research activities, and to stimulate and support international cooperation between the various involved disciplines. Looking back, in 1979 the Federal Republic of Germany established a research program, which was entitled "Luftung im Wohnungsbau", which means "Ventilation and air infiltration in residential buildings."

I remember quite well that there was some rumour which culminated in the question: do we really need these investigations? Today they are accepted. It may be that a German saying, formulated by Schopenhauer, the very famous philosopher, gives an answer to this observation: it reads as follows:

"Each innovation has to pass three stages until breakthrough: in the first one, it seems ridiculous, in the second stage common opinion is fighting against those new ideas; in the third it is business as usual."

This program was also part of two activities within the program "Energy Conservation in Buildings and Community Systems" of the IEA. To this program new annexes were added, and now 18 annexes are in progress or are already completed, with 3 more annexes in preparation. Germany was or is involved in many of them.

The annexes which are of main interest in connection and with regard to this conference are the so called ventilation annexes. They are:

Annex	Title
V	Air Infiltration and Ventilation Centre (AIVC)
VIII	Occupants Behaviour
IX	Minimum Ventilation Rates
XII	Windows and Fenestration
XIV	Condensation and Energy
XVIII	Demand Controlled Ventilation Systems (under discussion)

Objectives

The main programme objectives for the FRG were to contribute to energy efficiency by identifying proper technical solutions for minimising ventilation losses in buildings and to transfer such solutions into practical applications as soon as possible.

We have been supporting such research and development for many years now, in the fields of ventilation in residential, commercial and industrial buildings, usually by funding specific projects, often in close cooperation with the Federal Ministry for Regional Planning and Urban Development (BMBau). The learning curve to gain the necessary experience with modern infiltration and ventilation techniques is characterised from the early beginning in 1979 until today by about 23 projects funded by BMFT with an amount of 15,4 Mio DM.

As it became more and more evident that aspects of hygiene and comfort play an ever more significant role in defining requirements for air exchange and ventilation, the Federal Ministry of Youth, Family and Health (BMJFG) also became involved in our activity.

When we started the R+D-programme "Ventilation and air infiltration in residential buildings" eight years ago, we focused on energy conservation aspects and therefore we integrated the programme into our framework programme "Efficient energy use". Even today the contributions to the above mentioned IEA annexes are still funded through the "Efficient energy use" programme, but we expect results and technical solutions as spin offs, so to speak, which satisfy hygiene and comfort requirements too.

Facing more and more problems of indoor air quality as a result of new building materials, construction concepts or changes in the inhabitants' behaviour, we learned a lot from the outputs of the ventilation projects and about the important role which ventilation and air exchange play in increasing indoor air quality. But we also learned about the limitations of controlling indoor air quality by ventilation alone, hence an integrated view of ventilation in conjunction with a total control of the indoor air environment may become necessary.

For this reason the Federal Ministry for Research and Technology initiated a new R&D programme this year named "Indoor air pollutants and the indoor environment", and integrated into this programme some research activities from the programme "Humanization of the place of work", related to maintaining indoor air quality at the industrial work place.

We expect that a closer cooperation between these various research disciplines will initiate novel energy conserving technical solutions which nevertheless meet indoor air quality requirements which are accepted by building occupants.

R&D efforts and ongoing activities

Energy conservation must be regarded above all, as a practical, short to medium-term contribution towards solving our environmental problem. In my opinion "Energy and Environment" are like Siamese twins or both sides of a medal. The environmental issue, as a whole, is becoming more and more critical and more urgent.

As all of us have become more aware in recent years, the question of energy supply in the future is not only a problem of resources and analyses of their scarcity. Concerns about irreversible changes to our environment which are also caused by increased energy consumption in all parts of the world are more often being mentioned in debates on future supply structures. I would like to mention just two examples:

Climatic changes caused by the "greenhouse effect" are no longer just speculations but phenomena which have to be seriously and intensively investigated. Should these risks be realistically assessed then this could lead to changes in living conditions over the whole world which cannot be estimated. Suitable compensating measures would be necessary. This would directly affect today's energy supply structures and would put the utilisation of renewables, for instance, in a completely different light.

The question of climatic changes and their results cannot be answered today or even in the next few years. However, even now, emissions of gases during the utilisation of fossil sources of energy are made responsible for considerable ecological damage. I would like to mention the new type of forest damage that has occurred particularly in Europe, and the most recent catastrophes caused by bad weather conditions in the Alps during the last few weeks. In public opinion these were the result of emissions and regional climatic changes caused by energy supply. Independent of whether this is provable scientifically or not, these events lead to reactions in communities which can affect and change the acceptance of the use of fossil sources of energy.

In other words, in addition to the question of resources, environmental acceptability of energy supply has become a new dimension which must be considered. As environmental problems - climatic changes are the best example - do not generally have a regional or national character, then the international exchange of experiences and cooperation in the fields of research and development are particularly important. The FRG has accepted this fact and is looking for cooperation with other countries, first of all in the framework of the European Community and, in addition, the exchange of information particularly with the Western industrialised countries within the framework of the IEA.

For this reason the Federal Government has participated in most of the IEA R&D programmes. A total of more than 110 million DM financial support from the budget of the Federal Ministry for Research and Technology alone has been spent for 43 projects of the IEA in the field of renewables and efficient use of energy over the past 12 years.

As a result of international cooperation in the framework of the IEA, research and industry in Germany has very quickly managed to reach an international standard in the field of solar technology and efficient use of energy.

Even in the future we will attach great importance to this international cooperation and the exchange of information as well as the development of joint strategies to introduce new energy technologies. Here the IEA plays an important role, which goes much further than its original tasks of guaranteeing the supply of energy to member countries independent of disruptions in the oil market.

Measures for efficient use of energy in particular are required therefore still providing reasonable and concrete options for private homes, for the community and for business to maintain indoor air quality without any reduction to comfort. What we need are reliable and broadly available peripheral data, which is not solely or exclusively oriented towards the economic mood of the day.

Hence it follows that all projects within these programmes or within our IEA contribution should focus on practical applications and lead towards a practical benefit. An example are the results and recommendations of Annex IX "Minimum Ventilation Rates", which influenced the standardisation activities in the FRG in a very constructive way.

But on the other side, the mission of the BMFT is limited to that of an initiator and catalyst to bring about technical solutions, which have to be proven by the economics. The possibility of influencing legislation and regulations derived from it, is limited; setting regulations is the task of other departments with the appropriate instruments and competences. The BMFT must approach these other departments or the parliamentary institutions and convince them, based on the results and experience from the research and development carried out, that the relevant legislation and regulations should be revised and adapted to the latest state-of-the-art technology.

The German ventilation programme and accompanying projects started officially in December 1980 and has a volume in the order of 15.4 million DM (now about 8.4 million US dollars). A major portion of these funds went to demonstration project investigations in occupied buildings. The German contribution to IEA's Annex VIII "Inhabitants Behaviour" had been integrated into these investigations.

During our work in the field of ventilation technology we became aware of a variety of problems. Quite uncommon for engineers - but on the other side very challenging, interesting and important - was the necessity to understand totally foreign subjects and sciences like medicine, hygiene, biology, chemistry and physiology. And at least, after the Indoor Air Conference 1987 in Berlin, we know how important it is, that these sciences influence our further strategies on ventilation developments.

Many international experts from all fields worked together in the IEA-Annex IX "Minimum Ventilation Rates". The final report is about to be finished and a big step has been made towards introducing better ventilation in residential buildings.

The Occupants Behaviour IEA Annex VIII - a very important study - was finished last year and as a next step, these results must be used to develop better ventilation strategies. This can be performed by indoor tests with new advanced ventilating devices, as proposed in the IEA-Annex XVIII and by the very important study on air movement in rooms, which is the objective of the new IEA-Annex XX "Optimization of Air Flow Patterns", presently under discussion as one of the next IEA-annexes.

The last mentioned topic is an example for the engagement of the BMFT. Ventilation technology is a typical technology and business for small to medium sized firms in Germany.

For example they don't have the expertise to develop calculation procedures to simulate the highly sophisticated behaviour of air flow in rooms, including heat mass, heat momentum transfer and turbulence models, and to verify these models by experiments; besides, these firms don't have the necessary computing equipment, the personal capacity and financial resources to do this job. We all know, that we need good tools for simulation, because real-scale experiments are too time-consuming and too expensive, and even can't give adequate information on optimisation possibilities. For this reason the BMFT provides funds for research to develop simple computing tools, which can be used on personal computers (PC's) by architects and small and medium sized firms in industry.

The German ventilation standards are presently under discussion. These standards have to be revised according to recommendations on Indoor Air Quality (IAQ) to include recommendations on basis- and demand-related additional auxiliary ventilation.

Some regulations in Germany concerning ventilation are not so well coordinated in some points. Among the problems in revising our standards is one difficulty: up to now nobody has come up with a satisfying definition for "good indoor air quality", a precise definition of what can be checked by measurements and used in practice. I see one approach to achieving this and that is to advance our knowledge through international cooperation. Our experience is that a lot of results from our international cooperation - especially in the IEA - have given important inputs to the members of the various standardisation committees.

Some aspects of energy consumption in the FRG

After these general comments on air infiltration and ventilation, which are naturally also coloured with German experiences, let me now briefly give some details of the energy situation in Germany.

Energy supply in the FRG is well balanced as far as the utilisation of the different sources of energy is concerned and its supply structure is extremely well organised. On the heating market in particular there is a healthy competition between the different sources of primary energy with a strong interrelation. A dependency on individual sources of primary energy does not exist. Although the Federal Republic is a net importer of energy, the supply structure is so balanced that there is no dependency on individual supplying countries. This has led to the fact that the price of gasoline, for instance, is lower now than before the first oil price crises after inflation has been taken into account. A reaction to this situation by industry and public spending at the beginning of the 1980s could not be avoided. This became noticeable by a reduction in the attention given to energy options necessary for the future, and in particular to efficient use of energy.

During this period of reduced public interest until today, the support of the research and development programmes running internationally, for instance within the framework of the EEC or the IEA, was particularly important both for science and for industry. Today, there is an altered attitude in the Federal Republic resulting from two factors:

The occurrence of forest damage, already mentioned, and increasing warnings of ecological damage and climatic changes have given the environmental acceptability of energy systems more importance. New energy systems such as the utilisation of solar energy, perhaps using hydrogen as a store and efficient use of energy (the so called "NEGAWATT-market"), clearly have an advantage over fossil fuels.

In 1986, the reactor catastrophe in Tschernobyl made the risks of nuclear energy in the case of serious breakdowns only too clear, and particularly in Germany this caused an intense discussion on the dangers and benefits of nuclear power. This event also proved the necessity of investigating new energy options for the future, of developing promising alternatives and so making safe and flexible energy supply structures possible for the future.

Basically it can be assumed that the supply structure in the Federal Republic based on domestic coal, nuclear energy, oil and gas, will only change marginally in the foreseeable future. The awareness of possible risks involved in using traditional sources of energy has induced new initiatives, both in the supply industries and in public spending, to develop processes for the efficient use of energy and to utilise renewable energy sources.

On the other hand, various methods to save energy in industry and housing have already shown successful results. Using more efficient heating plants and improved thermal insulation, the heating demand of houses in Germany was reduced considerably from about 45 litres/m^2 a oil equivalent before the first oil price crisis to about 20 litres/m^2 a as a figure for the average.

If we consider that 25-50% of the total energy for space heating are ventilation heat losses, we talk about an amount of 400-800 Petajoule.

I think you will agree that this amount is worth thinking about carefully and deeply, especially as to whether it can be reduced.

Although the oil price is fairly low today, we shouldn't stop our R&D activities in the field of energy savings. On the contrary we should continue following a very steady path towards more independence of oil and other energy carriers.

But we should consider another very important aspect: every kilowatt hour for heating purpose consumed, puts stress on our environment, and this is important when we consider that the production of electricity is now performed with an efficiency of between 30 and 40% at maximum. In residential buildings, the production of heat for space heating and hot water supply with a common oil or gas furnace has an average annual efficiency of between 50 and 80%.

The picture becomes worse if we look at the transition of our primary energy (fig. 1). We use highly valuable primary energy carriers with which we could produce heat at a level above 1,000°C and we devaluate this valuable energy solely to produce hot water between 40 and 70°C. The exergetic efficiency - exergy is the part of the energy which can be usefully transformed - the exergetic efficiency of these processes are often below 8-12%. In other words whenever we do not use all available exergy, we are always wasting energy°

The tremendous amount of wasted energy can be seen by the energy flow diagrams, which show for the FRG (Slide 2) a ratio of wasted to useful needed energy of 2±3 to 1±3, for the USA this ratio is about three quarters to one quarter, for Austria the ratio is about 50:50%. One of the main aspects for modernization of the national economics should be to improve this ratio for instance by district heating, cogeneration, heat pumps and consequently heat recovery and better insulation.

In 1973 the ratio of used to wasted energy for private households was calculated in the FRG to be 45 to 55% (Fig 2).

It was estimated to reverse this ratio on 1990, in changing the figures for used and wasted energy. We reached this goal in 1982, some years earlier than forecasted in the 70's (Fig 3).

AIMS OF THE BMFT

At the end I'd like to offer a few remarks about the present status, especially about the necessity and motivation for this program, to give some views as I see it, on the trends for the future:

- The final goal with respect to the German research program "Ventilation and air infiltration in residential buildings" is to minimise ventilation heat losses by means of improvements in building physics and in ventilation strategies in the framework of economic perspectives and - what turned out to be very important - to make the inhabitant sensitive to ventilation, to inform him about the appropriate handling of new ventilation techniques.

- Due to passive measures (better insulation, double and triple glazing) we could decrease the transmission-heat losses so much, that ventilation heat losses become the dominant heat loss. Therefore there might be some advantages in the proper combination of heating and cooling systems with ventilation, by using air and hot water as the heat fluid medium.

- In the FRG for instance with air to air heat pumps already under operation in Denmark and Sweden, the renaissance of the well-known so called "Kachelofen" or Ceramic furnace, or solar collectors (Fig.3), supporting the heating system in commercial and industrial buildings with the result of saving between 30 to 50% of the oil consumption in comparison before installation on the roof is underway.

- It becomes important for architects and design engineers to keep an overall view of the building and of its ventilating system. Building, heating and ventilating system, the user, and the environment are one entity which have to be monitored as a whole. An integrated design method would not only result in better indoor air quality and an efficient use of energy but would also cut back the immense amounts of money for damages to the building fabric.

- This of course implies that R&D activities have to hand in hand with what is needed in practice. The research results have to be translated into a language which can be understood and applied in practice.

- At least it should not be forgotten, that the introduction and diffusion into the market is not only dependent on a proper functioning technical solution. To say it quite frankly, technical innovations can only enter the market and survive, when there are existing innovations too in organisation and administration for example tariffs for surplus electricity produced by cogeneration or renewables and other incentives, which encourage consumers and producers to save energy and not just to sell.

- I'm sure that the exchange of information and experiences at this conference will contribute to achieving better indoor air quality, to reduce ventilation heat losses, and to identify economic and user-accepted ventilating systems.

I wish for all of us fruitful discussions and a successful conference accompanied by having some nice days together here at Ueberlingen in the Bodensee region.

Thank you very much.

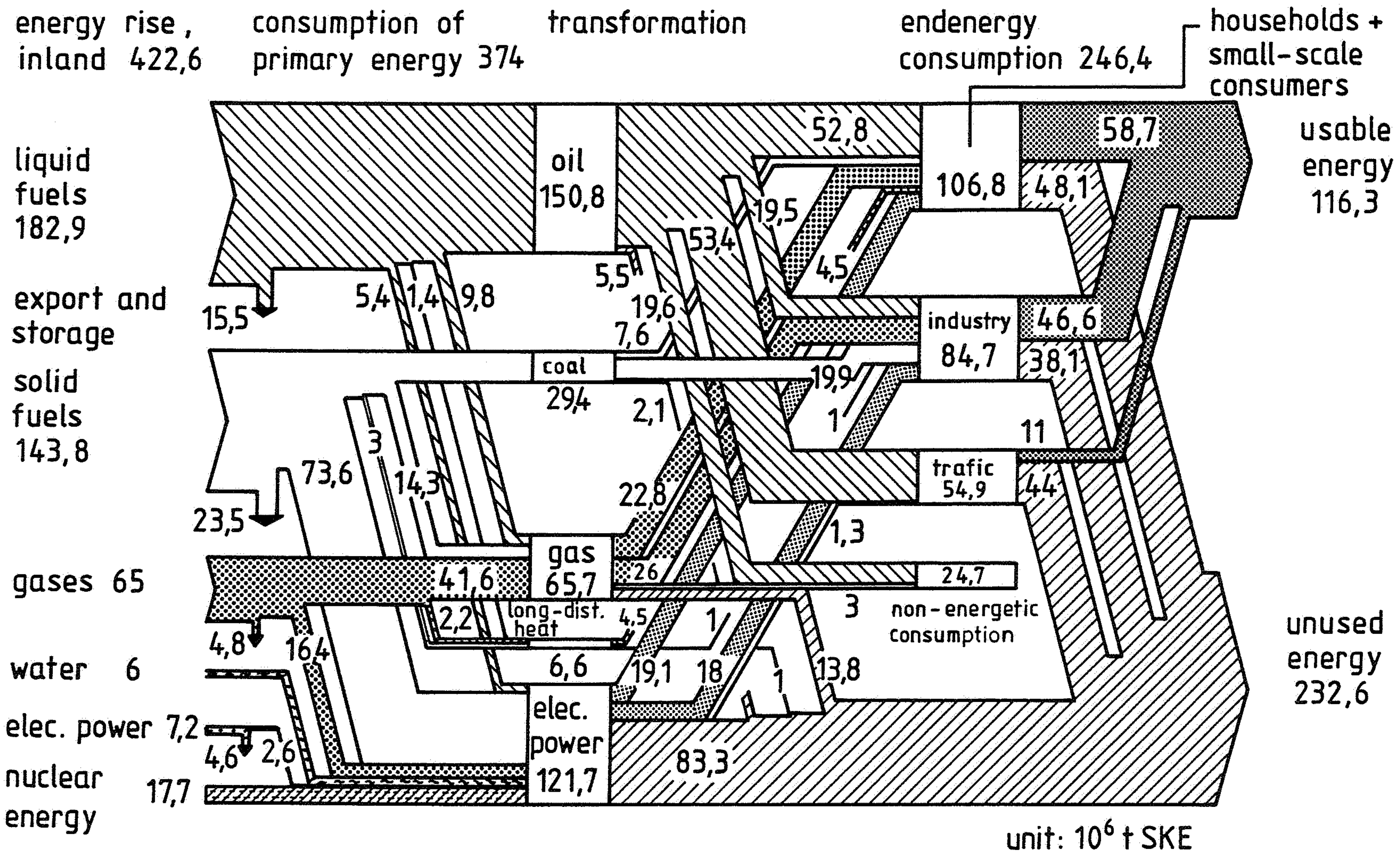

energy rise, inland 422,6
consumption of primary energy 374
transformation
endenergy consumption 246,4
households + small-scale consumers
usable energy 116,3
liquid fuels 182,9
export and storage
15,5
solid fuels 143,8
23,5
gases 65
4,8
water 6
elec. power 7,2
4,6
2,6
nuclear energy
17,7
oil 150,8
52,8
58,7
106,8
48,1
19,5
53,4
4,5
5,4
1,4
9,8
5,5
19,6
7,6
industry 84,7
46,6
38,1
coal 29,4
19,9
2,1
1
11
73,6
3
14,3
22,8
trafic 54,9
44
1,3
gas 65,7
41,6
26
24,7
2,2
long-dist. heat
4,5
1
3
non-energetic consumption
16,4
6,6
19,1
18
1
13,8
elec. power 121,7
83,3
unused energy 232,6
unit: 10⁶ t SKE

Fig. 1

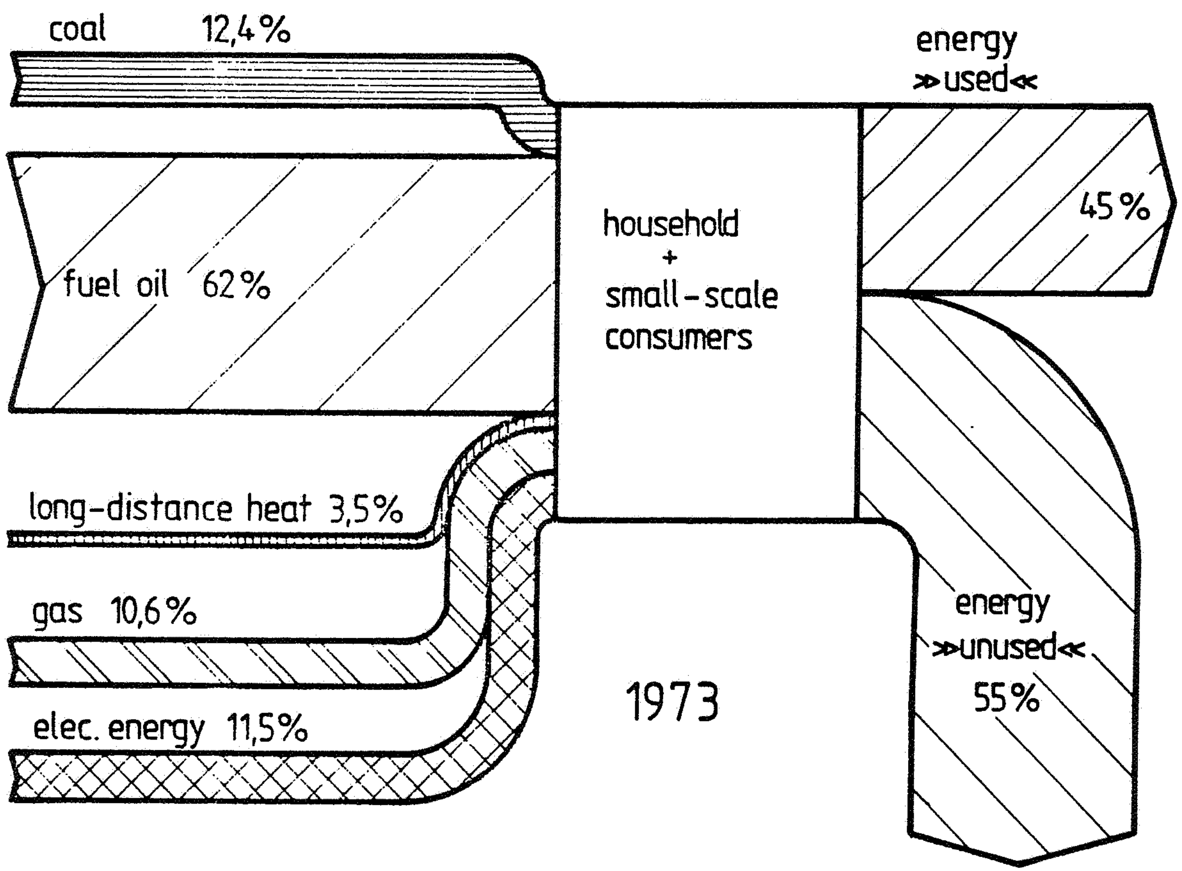

coal 12,4%
fuel oil 62%
long-distance heat 3,5%
gas 10,6%
elec. energy 11,5%
household
+
small-scale
consumers
1973
energy
»used«
45%
energy
»unused«
55%

Fig. 2:

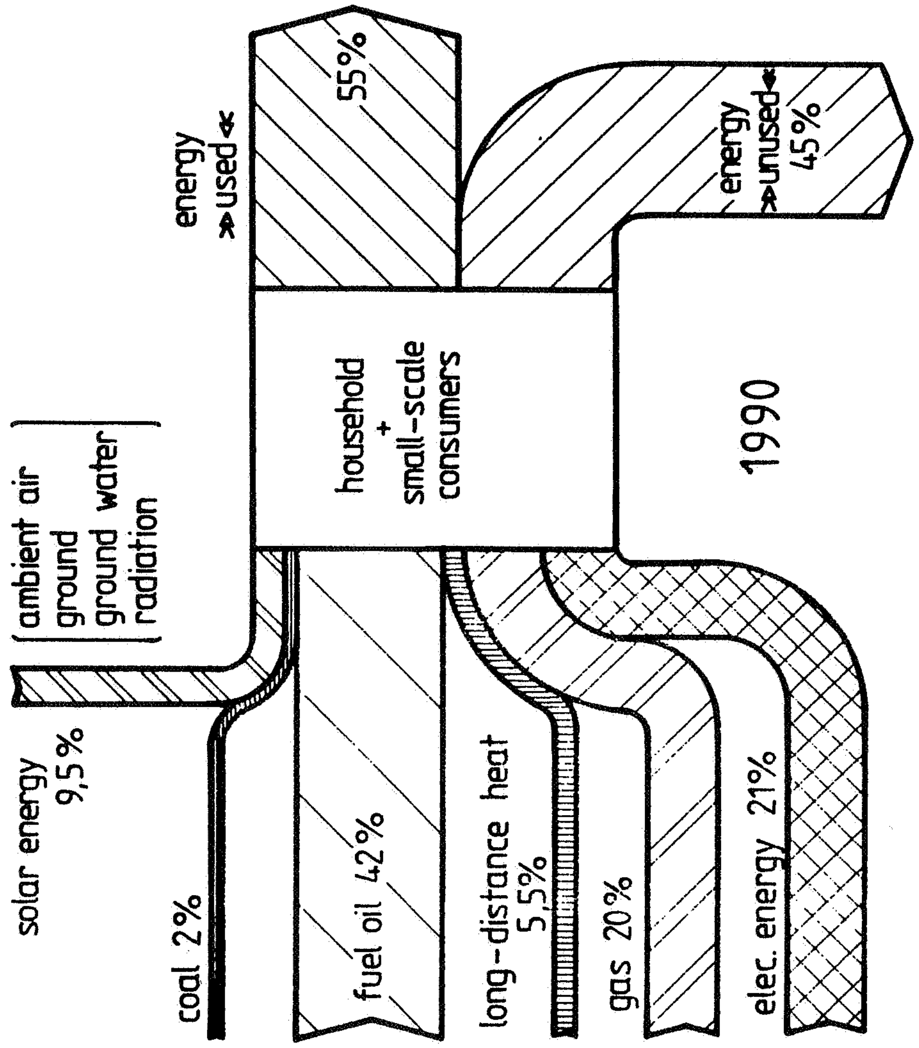

solar energy
9,5%
ambient air
ground
ground water
radiation
coal 2%
fuel oil 42%
long-distance heat
5,5%
gas 20%
elec. energy 21%
household
+
small-scale
consumers
1990
energy
≫used≪
55%
energy
≫unused≪
45%

Fig. 3:

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

PAPER S.2

EVALUATION THROUGH FIELD MEASUREMENTS OF BNL/AIMS, A MULTIPLE TRACER GAS TECHNIQUE FOR DETERMINING AIR INFILTRATION RATES.

Niels Bergsoe
B. Sc., Civil and Structural Engineering

Danish Building Research Institute
Indoor Climate Division

Synopsis

Brookhaven National Laboratory (BNL) in the USA has developed a multiple tracergas technique called BNL/AIMS (Air Infiltration Measurement System) for determination of air infiltration rates. The technique is applicable in occupied dwellings and might be promising for wide-scale measurements. This paper discusses the main results of field measurements made by the Danish Building Research Institute with use of BNL/AIMS. The results obtained are compared with the results of parallel measurements made in the laboratory and by using computer controlled field measuring equipment.

The aim of the measurements was to gain experience in the use of the BNL/AIMS equipment, and to obtain a basis for evaluation of the application and applicability of the method.

With regard to whole-house air infiltration rates, the results prove to be in good agreement with results from known methods. However, there seems to be some inconsistency regarding zonal air infiltration rates and air exchange rates between zones.

Introduction

Since the beginning of the 1970'ies focus has been on efficient sealing of new buildings and on developing better insulating materials and techniques for use in existing and new buildings.

The aim was not to reduce the ventilation rate in the buildings, but merely to reduce the air infiltration through random cracks in the building envelope. This allows for improved possibilities for controlling ventilation and air distribution within the building.

To gain full profit from these improved possibilities thorough knowledge about air infiltration and internal air transport within buildings is essential, taking the principle of ventilation and the behavior of the occupants into consideration.

The Brookhaven National Laboratory/Air Infiltration Measurement System (BNL/AIMS) is a tracergas technique, developed by Brookhaven National Laboratory (BNL) in the USA, based on the use of multiple tracers and passive sampling (ref 1). BNL/AIMS determines the average air infiltration rate. By zone-dividing a building and by simultaneous use of several different tracergases, the average zonal air infiltration rate and the air exchange rate between different zones can be determined as well.

With the object of obtaining better knowledge of the mechanisms of air infiltration, air movements and distribution of gaseous contaminants in multizoned occupied dwellings, The Indoor Climate Division at The Danish Building Research Institute and the Tracer Technology Center of Brookhaven National Laboratory have entered an agreement upon collaboration on testing the BNL/AIMS through field and laboratory measurements.

BNL/AIMS (outline of features)

Reference 1 gives a detailed describtion of the method and the measuring equipment, therefore only the outlines of the equipment, the application, and the performance will be given here.

Equipment

The equipment consists of passive tracer emitters (PFT's - Perfluorocarbon Tracers), glasstubes for passive adsorption of the tracergases (CATS - Capillary Adsorption Tracer Sampler), and, as a possibility for active collection of tracergases, a programmable sampler (BATS - Brookhaven Atmospheric Tracer Sampler). The CATS and the adsorptiontubes in a BATS are analyzed in the laboratory by means of gaschromatography.

Application

Prior to a measurement the building is divided into zones. A different type of tracergas is used in each zone. The sources are usually distributed with one per every 50 m^2 of living area.

Dependent on the expected air infiltration rate in the building and the duration of the measurement the CATS and/or BATS are placed 2-24 hours after the distribution of the sources. Also the CATS are distributed one per every 50 m^2 of living area.

The measuring period can be from a few hours to several months.

Performance

Reference 1 describes a series of laboratory tests of the performance of the equipment. The results show that the equipment generally is reliable with a satisfactory reproducibility, though caution to the temperature sensitivity of the source rate must be observed, about 4 per cent change per 1 ^{o}C at room-temperature.

The BNL/AIMS is based on the assumption that a constant emission of tracergas, after some time, depending on the ventilation rate in the building, will establish an almost constant concentration. However, the ventilation rate normally varies in time, and therefore the concentration of tracergas will vary as well.

The adsorption tubes performe a long term registration, and analyses of the tubes gives the average tracergas concentration in the measuring period. As it can be mathematically proved, calculation of the air change rate on the basis of the average concentration, using the equilibrium equation, will invoke an error. The reciprocal of the average concentration is less than the average of reciprocal concentrations, hence the BNL/AIMS has a negative bias.

Measurements

This paper describes measurements made in a two-storey flat, a kindergarten and a non occupied testflat set up in a laboratory (ref 3).

The Brookhaven National Laboratory (BNL) placed the BNL/AIMS measuring equipment at our disposal and they also carried out the gaschromatographic analyses of the adsorption tubes.

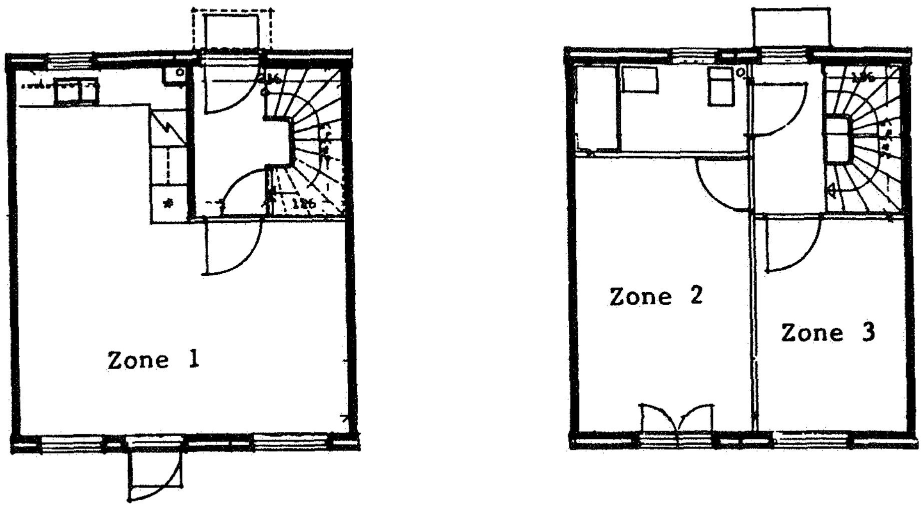
The field tests (two-storey flat, kindergarten) were made in collaboration with the Technological Institute of Denmark (TI), who carried out parallel measurements using their computer controlled measuring equipment (ref 2). This equipment performs a continuous measurement of the supply of outdoor air in up to ten different rooms simultaneously.

The tests in the laboratory flat were made in collaboration with The National Swedish Institute for Building Research (SIB).

Two-storey flat

The flat (fig 1) was divided into three zones. Zone 1 was first floor, zone 2 was master bedroom and zone 3 was small bedroom.

The measuring period lasted 94 hours. Active sampling by means of BATS were performed in 11 periods each lasting 8 hours (11 h - 19 h, 19 h - 3 h, and 3 h - 11 h). Table 1 shows the zone data, and table 2 the results of the measurements.



First floor

Second floor

Figure 1. Two-storey flat. Floor plans.

Zone	Vol. (m^3)	Avg. temp.	Number of sources	Source type	Number of CATS	Number of BATS
1 First floor	90	21.0	2	PDCH	2	1
2 Master bedroom	35	21.0	1	PMCH	1	1
3 Small bedroom	23	21.0	1	PDCB	1	1

Table 1. Two-storey flat. Zonedata.

As seen from table 2 both the BNL/AIMS-measurement and the measurement made by TI showed that zone 1 had the greatest supply of outdoor air, subsequently zone 2 and 3. Zone 3 was, according to BNL/AIMS, an almost isolated zone. The standard deviations (SD's) stated in the table result from estimated standard deviations in the source strength (10 pct.) and zonevolume measurements (5 pct.) in the computer calculations and furthermore from differences in tracergas registrations in a zone.

Table 3 shows the air flow between the three zones. The largest air flow is from first floor to the master bedroom and vice versa and very small airflow to and from zone 3.

Figure 2 shows the measuring period divided into 9 8-hour periods corresponding to the working periods of the BATS (2 periods were cancelled due to malfunctioning of the BATS). In each period the concentration measured by BNL/AIMS, respectively TI, is shown.

Zone	Vol.	BNL/AIMS (CATS)	BNL/AIMS (BATS)	TI
	(m^3)	BNL +/- SD	BNL +/- SD	
1 First floor	90	0.82 +/- 0.10	2.28 +/- 1.38	1.40
2 Master bedroom	35	0.43 +/- 0.21	-1.72 +/- 0.76	0.48
3 Small bedroom	23	0.02 +/- 0.07	0.03 +/- 0.25	0.22
Total	148	0.60 +/- 0.06	0.99 +/- 0.86	1.00

Table 2. Two-storey flat. Measured air infiltration rates (m^3/h per m^3). SD: Standard deviation, see text.

Zone to zone	Air flow (m^3/h)	Zone to zone	Air flow (m^3/h)
1 - 2	68.0 +/- 16.7	2 - 3	9.3 +/- 2.9
1 - 3	8.9 +/- 3.5	3 - 1	2.5 +/- 1.4
2 - 1	41.9 +/- 10.2	3 - 2	7.2 +/- 2.1
1 - outside	41.2 +/- 15.3	2 - outside	39.1 +/- 12.0
outside - 1	73.7 +/- 8.3	outside - 2	15.1 +/- 7.4
3 - outside	8.9 +/- 2.4		
outside - 3	0.4 +/- 1.7		

Table 3. Two-storey flat. Air flow (m^3/h) between zones.

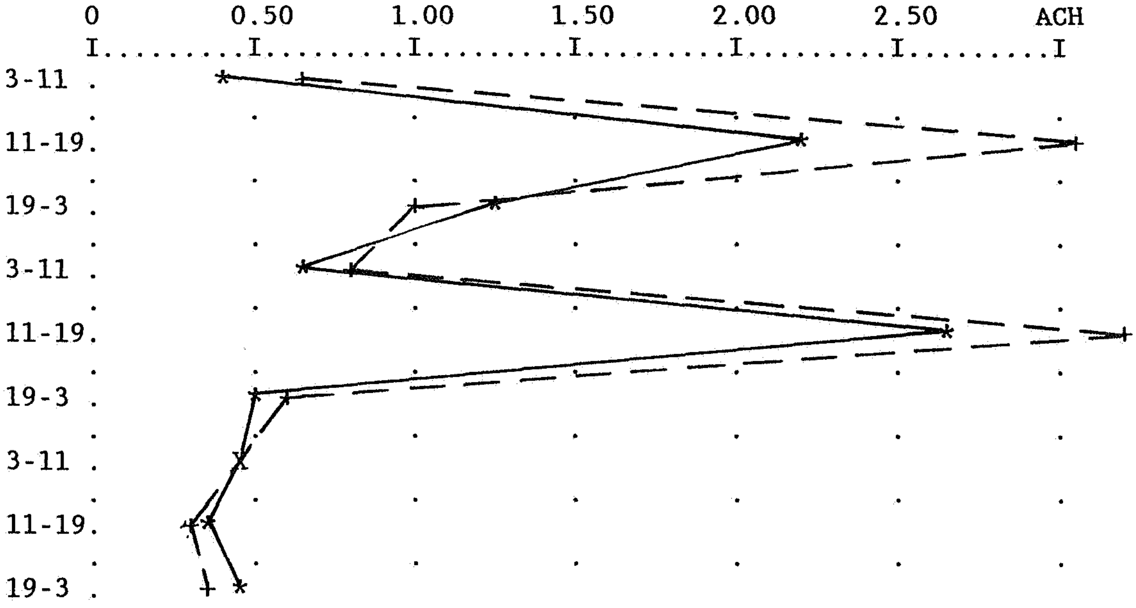


Figure 2. Two-storey flat. Whole-house average air infiltration rates (m^3/h per m^3), measuring period divided into BATS periods.
Continuous line: BNL/AIMS-BATS measurement.
Broken line : TI measurement.

Figure 3 shows the BNL/AIMS-CATS measurement vs. the TI measurement. The bars indicate the SD's of the BNL measurement. As previously discussed the BNL/AIMS has a negative bias. As appears from figure 2, significant variations in the air change rates did occur. This might explain the BNL/AIMS measurement using CATS being generally lower than the TI results (as seen from table 2 and figure 3) and the average of the measurement using BATS being closer to TI results.

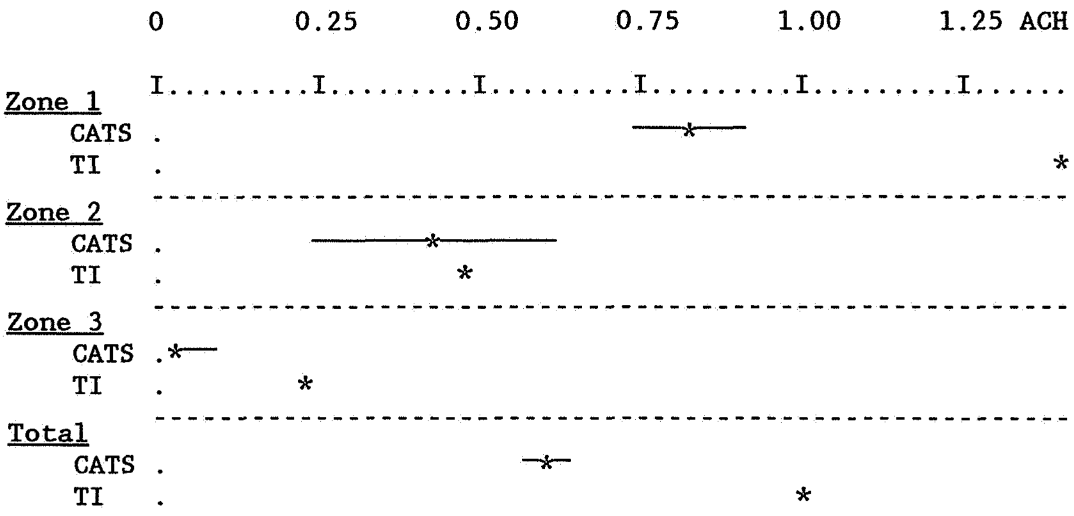


Figure 3. Two-storey flat. Measured air infiltration rates (m^3/h per m^3). BNL/AIMS-CATS measurement vs. the TI measurement.

Kindergarten

The kindergarten is a one floor building and it was treated as a 4-zone case. Each of the zones 1, 2, and 3 consists mainly of two play rooms. Zone 4 is a large room for common use with kitchen, staff quarters and toilet (fig 4).

The building is mechanically ventilated. Air is supplied to zones 1, 2, and 3 and air is exhausted from zone 4. There was no recirculation of air. The air passes from zone 1, 2, and 3 to zone 4 through doors and grilles placed above the doors. Exhaustion from toilets was deactivated during the measuring period.

Duration of the measurement was 10 days and nights, and BATS registered in two periods, each of 4 x 12 hours.

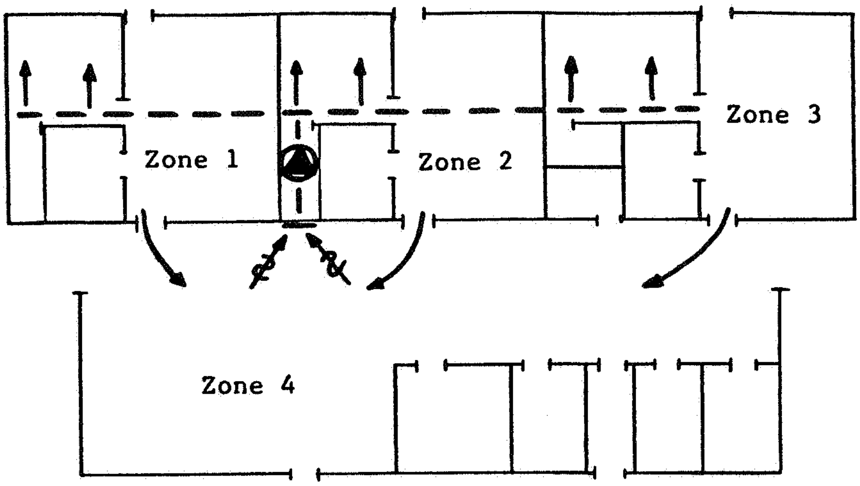


Figure 4. Kindergarten. Floor plan.

Zone	Vol. (m^3)	Avg. temp.	Number of sources	Source type	Number of CATS	Number of BATS
1 Rooms 101/2	175	22.0	2	PDCB	2	1
2 Rooms 103/4	175	21.0	2	PMCH	2	1
3 Rooms 105/6	230	21.0	2	PMCP	2	1
4 Room 118	850	21.5	4	PDCH	4	1

Table 5. Kindergarten. Zonedata.

As can be seen from table 6 and figure 5, the two measuring methods show the same tendency: largest air infiltration rate to zone 2, less to zone 1, 3, and 4.

Zone	Vol. (m^3)	BNL/AIMS (CATS) BNL +/- SD	BNL/AIMS (BATS) BNL +/- SD	TI
1 Rooms 101/2	175	0.95 +/- 0.26	0.80 +/- 0.18	1.04
2 Rooms 103/4	175	1.47 +/- 0.52	1.15 +/- 0.12	1.07
3 Rooms 105/6	230	0.58 +/- 0.14	0.51 +/- 0.08	0.86
4 Room 118	850	0.30 +/- 0.13	0.50 +/- 0.18	0.26
Total	1430	0.57 +/- 0.06	0.62 +/- 0.12	0.55

Table 6. Kindergarten. Measured air infiltration rates, (m^3/h per m^3). SD: Standard deviation, see text two-storey flat.

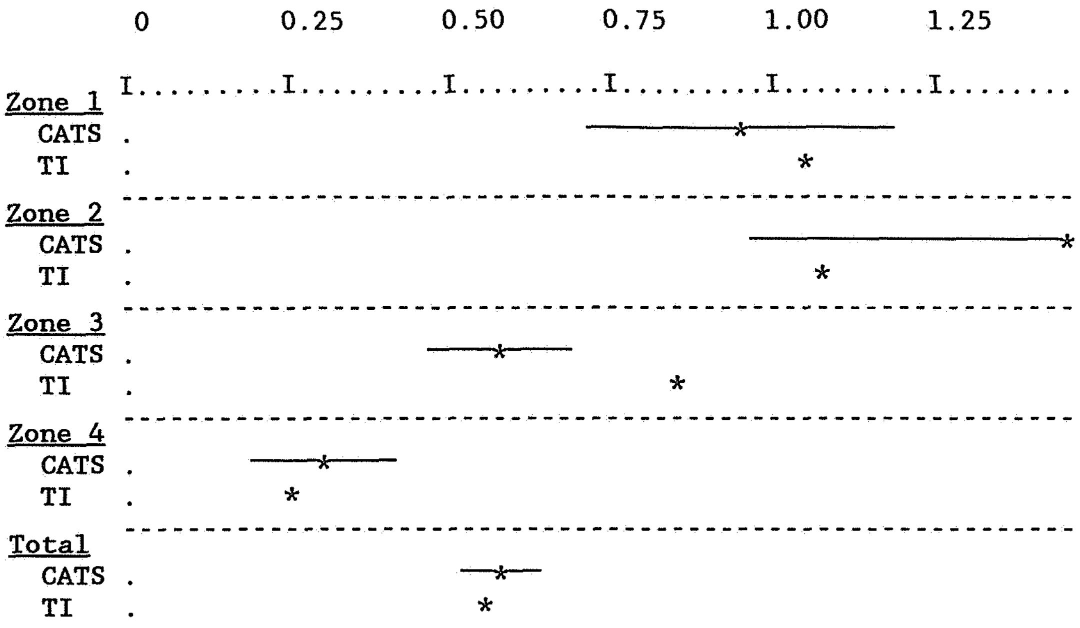


Figure 5. Kindergarten. Measured air infiltration rates (m^3/h per m^3). BNL/AIMS-CATS measurement vs. the TI measurement.

Results of measurements in zone 1 and 4 can be considered equal, and measurements of the whole-house air infiltration rate are almost identical.

The ventilation system can be characterized as well balanced (table 7), and as could be expected, air exchange rate between zone 1, 2, and 3 was low.

To be able to compare passive and active collection of tracergas, one of the two adsorption tubes in each of zone 1, 2, and 3 was placed near the BATS. Results (not shown in this paper) indicates that CATS and BATS register identical concentrations of tracergas.

Zone to zone	Air flow (m^3/h)	Zone to zone	Air flow (m^3/h)
1 - 2	8.6 +/- 8.4	3 - 1	-3.9 +/- 4.0
1 - 3	2.4 +/- 1.5	3 - 2	5.5 +/- 12.3
1 - 4	195.0 +/- 81.2	3 - 4	199.9 +/- 66.2
2 - 1	15.9 +/- 7.8	4 - 1	37.8 +/- 17.2
2 - 3	17.4 +/- 7.2	4 - 2	45.5 +/- 28.7
2 - 4	215.9 +/- 88.1	4 - 3	13.8 +/- 5.0
1 - outside	9.2 +/- 62.6	2 - outside	67.1 +/- 60.0
outside - 1	165.5 +/- 44.4	outside - 2	256.6 +/- 90.2
3 - outside	-35.2 +/- 49.3	4 - outside	770.0 +/-157.0
outside - 3	132.6 +/- 31.2	outside - 4	256.5 +/-106.1

Table 7. Kindergarten. Air flow (m^3/h) between zones.

In each of the play rooms in zone 1, 2, and 3 TI supplied tracergas and measured the concentration. In each zone a significant difference between air infiltration rates in the two play rooms could be observed, with considerable fluctuations in the air flow to the bigger room.

Figure 6 shows the whole-house air infiltration rate measured by means of BATS. As can be seen, steady state conditions prevailed during the first period, whereas conditions were more unstable during the second period.

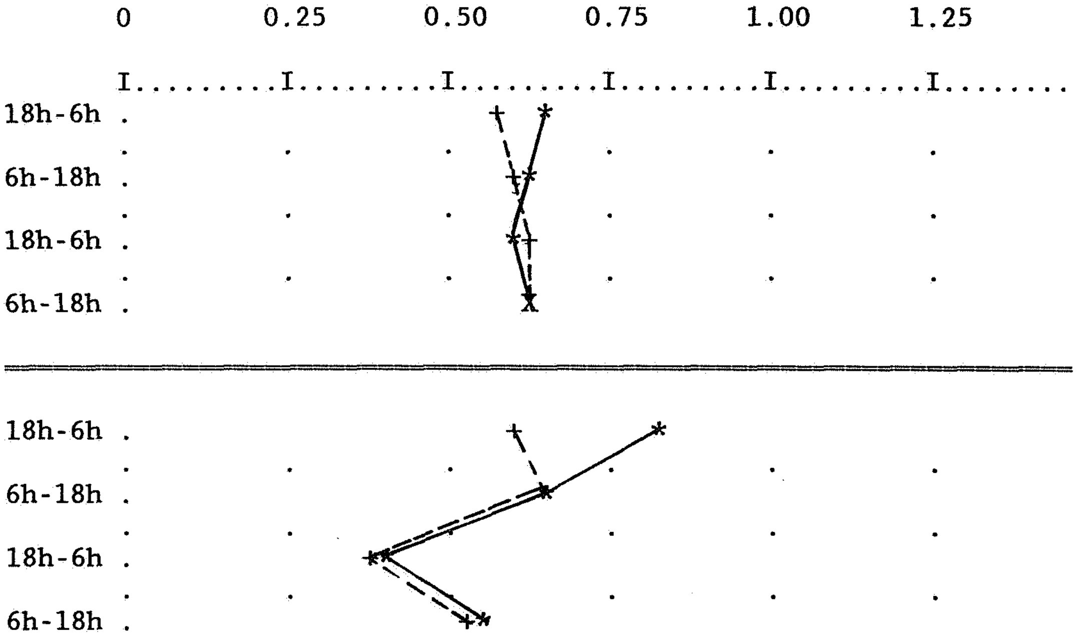


Figure 6. Kindergarten. Whole-house average air infiltration rates (m^3/h per m^3), measuring period divided into BATS periods.
Continuous line: BNL/AIMS-BATS measurement.
Broken line : TI measurement.

Test flat in Sweden

In the laboratory at the National Swedish Institute for Building Research (SIB) a full scale one floor test flat is built. The flat consists of living room, bedroom, kitchen, bath and hall. In the test flat it is possible - with great accuracy - to control and measure the supply of outdoor air to each room.

The aim of the measurements made in this flat was to test the performance of BNL/AIMS under controlled laboratory conditions.

Two sets of measurements were carried out: internal doors open and internal doors shut. Each measurement lasted 3 days and nights. Only CATS were used, and the flat was treated as a four zone case. Zone 1: living room, zone 2: bedroom, zone 3: kitchen and zone 4: bath and hall.

Mechanical exhaustion from kitchen and bath (67 m^3/h and 28 m^3/h respectively) was active during both measurements. Outdoor air was supplied through openings in the ceiling in the living room and in the bedroom. Simultaneous measurements were carried out by the standard measuring equipment in the flat. Mixing fans were used during both measurements.

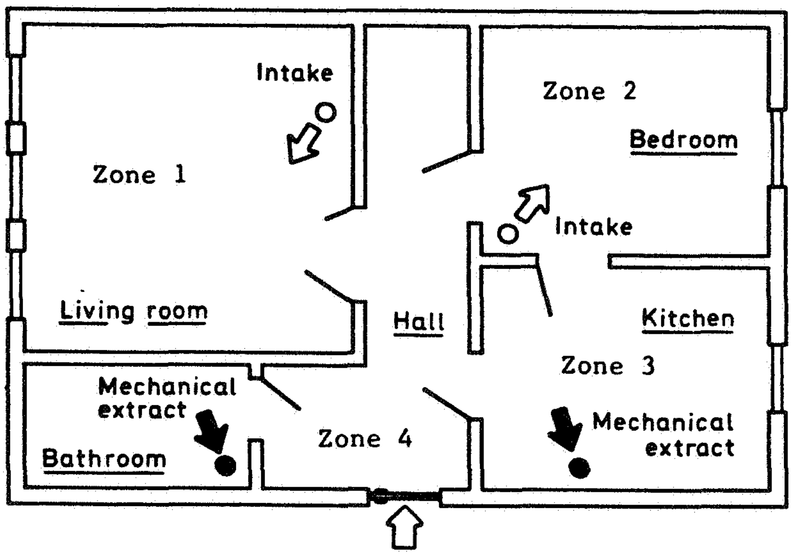


Figure 7. Laboratory flat. Floor plan.

Zone	Vol. (m^3)	Number of sources	Source type	Number of CATS	Number of BATS
1 Livingroom	56	1	PDCB	3	0
2 Bedroom	36	1	PMCH	2	0
3 Kitchen	35	1	PMCP	2	0
4 Bath/Hall	49	1	PDCH	3	0

Table 8. Laboratory flat. Zonedata.

Internal doors open

The measurements indicate a uniform distrution of tracergas in the whole flat. As could be expected: Air exchange rates between zones were comparatively high and directions of air movements diffuse, see table 9.

Zone to zone	Air flow (m^3/h)	Zone to zone	Air flow (m^3/h)
1 - 2	132.1 +/- 74.5	3 - 1	69.5 +/- 43.8
1 - 3	130.2 +/- 38.5	3 - 2	9.5 +/- 34.3
1 - 4	40.1 +/- 42.6	3 - 4	103.1 +/- 90.4
2 - 1	126.9 +/- 48.1	4 - 1	61.0 +/- 57.6
2 - 3	0.4 +/- 19.0	4 - 2	6.4 +/- 27.6
2 - 4	39.7 +/- 36.6	4 - 3	58.7 +/- 53.9
1 - outside	-3.0 +/- 37.7	2 - outside	10.3 +/- 24.9
outside - 1	41.9 +/- 11.5	outside - 2	29.3 +/- 12.1
3 - outside	17.1 +/- 37.0	4 - outside	60.9 +/- 55.1
outside - 3	9.9 +/- 4.4	outside - 4	4.2 +/- 5.0

Table 9. Laboratory flat. Air flow (m^3/h) between zones. Internal doors open.

Table 10 and figure 8 show the result of the BNL/AIMS measurement compared with the SIB measurement. As can be seen, there is good agreement between the two, especially with respect to the whole-house air infiltration rate.

Zone	Vol. (m^3)	BNL/AIMS (CATS) BNL +/- SD	SIB
1 Livingroom	56	0.75 +/- 0.21	0.95
2 Bedroom	36	0.81 +/- 0.34	0.94
3 Kitchen	35	0.28 +/- 0.13	0.11
4 Bath/Hall	49	0.09 +/- 0.10	0.05
Total	176	0.49 +/- 0.03	0.53

Table 10. Laboratory flat. Measured air infiltration rates (m^3/h per m^3). Internal doors open. SD: Standard deviation, see text two-storey flat. SIB: The National Swedish Institute for Building Research.

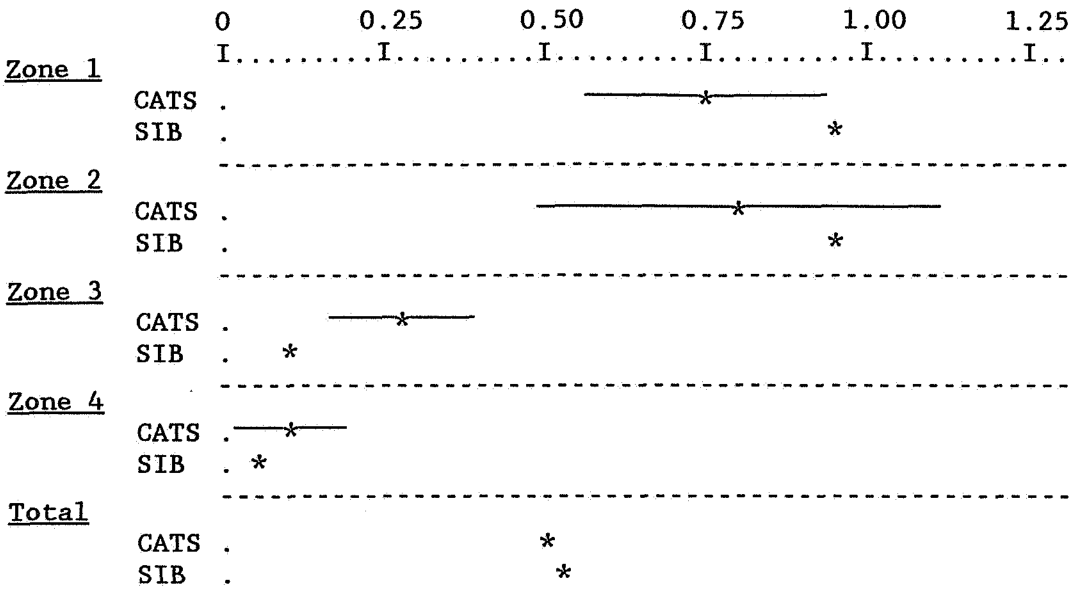


Figure 8. Laboratory flat. Measured air infiltration rates (m^3/h per m^3). Internal doors open. BNL/AIMS-CATS measurement vs. the SIB measurement. SIB: The National Swedish Institute for Building Research.

Internal doors closed

Internal doors were closed with a 10 mm fissure above doors.

Standard deviations of average concentrations measured of each tracer in each zone are below 10 per cent - not considering PMCP placed and measured in zone 3.

Zone to zone	Air flow (m^3/h)	Zone to zone	Air flow (m^3/h)
1 - 2	0.0 +/- 0.0	3 - 1	0.0 +/- 0.0
1 - 3	22.2 +/- 5.6	3 - 2	0.3 +/- 0.1
1 - 4	17.1 +/- 3.1	3 - 4	-0.1 +/- 0.0
2 - 1	0.1 +/- 0.0	4 - 1	0.1 +/- 0.0
2 - 3	27.6 +/- 6.9	4 - 2	0.2 +/- 0.0
2 - 4	9.8 +/- 1.7	4 - 3	0.1 +/- 0.0
1 - outside	-1.5 +/- 7.3	2 - outside	1.9 +/- 8.1
outside - 1	37.5 +/- 4.2	outside - 2	38.8 +/- 4.0
3 - outside	60.3 +/- 14.3	4 - outside	32.4 +/- 4.6
outside - 3	10.6 +/- 3.8	outside - 4	6.0 +/- 2.3

Table 11. Laboratory flat. Air flow between zones. Doors closed.

Significant air movements from living room and bedroom to kitchen and bath were observed (table 11), whereas no other air movements were observed. Air flows were small compared to the case with internal doors open.

Zone	Vol. (m^3)	BNL/AIMS (CATS) BNL +/- SD	SIB
1 Livingroom	56	0.67 +/- 0.08	0.75
2 Bedroom	36	1.08 +/- 0.12	1.06
3 Kitchen	35	0.30 +/- 0.11	0.20
4 Bath/Hall	49	0.12 +/- 0.05	0.15
Total	176	0.53 +/- 0.04	0.54

Table 12. Laboratory flat. Measured air infiltration rates (m^3/h per m^3). Internal doors closed. SD: Standard deviation, see text two-storey flat. SIB: The National Swedish Institute for Building Research.

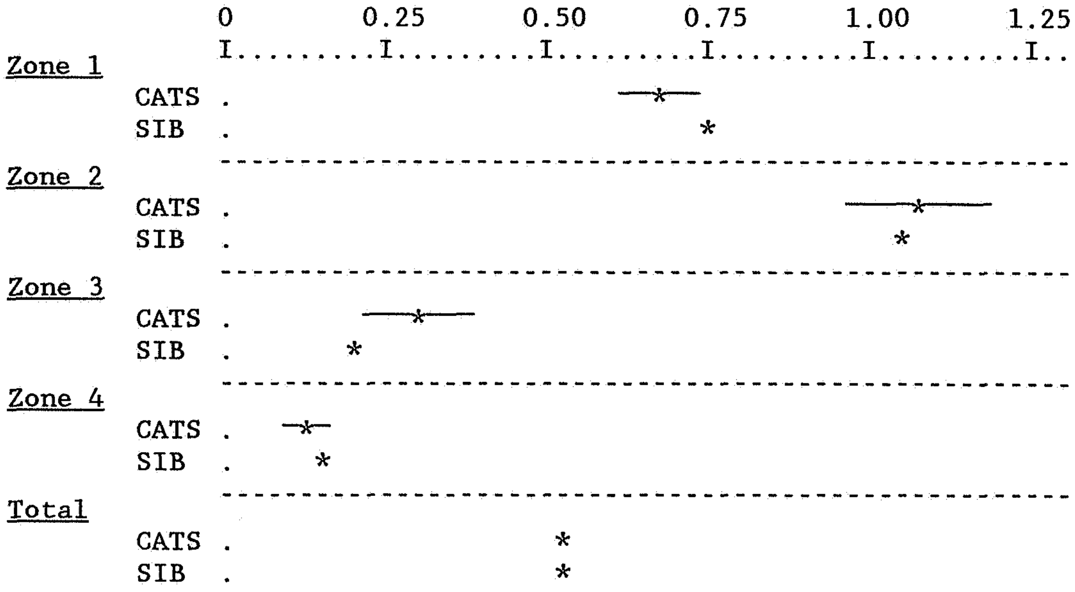


Figure 9. Laboratory flat. Measured air infiltration rates (m^3/h per m^3). Internal doors closed. BNL/AIMS-CATS measurement vs. the SIB measurement. SIB: The National Swedish Institute for Building Research.

Generally there is good agreement between measurements made with BNL/AIMS and by SIB. Exfiltration from zone 3 measured by BNL/AIMS was 60,3 m^3/h and from zone 4 32,4 m^3/h, which is close to SIB's preset exhaustion rates mentioned above.

Conclusion

Experience gained from field use of BNL/AIMS shows the measuring equipment to be easy and uncomplicated to handle. However, the importance of keeping the sources and the samplers well separated during storage and transportation (in order to aviod unintentional contamination of the samplers) is a minor irritant.

Placed in a dwelling the measuring equipment is practically invisible, thus interference with the occupants are not induced.

In spite of the very few measurements made, and even though the primary aim of this project was to gain experience with the practical use of the measuring equipment, the measurements do indicate the BNL/AIMS-method to be useful. Further investigations, theoretically as well as based on laboratory tests and field use, are however essential before the method can be widely accepted.

The mathematical multi-zone infiltration model used may be modified (in order to reduce the negative bias) through questionnaires to the inhabitants about their airing routines. Distribution of tracergases (single-zone and multi-zone) must be examined under laboratory conditions and comparisons to known methods must be made through extended field studies. In the future The Indoor Climate Division at The Danish Building Research Institute plans to carry out such investigations.

Acknowledgements

The Danish Building Research Institute wants to thank Dr. Russell N. Dietz, Brookhaven National Laboratory for being an invaluable adviser to the Danish Building Research Institute, for placing the measuring equipment at our disposal and for carrying out the analyses of the adsorption tubes.

The Danish Building Research Institute also wants to thank M.Sc. Peter F. Collet and M. Sc. J. Kure, Technological Institute of Denmark and Dr. Mats Sandberg, The National Swedish Institute for Building Research for their co-operation in the measurements.

References

(1) Russell N. Dietz, Robert W. Goodrich, Edgar A. Cote, Robert F. Wieser
Detailed description and Performance of a Passive Perfluorocarbon Tracer System for Building Ventilation and Air Exchange Measurements.
BNL 36327, February 1985.

(2) B. Kvisgaard, P. F. Collet, J. Kure
Boligers luftskifte i brugstilstand. Måleudstyr og målinger.
Byggeteknik, Teknologisk Institut, januar 1984. In Danish.
(Air-exchange in occupied dwellings)
(Building Technology Division, Technological Institute of Denmark)

(3) Mats Sandberg
Provlagenhet for ventilationstekniska studier.
Beskrivning av provlagenhet vid Statens Institut for Byggnadsforskning.
SIB, 821273. In Sweedish.
(Description of a laboratory flat at The National Sweedish Institute for Building Research).

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

PAPER S.3

SIMPLIFIED TECHNIQUE FOR MEASURING INFILTRATION AND VENTILATION RATES IN LARGE COMPLEX BUILDINGS: PROTOCOL AND MEASUREMENTS

M D A E S PERERA, R R WALKER AND J J PRIOR

Building Research Establishment
UK Department of the Environment
Garston
Watford
UK

SYNOPSIS

The 'Simplified Technique' is a method by which it is possible to determine approximately the infiltration and ventilation rates of large and complex buildings. The aim is to provide a reliable and easy-to-use procedure for non-specialists.

This paper describes a working protocol for using this technique. Results from computer model studies are given to provide guidance on use of the technique and its potential accuracy. The paper concludes with a description of field measurements in two naturally ventilated office buildings using simple, robust and inexpensive hardware designed for this purpose.

1. INTRODUCTION

Adequate ventilation is essential for the health, safety and comfort of the occupants of buildings but excessive ventilation leads to waste and in some cases to discomfort. Guidance has to be provided on means of ensuring that these requirements are met while avoiding the waste of resources inherent in excessive ventilation. Data are therefore required on ventilation rates in existing buildings for assessing the effects of remedial measures and for improving methods for predicting ventilation rates.

Air enters a naturally ventilated building either through purpose-built openings like windows or by uncontrolled leakage (infiltration) through cracks etc. Despite the fact that the majority of buildings, whether for commercial, public or domestic use, are naturally ventilated, there is a dearth of experimental data on complex buildings like offices. This is because large, multicelled and naturally ventilated buildings pose many inherent difficulties when conventional tracer gas techniques are used to measure ventilation rates. Techniques employing multiple tracer gases can be used [1,2,3] but these are labour intensive and require both specialist equipment and staff. To overcome these difficulties, a 'simplified technique' was originally proposed in a previous paper [4] and evaluated through computer modelling [5] and field work [5,6].

This technique is a method for determining approximately the overall airchange rate (i.e. total volumetric air inflow rate divided by the building's volume) of large and complex buildings using a single tracer gas. The aim is to provide a reliable and easily implemented procedure which can be used by non-specialist personnel. Analysis can be done off-line at a central laboratory which allows this method to be used in buildings at remote sites.

In practice, this involves dispersing a tracer gas (such as sulphur hexafluoride, SF_6) within a building. No particular attention is paid to how completely or uniformly the tracer gas is dispersed either initially or during the period of the test. This feature is significantly different from the conventional single tracer ventilation measurement methods. No artificial mixing of tracer with the internal air is required.

Once the gas has been injected, a suitable period of time is allowed to elapse after which two averaged air samples are taken at one or more representative locations. Sample concentrations, usually in the parts per billion (ppb) range, are then analysed off-line in the laboratory to determine the infiltration or ventilation rates.

This paper extends previous studies [4,5,6] in the following ways:

- A working protocol for implementing this technique is described.
- Results from new computer model studies are given to provide guidance for the required delay period, t_d, between seeding and sampling. Results are also used to give an indication as to the closeness of the decay rate obtained with the true whole-building airchange rate.

- Hardware, which could be used with this technique, is described. This includes automated and portable sampling units which have been designed for ease of use.
- Exploratory field measurements in two naturally ventilated office buildings are described to illustrate the use of this technique in practice. Predicted delay periods are compared with those obtained during the field measurements.

2. THEORETICAL DESCRIPTION

The theory and assumptions governing the simplified technique are described fully in an earlier paper [4] but the essential features and assumptions are given here for sake of completeness. In a multicelled building with n-cells, the concentration, c(t), of tracer gas in any one cell will vary with time t according to,

$$c(t) = a_1e^{-\lambda_1 t} + a_2e^{-\lambda_2 t} + \dots\dots\dots + a_ne^{-\lambda_n t} .$$

where $\lambda_1, \lambda_2, .., \lambda_n$ are constants (eigenvalues) which can be computed numerically [4,5] along with the coefficients, $a_1, a_2, ..., a_n$.

In single-celled buildings where the tracer gas can be well-mixed with the internal air, the building's airchange rate is determined by measuring the slope of the logarithm of the tracer concentration as it decays with time. In multicelled buildings, and/or in conditions of poor mixing, this approach is not valid since the concentration profiles will not only be influenced by the air exchanges with the outside but also by those between individual spaces.

In such situations, two distinct 'decay' regions would be present in the semilogarithmic plots of concentration profiles taken within any of the multicelled spaces. The first of these, termed the 'transition' region, occurs as soon as decay begins. This region is influenced by contributions from each eigenvalue. Within this region, the slope of the semilog plot varies with time.

With increasing time, this variation is reduced and a 'dominant' region is established in which the slope is nearly constant and equal to the smallest eigenvalue. It has been shown [4] that this eigenvalue, λ_{min}, would, under certain circumstances, approximate to the overall whole building airchange rate.

It was also shown that the eigenvalues depended only on the intercell airflows and were totally independent of either the initial tracer gas concentration or its distribution. This is significant when implementing the 'simplified' technique since it means that a tracer need not be initially dispersed either uniformly or throughout a building because all concentration profiles, obtained at any point within the building, would have a dominant region with the same slope.

The closeness of the minimum eigenvalue, λ_{min}, to the overall airchange rate is primarily dependant on the extent of internal mixing that is present within the building. It also depends on whether the building is well-connected, i.e. there is unrestricted communication between each zone (a collection of cells which behaves similarly) with its immediate neighbours or, if not, individual rooms (cells) within a zone of interest are well-connected.

3. COMPUTER SIMULATION

A computer simulation study was carried out to determine the closeness of λ_{min} to the overall building airchange rate in a mathematical model of a multicelled building. The time delay, t_d, required for this rate to be established (within $\pm$ 10% of the final value), on a tracer gas semilog decay plot, was also studied. The computer program used was designed to study movement of contaminants in a multicell environment and had previously been used in field [2,3] and prediction [4,5] studies.

In the present study, two models of a nominal multicell building were considered. Model I concentrated on dispersion within a single storey when there was restricted air movement between individual storeys but free movement within each storey. In the second study (Model II), airflows through a common stairwell allowed three individual storeys to communicate with each other.

It was also recognised that even though eigenvalues depended solely on the internal air movements, the time delay t_d was a function also of the distribution of the tracer within the building. In Model II simulations, therefore, various tracer dispersion strategies were considered.

3.1. Model I (Single Storey)

The model consisted of seven cells (Fig 1), representing two sets of three rooms with each set on either side of a corridor running along the width of the building. Each room volume was set to unity with the corridor volume taken to be twice that value. Figure 1 also shows the two airflow configurations, Cases I.A. and I.B., were chosen to give a whole building airchange rate of unity. The flows were configured to represent conditions when the external wind was blowing parallel to the wide face of the building or normal to it.

In previous papers [4,6], a 'mixing parameter' β was superimposed on internal airflows to simulate interzonal mixing. Values for β were chosen, somewhat arbitrarily, to represent conditions ranging from good to bad mixing. For this paper a range of values for β were obtained by considering airflows obtained from a previous prediction [7] on an existing three-storey office building where total inflows into the the major central area of each of these storeys ranged from 470 to 800 m^3/hr.

Lidwell [8] showed that inherent air turbulence within buildings permits a two-way exchange of air through open doorways. For a typical open doorway (1.9 m high by 0.8 m wide) connecting an office to a central corridor, calculations [8] indicate a two-way turbulent exchange of 430 m^3/hr through each half of the doorway, similar to the exchanges [9] brought about by a temperature difference of 2^oC between the room and corridor. Using a previous [4] definition for the mixing parameter, i.e. ratio of mixing to total inflow (in this instance into a single storey), β will then take values lying between 0.5 and 0.9 In the present simulation, these are covered by values of 0.3 and 1.0 for β to maintain consistency with previous work.

Table 1 lists the eigenvalues obtained for each of the four simulations. In each instance, λ_{min} is shown to be considerably smaller than the others. As expected, λ_{min} approximates to the whole-storey airchange rate and the correspondence between these two parameters increases (from within 20% of each other to within 10%) as mixing increases.

With the tracer gas dispersed throughout the whole storey, time delays t_d, expected in each of the seven cells were calculated and given in terms of a system time constant, defined as the reciprocal of the overall airchange rate. Results showed that in all cases, t_d never exceeded a value of 0.6 time constants. As an example, Figure 2 shows how quickly the dominant region is established in a windward room, a leeward room and the corridor when β=0.3 for Case I.B. The closeness of the dominant slopes of these profiles to the whole-storey airchange rate is shown by comparison with the decay profile obtained when there is perfect mixing ($\beta=\infty$) between cells.

3.2. Model II (Three-storey Building)

This consisted of three storeys, connected through a common stairwell (Fig 3). The volumes of the four zones were each set to unity. Three airflow configurations, considered previously [6], were used to represent conditions which were solely temperature (i.e. buoyancy) driven, wind driven or a combination of buoyancy and wind induced. Also, three tracer gas dispersion strategies were considered, namely;

- tracer distributed only in stairwell,
- on all storeys except in stairwell, and
- tracer dispersed throughout building.

The mixing parameter for this model was obtained by considering results from previous field measurements in two naturally ventilated office buildings. In one building, multiple tracer gas measurements [3] showed that β was about 0.1 for two-way flows between each storey and a common stairwell.

In the other building, measurements [5] indicated ventilation rates between 3,400 and 3,900 m^3/hr. Within this building, each storey connected to a common stairwell through a 1.7 m wide by 1.9 m high doorway. Two-way exchanges between each storey and the stairwell were calculated using the same calculation procedure described earlier giving β a value between 0.2 and 0.25. Considering values of β obtained for both these buildings, it was decided that values of 0.1 and 0.3 would be appropriate for use in the computer simulations.

Table 2 lists the eigenvalues obtained for each of the computer simulations. It can be seen that λ_{min} is considerably smaller, and hence more dominant, than the other rates and that its value is usually within 30% of the true whole-building airchange rate.

Table 2 also lists delay times, t_d, obtained in each zone. Although no specific pattern can be identified, the following general trends are seen;

- t_d can vary between zero (immediate dominant decay) and 6 time constants,
- time delays are smaller when there is increased internal mixing, and
- t_d averaged from all cases lies between 1.6 $\pm$ 0.5 time constants at the 95% level of confidence.

3.3. Discussion of computer model studies

Computer model studies were used to determine how soon a dominant decay region is established when using the simplified technique and how well the semilogarithmic slope approximated to the overall ventilation rate. A variety of airflow configurations, approximating as much as possible to real-life situations, were considered.

Results from representation of tracer dispersion in an *isolated* storey of a multi-storey building show that a dominant slope, equivalent to λ_{min}, is established on a 'decay' plot within at least 0.6 time constants and that the magnitude of this slope is within 20% of the true ventilation rate of that single storey.

In a multistorey building, where each storey is interconnected, computer simulations show that semilogarithmic concentration decay profiles will give an approximation to the building ventilation rate provided sufficient time has elapsed after the tracer gas is dispersed. This study indicates that this could be as close as 30% of the true rate and is similar in value to that found in an earlier study [5]. The closeness of this approximation will depend on the extent of internal mixing.

Simulations also indicate a variation in the period needed before the decay rate approximates towards the overall airchange rate. For these particular cases, results show that a period of two time constants would be sufficient in most instances.

4. HARDWARE FOR FIELD MEASUREMENTS

The aim of the simplified technique is to provide a simple and robust ventilation measurement procedure which could be used by non-specialists. The technique requires the operator to inject a tracer gas into a building and, after a suitable period has elapsed, to take samples of air at various locations within the building.

Although the measurements can be carried out at remote sites, subsequent analysis requires the samples to be sent to a central laboratory. Suitable gas analysers can then be used to measure the sample concentrations.

The proposed user of this technique would therefore require, in addition to the protocol for conducting these measurements, the following hardware;

- portable tracer gas cylinders, together with an outlet valve preset to a specified delivery rate.
- suitable containers in which to collect and retain air samples while they are sent to a central laboratory for analysis.
- sampling units, each pre-programmed to collect air samples into the containers at specified times and for specified durations.

4.1. Tracer injection

Sulphur hexafluoride, SF_6, was the natural choice since it satisfied all the properties that are either necessary or desirable in a tracer gas [7]. The ability to measure concentrations at levels of parts per billion (ppb) volume, using electron-capture gas chromatography, made it additionally desirable for the simplified technique.

Small pressurised cylinders containing liquified SF_6, each weighing 3 kg in total when full, were used since they were sufficiently light for portability. Each contained a sufficient quantity of gas for many tests to be carried out from one cylinder. The exact number depended on factors such as initial target concentration, volume seeded and building airchange rate. As an example, one SF_6 cylinder can be used for approximately 100 tests in a 5,000 m^3 building if the initial required tracer concentration is set at about 300 ppb.

A constant flow rate of about 75 ml/min was maintained by attaching a needle-valve to the two-stage pressure regulator fixed to the cylinder outlet. This was sufficient to seed a 40 m^3 room to an initial 300 ppb by injecting the gas for about 10 seconds.

Additional to SF_6, two further gases (Freon 13B1 and nitrous oxide, N_2O) were used in parallel experiments. While SF_6 and Freon 13B1 were analysed using electron-capture detection, N_2O concentrations were measured using an infrared analyser.

4.2. Automated bag-sampler units

Air samples were collected in 3-litre Tedlar (polyvinylfluoride) bags. It has been shown previously [6,7] that these bags would retain SF_6 over a period of at least a month without any measureable tracer loss.

Pairs of these bags were connected to automated sampler units (Fig 4). The units were designed and built to be robust, compact, easy-to-use and inexpensive. Each unit comprised a pump delivering a continuous air sample (0.2 l/m) to either of two sample bags via a solenoid-valve flow diverter. The timing and duration of the two samples were controlled by two pre-set mechanical timers.

These were set-up so that each bag would be filled continuously over about 15 minutes. This period was chosen so that averaged samples could be taken, minimising local fluctuations in tracer concentrations. An average decay rate over a 1½ hr period was obtained at each measurement location by filling the second bag 1½ hrs after the start of the first.

4.3. Gas chromatographic (GC) analysis

Air samples, with tracer at ppb levels, were analysed using a Perkin-Elmer Model 8310 GC employing a nickel-foil electron-capture detector (ECD). A 2m long glass tube (6 mm OD) packed with 80-100 mesh Porapak Q (an ethyl vinyl benzene polymer) was used as the separating column.

The detector was operated at 350 ^{o}C and the oven temperature set at 100 ^{o}C. Argon/methane at 15 ml/min was used as the carrier gas. With these operating conditions, atmospheric oxygen separated at 1.2 minutes, while SF_6 and Freon 13B1 (bromo-chloro-difluoro methane), used as a second tracer in the field measurements, gave sharp and distinct peaks on a chromatograph at 2.4 and 5.2 minutes respectively.

Pre-calibration work showed that the ECD was approximately five times more sensitive to SF_6 than to Freon 13B1. Analysis was restricted to the linear response regions, 0-100 ppb for SF_6 and 0-850 ppb for Freon 13B1 and, when necessary, gas samples were pre-diluted with laboratory air using a large (100 ml) glass syringe.

5. FIELD MEASUREMENTS

Field measurments were carried out simultaneously in two naturally ventilated office buildings. Building A, which is rectangular in plan, comprises two storeys with a volume of 2153 m^3. Building B (with a volume of 4840 m^3) is T-shaped and consists of a four-storey block (running approximately EW) linked to the southern end of a two storey block aligned NS. A stairwell leading from the first level foyer provides common access to all four levels while a stairwell at the northern end linked the two lower levels. These buildings are described more fully in Reference 5.

5.1. Description of tests

A total of five tracer gas decay-type tests (summarised in Table 3) were performed - two in Building A and three in Building B. Tests within each building were carried out in parallel and were designed to provide complementary results. In addition to the use of SF_6, one further tracer gas (Freon 13B1) was used in Building A and two (Freon 13B1 and N_2O) in Building B.

Tests 1 and 3, in Buildings A and B respectively, were designed to be straightforward tests of the proposed protocol for the simplified technique. Dispersion of SF6 was completed one hour before sampling on the assumption that this delay would be sufficient. To cater for the possibility that this would not be so, Freon 13B1 was dispersed in two further tests (Tests 2 and 5) five hours before sampling was due to begin.

Since only two discrete samples (from any one location) were to be taken during the above tests, it was considered that a useful check would be provided by dispersing N_2O as a third tracer and analysing it continuously in real time. This was done as Test 4 in Building B when N_2O was dispersed at the same time as SF_6 (Test 3). An automated sampling and data-logging system was used to draw air samples continuously from locations in Building B at the same locations as for the discrete samples. Samples were sequentially drawn through nylon tubing from each location and directed through a Leybold-Heraeus infrared gas analyser. The output was logged on a digital recorder for subsequent processing.

5.2. Location of tracer sampling points

Within each of these buildings, samples were taken at various locations (Table 4) which were mostly along corridors. Previous work [5] has shown that these corridor locations can be considered as good representative points for taking air samples. Of the three in Building A, two were located in the long corridors on each of the two levels and the third was placed on the short corridor of the second level near to the stairwell connecting the two storeys.

Four locations were chosen in Building B. Two were on the first level at either end of the building; one was placed at the northern end of a central corridor (with office rooms on either side) and the other was placed at the southern end in a foyer area. Two others, one at the northern end and the other at the southern end, were placed on level 2 and 3 corridors respectively.

5.3. Test Conditions

As before, all tests were conducted when the buildings were unoccupied. Even though it was warm, the space heating was kept on to enhance any mixing between the tracer gases and the internal air. All internal doors were kept propped open but all outside windows and doors were shut. Outside weather conditions were monitored at a height of 10 m at a nearby open site.

Tracer gases were manually injected into each of the buildings. Table 3 lists the durations and completion times. Assuming airchanges around 0.5 ach, this target level was set to allow subsequent samples to be within the linear calibration range of the GC. Similarly, the release rate of gas from a cylinder containing liquified Freon-13B1 was set at 1.4 l/min for an initial target concentration of about 3.5 ppm.

For N_2O, the initial target concentration was set at about 200 ppm. This relatively high initial value was a consequence of the limitation imposed by the range (1 to 150 ppm) measurable on the on-line infrared gas analyser.

Automated bag sampler units were placed at each of the sampling locations. These were set to take samples beginning at 1600 and 1730 GMT in Building A and 1525 and 1655 GMT in Building B. Each sample was taken over a continuous period lasting either 12 or 15 minutes depending on how the clock timers in each unit were set.

During the four hour period when measurements were being made, conditions were as follows;

- air temperature within Buildings A and B were constant at 23 and 25°C respectively,
- outside air temperature constant at 11°C,
- wind speed varied around 4 m/s (Fig 5), and
- the wind was mainly from the north.

5.4. Results and discussion

Air samples collected in each of the sampling bags were analysed using the GC. Table 4 tabulates the decay rates obtained from the automated units at each of the sampling locations. Rates obtained from the N_2O decay profiles (Fig 6) in Building B are also tabulated.

Results for Building A show decay rates of 0.7 hr^{-1} for two locations and 0.5 hr^{-1} for the remaining (2nd level corridor) location obtained one-hour after SF_6 was dispersed. Rates computed from tracer gas (Freon 13B1) dispersed five hours before the first sample showed a longer term rate of 0.5 hr^{-1} for two locations and 0.2 hr^{-1} for the one on the first level corridor.

It is difficult to explain this low value. Previous work [5] has, however, shown that these discrepancies can occur. With regard to using the simplified technique in the field, such an anomalous result suggests that at least three locations should be monitored for any given building.

Results for Building B indicate a building which is not too well-connected and where one zone is highly ventilated relative to the others. Results from Test 3 show a higher decay rate at the northern sampling location in Level 1. This appears to be the result of the wind blowing from the north during the tests, thereby inducing a higher infiltration rate at this location compared to the more sheltered locations at the southern side of Level 1.

Comparison with rates calculated from Test 4, using the on-line N_2O measurements, shows good general agreement between the data sets and gives confidence in the discrete samples. The largest variation is the difference between 0.3 (from SF_6) and 0.4 hr^{-1} (from N_2O) for the location at the northern end of Level 1.

Results from the long-term decay experiment (Test 5) suggest a reducing decay rate on three of the four locations. While the decay rate on the northern side of Level 1 remains at 1.0 hr^{-1}, the rate at the southern side is reduced. The other two locations settle to rates in the region of 0.3 to 0.4 hr^{-1}.

5.5. Conclusions

Field measurements indicate that the simplified technique can identify either a well-connected building or one where distinctive ventilation patterns occur. In the former, as in Building A, an overall steady decay rate is obtained. Prediction analysis, arrived at earlier show that this value is a good measure of the buildings overall airchange rate.

In Building B, the simplified technique appears to identify portions of the buildings with distinctive airchange rates, i.e. those which do not communicate well and which may be either greater or less ventilated than the building overall. These results indicate that in such instances, it would be incorrect to ascribe a unique value to the airchange rate of the building.

6. PROPOSED PROTOCOL AND OVERALL CONCLUSIONS

The 'simplified' technique relies on decay rate measurements made during the dominant period as an approximation to the overall airchange rate of a multicelled building. Currently, it is difficult to experimentally assess how good this approximation is because of the lack of proven and practical techniques, especially in naturally ventilated buildings.

At present, therefore, recourse has to be made to computer modelling. Two models, one representing a single storey and the other a multistorey building were tested through various airflow configurations for realistic degrees of internal mixing. Results indicated that rates measured using the simplified technique would be usually within 30% of the true airchange rate and that this approximation would be better with increased internal mixing. Given the ease with which this method can be used in the field, it is considered that this approximation is acceptable. Bearing in mind the known possible variation (by a factor of four) in the ventilation rate [10] for housing between nominally identical buildings, the simplified method gives results which are much better than commonly used estimates.

Computer modelling also predicted that dominant decay regions would be set-up relatively fast (within 0.6 time constants) within any single isolated storey. In an interconnected multistorey building, however, this could increase up to six time constants. Two time constants would, however, be a more likely figure.

Using hardware, designed specifically for robustness and ease of use, field measurements were carried out in two naturally ventilated office buildings. Parallel measurements, using additional tracer gases, were carried out to determine the integrity of the computed rates.

Measurements indicated that the one hour delay between dispersing and sampling a tracer gas was insufficient for the dominant decay to be established and that a longer time interval would have been better. Results from the tests in the second building showed, for the particular weather configurations for that day, a building where one zone was highly ventilated relative to the others.

From this and previous studies, a protocol for using the simplified technique in a multicelled building would be as follows:

1. Conduct tests during stable weather conditions (e.g. absence of blustery winds).
2. Open all internal doors and shut all openings to the outside.
3. Disperse the tracer gas within as much of the building as possible. The injection rate should be set according to the intial target concentration which is determined by;
   - time period over which the test is taking place, and
   - concentration range over which it is possible to analyse the samples.

4. Allow time for the gas to disperse within the building so that a dominant decay region can be established. It appears from these limited tests and computer modelling that four hours would be sufficient in medium-sized office buildings.
5. Take two 'spot' samples at each location of interest with at least three locations being monitored in any one building. Each of these samples should be an average over 15 minutes, and the times at which each filling starts should be separated by about 1.5 hrs. This would allow sufficient clarity between samples during subsequent GC analysis.
6. For off-line analysis, samples should be collected in Tedlar bags. Times and locations at which these bags were filled should be noted.

To summarise, this paper described a simple technique for determining approximately the ventilation or infiltration rates of large, multicelled buildings using a single tracer gas. The expected accuracy of the technique was tested in a computer model study. Field measurements, using inexpensive and robust hardware, show this technique yields useful information. Further field trials are planned and guidance given accordingly.

ACKNOWLEDGEMENTS

The work described here has been carried out as part of the research programme of the Building Research Establishment of the Department of the Environment and this paper is published by permission of the Director.

REFERENCES

1. Perera, M D A E S, Review of techniques for measuring ventilation rates in multicelled buildings, Published in Energy Conservation in Buildings - Heating, Ventilation and Insulation (Ed. Ehringer, H, Hoyaux, G and Zegers, P), Reidl Publishing Co., Dordrecht, (1982).

2. Perera, M D A E S, Walker, R R and Trim, M J B, Measurements of intercell airflows in large buildings using multiple tracer gases, Published in Energy Savings in Buildings - Results of the European Communities R and D Demonstration Programmes '1979 - 1983' (Ed. Ehringer, H and Zito, U), Reidl Publishing Co., Dordrecht, (1978).

3. Perera, M D A E S, Walker, R R, and Oglesby O D, Ventilation rates and intercell airflow rates in a naturally ventilated office building, Proceedings of the 4th AIC Conference held in Switzerland during September 1983.

4. Perera, M D A E S and Walker, R R, Strategy for measuring infiltration rates in large, multicelled and naturally ventilated buildings using a single tracer gas, Building Services Engineering Research and Technology, Vol 6(2), pp 83-88, (1985).

5. Perera, M D A E S, Walker, R R, and Oglesby, O D, Infiltration measurements in naturally ventilated, large multicelled buildings, Proceedings of the 1st International Symposium on Ventilation for Contaminant Control (Ed. Goodfellow, H), Published by Elsevier (1986).

6. Walker, R R, Perera, M D A E S, Hathaway, M B and Oglesby, O D, Evaluation of a simple technique for measuring infiltration rates in large and multicelled buildings using a single tracer gas, ASHRAE Transactions, Vol 91(2), (1985).

7. Perera, M D A E S, Walker, R R, Hathaway, M B, Oglesby, O D and Warren, P R, Natural Ventilation in Large and Multicelled Buildings: Theory, Measurement and Prediction, Report EUR 10552 EN, Commission of the European Communities, (1986).

8. Lidwell, O M, Air exchange through doorways. The effect of temperature difference, turbulence and ventilation flow, J Hygiene, Vol 79, pp 141-154, (1977).

9. BRE, Principles of Natural Ventilation, BRE Digest 210, Building Research Establishement, (1978).

10. BRE, Energy Conservation in Buildings - Memoranda Submitted to the Select Committee on Energy, BRE Reprint R4/81, (1981).

MODEL	--- I.A. ---		--- I.B. ---	
Mixing Ratio	0.3	1.0	0.3	1.0
Eigenvalues:				
min	0.96	0.99	1.19	1.08
2	11.30	33.68	14.41	36.93
3	2.88	8.48	4.40	9.99
4	9.27	8.87	4.99	10.59
5	3.06	8.67	3.81	9.41
6	3.16	8.76	5.16	9.24
7	2.97	8.57	3.64	10.76

TABLE 1 Eigenvalues for Single-Storey Computer Model

MODEL II	**Buoyancy**		**Buoyancy + Wind**		**Wind**	
Mixing ratios	0.1	0.3	0.1	0.3	0.1	0.3
Eignvalues						
min	1.06	1.26	0.75	0.85	0.60	0.81
2	4.97	8.00	2.58	5.18	2.19	4.89
3	2.08	2.34	1.86	0.85	1.29	1.85
4	2.90	3.60	1.01	1.70	1.72	2.44
With whole building seeded, delay periods as measured within;						
First storey	4.9	1.9	0.1	0.1	1.8	1.4
Second storey	1.1	1.2	1.6	0.9	6.1	2.2
Third storey	0.5	0.7	3.3	1.6	5.4	2.2
Stairwell	0.1	0.2	1.8	0.1	4.2	0.1
With only the three storeys seeded, delay periods as measured within;						
First storey	4.7	1.8	2.7	0.7	0.2	0.3
Second storey	0.1	0.1	0.3	0.4	5.8	2.1
Third storey	0.3	0.9	2.4	1.4	4.9	2.1
Stairwell	0.5	0.5	1.8	0.9	0.5	0.3
With only the stairwell seeded, delay periods as measured within;						
First storey	0.5	0.4	1.8	0.3	0.6	1.8
Second storey	0.3	1.7	3.1	1.4	1.1	0.7
Third storey	0.5	0.4	0.8	0.5	0.9	0.6
Stairwell	4.7	1.5	3.0	1.4	5.3	1.7

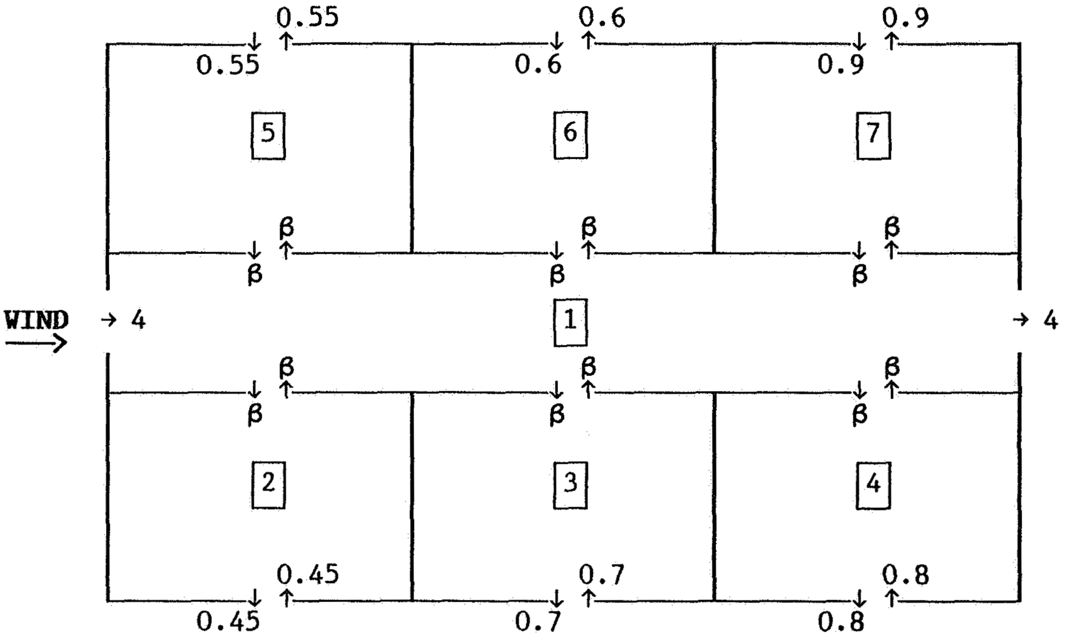
TABLE 2 Eigenvalues and Delay Periods for the Three-Storey Computer Model

TEST	BLDG	TRACER GAS	Target Concentration	Duration of tracer injection (min)	Completed at GMT	Delay to sampling (hrs)
1	A	SF_6	300 ppb	25	1500	1
2	A	F13B1	5.5 ppm	30	1045	5
3	B	SF_6	300 ppb	25	1425	1
4	B	N_2O	200 ppm	25	1425	1
5	B	F13B1	5.5 ppm	30	1015	5

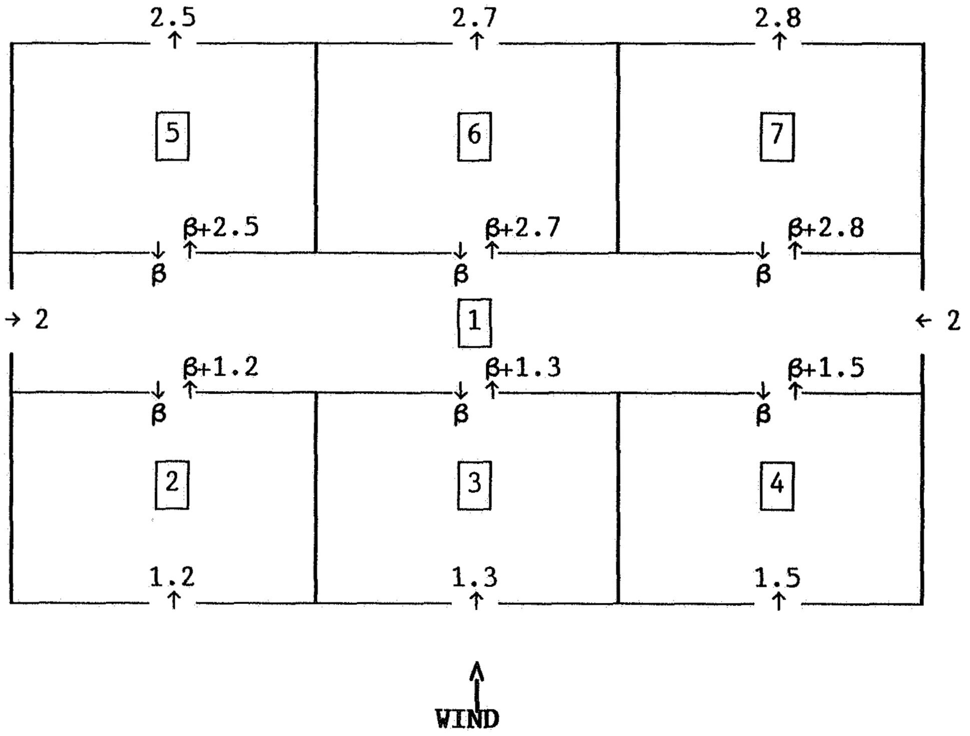
TABLE 3 Tracer Gas Dispersion Strategy for Field Measurements

BUILDING	LOCATION	Decay rates (per hour) using tracer gases;		
		SF_6	F13B1	N_2O
A	First Level (Corridor)	0.74	0.16	
	Second Level (Stairwell)	0.73	0.50	
	Second Level (Corridor)	0.48	0.51	
B	First Level (North)	1.03	1.00	0.92
	First Level (South)	0.28	0.12	0.41
	Second Level	0.67	0.37	0.59
	Third Level	0.83	0.27	0.87

TABLE 4 Sampling Locations and Measured Decay Rates (per hour)



CASE I.A



CASE I.B

Figure 1 Airflows in Model I (Single Storey)

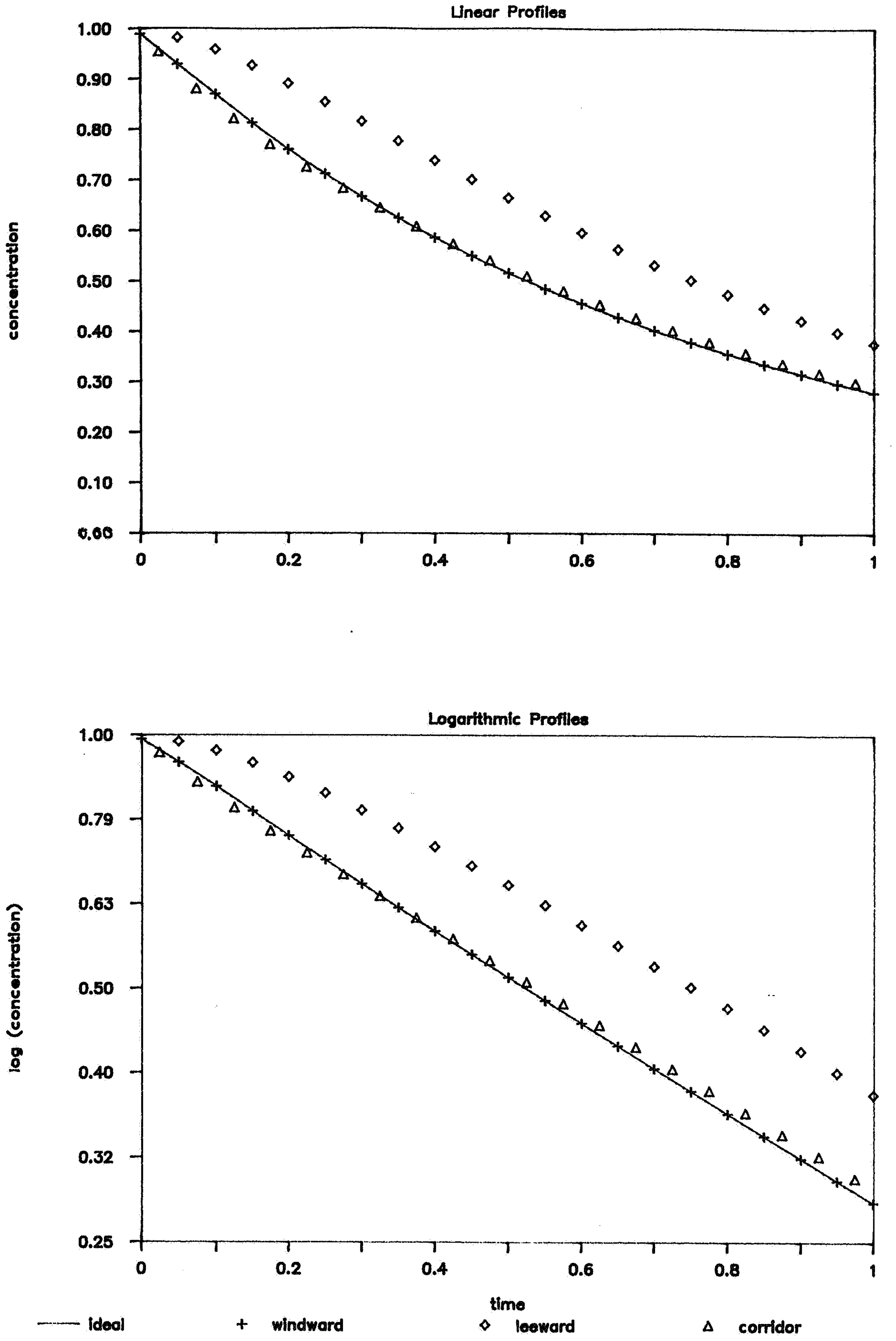


Figure 2 Example of Concentration Profiles from Computer Model I.B.

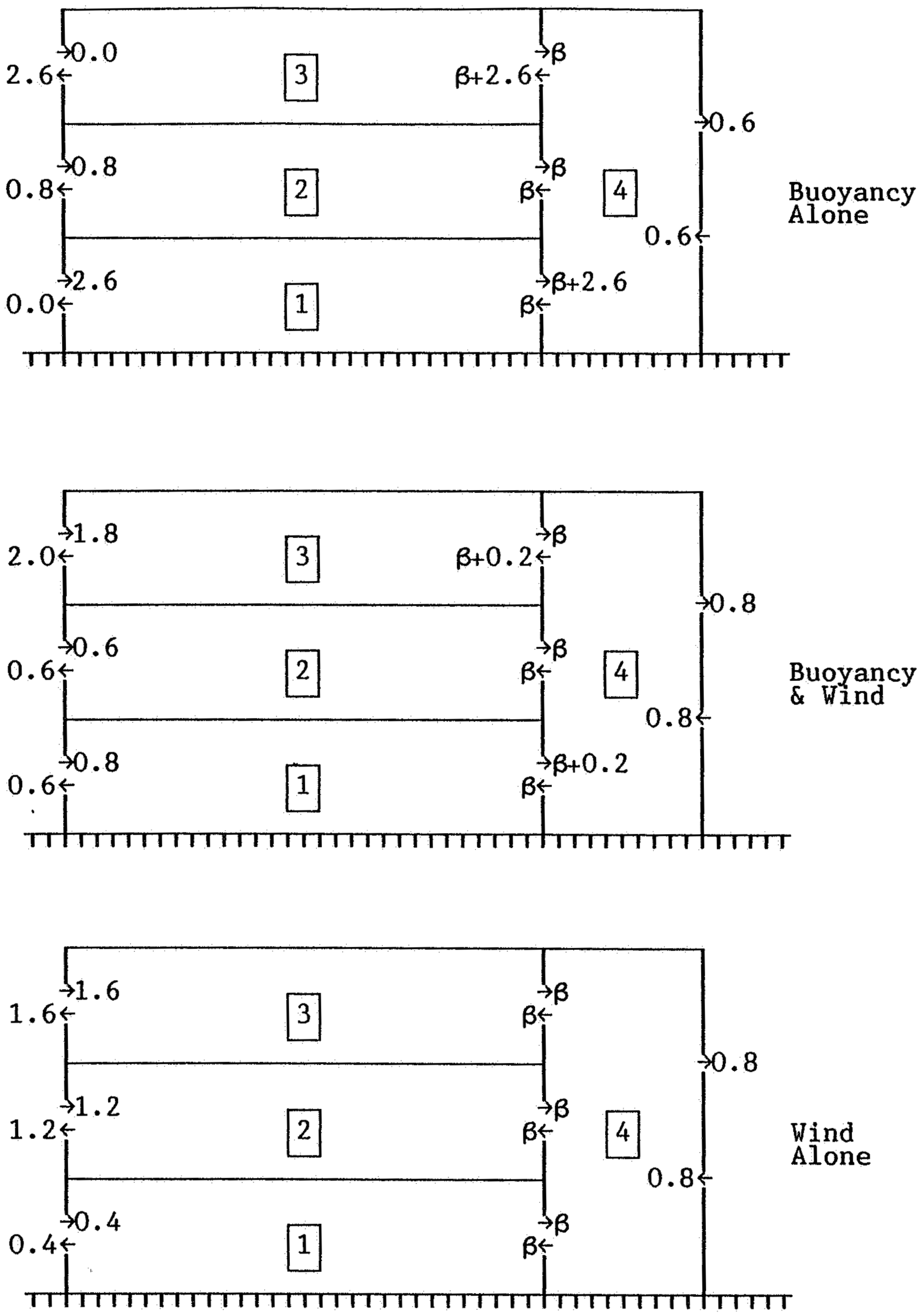


Figure 3 Airflows in Model II (Three-storey Building)

Figure 4 Two Automated Sample Units - one with Sampling Bags

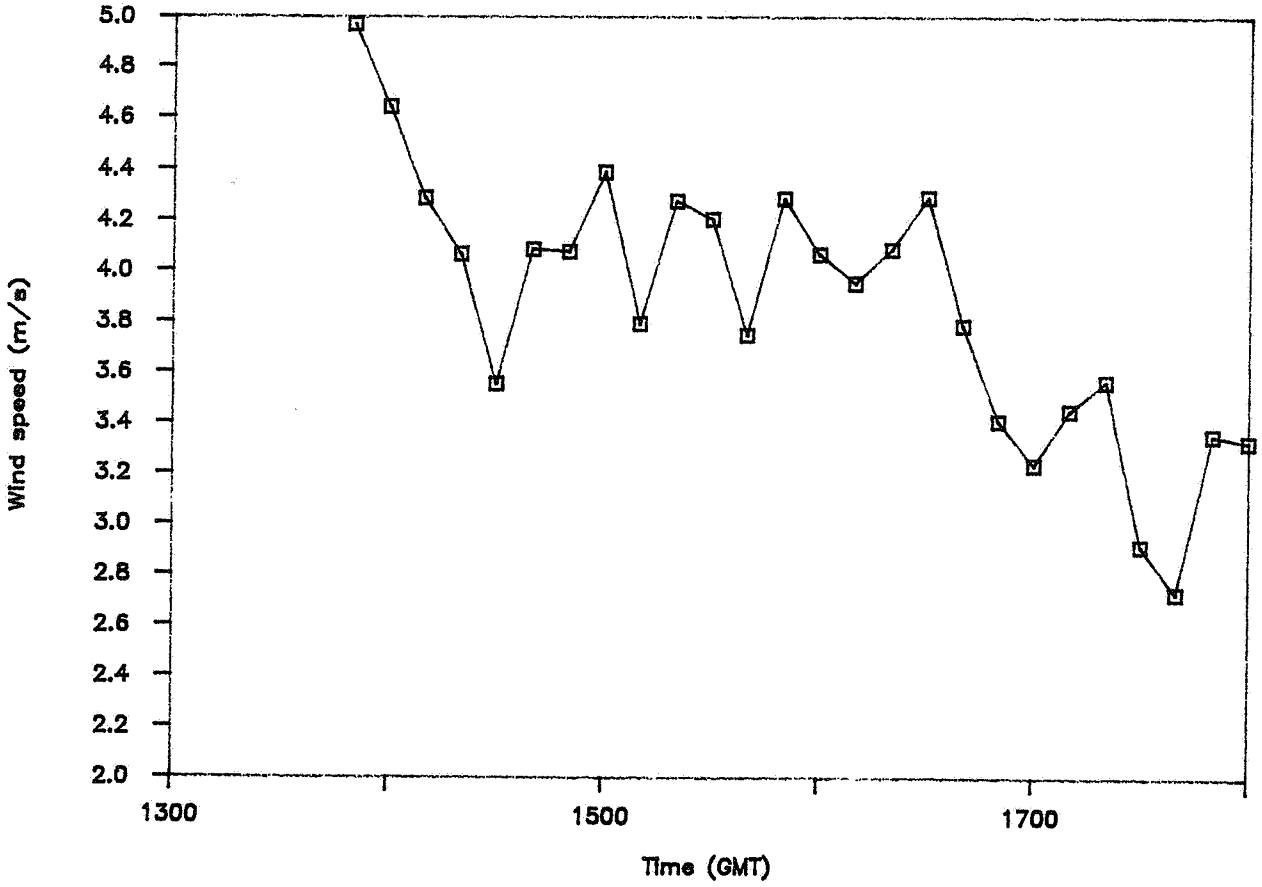


Figure 5 Wind Speeds during field measurements

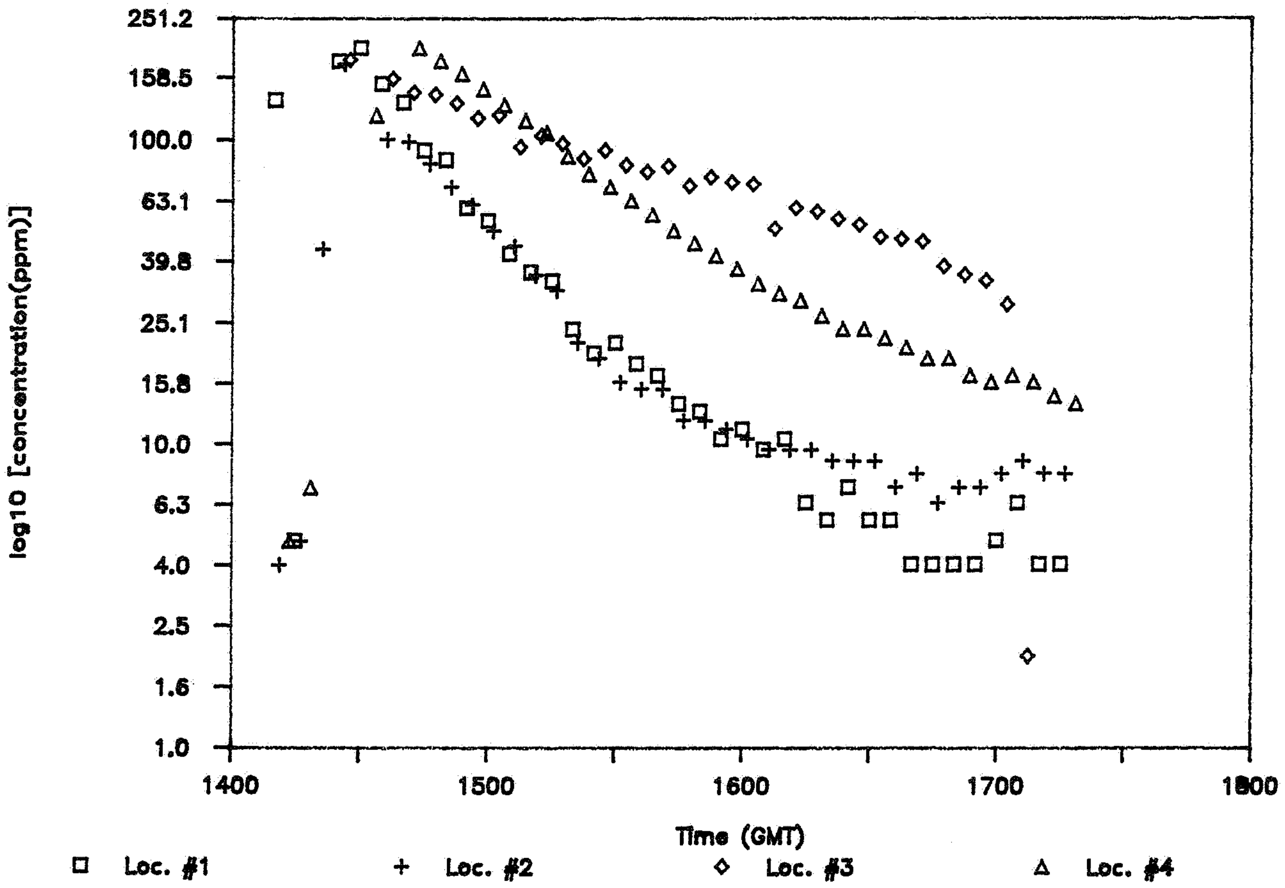


Figure 6 Nitrous Oxide Concentration profiles

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

PAPER S.4

FIELD STUDY COMPARISONS OF CONSTANT CONCENTRATION AND PFT INFILTRATION MEASUREMENTS

DAVID L BOHAC, DAVID T HARRJE AND GREGORY S HORNER

Centre for Energy and Environmental Studies
The Engineering Quadrangle
Princeton University
Princeton
NJ 08544
USA

SYNOPSIS

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 recommendations 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 consistantly 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%.

1.0 INTRODUCTION

The Perfluorocarbon Tracer (PFT) approach, as developed by Dietz et al[1] at the Brookhaven National Laboratories (BNL), is a efficient method for field measurements of multi-zone air flow rates and studies of indoor air pollutants. Questions have been raised about the accuracy of the method since it relies upon natural air movement in the zones for tracer mixing and some of the equipment used is presently unfamilar to much of the air infiltration research community. It has also been recognized that due to an approximation in the development of the air flow rate computation, the technique will generally underestimate the average air infiltration when the infiltration rate is not steady.

The purpose of this study is to evaluate the accuracy of field air flow measurements using the PFT technique. The initial portion of the study analyzes the expected error in the flow measurements resulting from inaccuracies in the PFT equipment. Simultaneous PFT and constant concentration tracer gas (CCTG) field measurements are then conducted to judge the actual performance of the method. These measurements are performed in unoccupied and occupied single family houses under various weather conditions.

2.0 DESCRIPTION AND ACCURACY OF SYSTEMS

2.1 Constant Concentration System

The constant concentration tracer gas system measures the air infiltration rate in separate zones of a multi-zone building by keeping the concentration of a single tracer gas constant at a target level in all the zones. This is accomplished by varying the tracer injection rate in each zone according to the concentration measurements and estimated air infiltration rates in the zones. Using this method, the air infiltration is approximately equal to the tracer injection rate for the zone divided by the target concentration.

The CCTG measurements were performed using two different 10 zone systems developed at Princeton University[2,3]. Both use sulphur hexaflouride (SF_6) as a tracer gas with target concentrations ranging from 50 to 350 parts per billion (ppb). Each system measures the concentration of SF_6 using a gas chromatograph (GC) with an electron capture detector (ECD). The original system has an aluminum oxide column and operates with a 60 second sample time. The most recent model, system two, uses a moisture trap, molecular sieve columns, and a backflushing arrangement to achieve a reduced sample time of 30 seconds (if necessary the sample time can be reduced to 15 seconds). Both systems have been modified to provide hourly adjustment for GC drift, on site graphic display of data, and remote access of on-going and past data via telecommunications.

Errors in the infiltration rates measured by the CCTG technique are the result of nonuniform mixing in a zone, fluctuations in the flow rates, and uncertainty in the injection flow rate, concentration measurement, concentration of the injection gas, and concentration of the calibration gas. For typical system operating conditions, a high degree of intrazone mixing, and adequate physical divisions between zones, the uncertainty in the air infiltration measurement is approximately 5%[4]. Since the unoccupied house had a large open staircase between the downstairs and upstairs the uncertainty in the air infiltration measurements is assumed to be 10%. The uncertainty of the measurements in the occupied house are also assumed to be 10% because no mixing fans were used and there were sometimes large fluctuations in the flow rates due to the opening and closing of windows (i.e. airing).

2.2 Perfluorocarbon Tracer System

The PFT method is a passive, constant emission tracer gas technique which can be used to measure average infiltration and interzone air flow rates in a multi-zone building. The measurements are performed by placing a constant source (or emitter) of a different type of tracer gas in each zone of the building and recording the average concentration of each gas in each zone.

A detailed description of the equations used to compute the multizone air flow rates is presented in Dietz et al[1]. A discussion of the development of these equations for a single zone case is presented here to illustrate the underprediction problem of passive methods. For a single zone building when the testing period is sufficiently long (greater than two to four days), the tracer emission rate is equal to the product of the concentration and the infiltration rate. Given a relatively constant emission rate, the average infiltration rate is equal to the product of the emission rate and the average of the inverse of the concentration. Because it is not practical to measure the average inverse concentration, the inverse of the average concentration is used instead. The two quantities are identical when the infiltration rate is steady but the inverse of the average is smaller for fluctuating infiltration rates. The effect of using the inverse average concentration on the underprediction of infiltration rates is discussed in the results section.

The passive sources and Capillary Adsorption Tube Samplers (CATS) used in these tests are the same as those developed at BNL[1]. The CATS are small glass tubes about the size of a cigarette. During sampling one of the two caps on the ends of the tube is removed allowing the tracer gases to diffuse into the tube where they are adsorbed by a charcoal-like material (Ambersorb) located near the center of the tube. The gas adsorbed in the CATS is driven off by heating the tube to 400-450°C in a desorbsion rack and the sample is sent to the GC. The GC measures the volume of tracer gas contained on the CATS. By knowing the tracer diffusion rate and exposure time of the CATS, the tracer gas volume can be converted to an average concentration. Experiments performed in our test chamber show that the standard deviation of the measured volume of a group of 10 CATS exposed for one day was 2.4% of the mean. Since this deviation is less than or equal to the accuracy of the GC, the precision of the CATS is assumed to be 2%. The passive CATS volume measurements were compared to samples taken directly from the test chamber and analyzed on the GC. The data from the tests indicate that volume measurements by the two methods were not statistically significant. Thus, the accuracy of the CATS sampling process is assumed to be 2%.

The passive sources consist of a small metal tube half the size of a cigarette containing the liquid tracer gas with a silicone rubber plug on one end. The tubes are filled with 0.4 mL of a individual tracer and last for two to seven years. A drawback to this type of emitter is that the emission rate is strongly temperature sensitive. The variation in temperature is approximately 5% per degree celsius and is described by the following relation[5]:

$$S_1 = S_2 \exp(-4000(1/T_1 - 1/T_2)) \qquad (1)$$

where S_i = steady state source rate measured at T_i (K)

The response of the emission rate to changes in temperature is not immediate - the steady-state rate is reached after 10 to 14 days. Thus, as long as there is not a steady trend in the indoor temperature during the measurement period, under typical conditions it is reasonable to use the average temperature over the test period to adjust the emission rate and to assume that the emission rate is constant. In our measurements it is assumed that the temperatures of the emitters are known to an accuracy of 2°C which yields an accuracy of 10% for the source rate.

The gas chromatograph used in the study is similar to the BNL two-trap atmospheric model[6]. Although it can provide direct ambient measurements, for this study the system was used only to analyze CATSs from the field. The CATSs are analyzed by placing them in a desorbsion rack where they are individually heated to drive the adsorbed gases onto one of the two GC traps. The GC trap is flash heated to 400°C to send the gases through a palladium catalyst, nafion drier, 15cm pre-column, 91.5cm analytical column, and a ECD. Backflushing through the catalyst, drier, and pre-column is provided at the proper time to prevent heavier gases from entering the analytical column. The desorbsion of a CATS and analysis is completed in nine minutes. A chromatogram of the three gases presently used by our group (perfluoromethylcyclopentane (PMCP), perfluoromethylcyclohexane (PMCH), perfluorodimethylcyclohexane (PDCH)) is displayed in figure 1. The desorbsion rack and GC are connected to a microcomputer-based data acquisition and control system. The software for the system, developed at Princeton University, provides automated analysis of a full (23 position) rack, system calibration, and storage of the measurements in a disk file. The disk file can be read directly into a multi-zone air flow rate computation program.

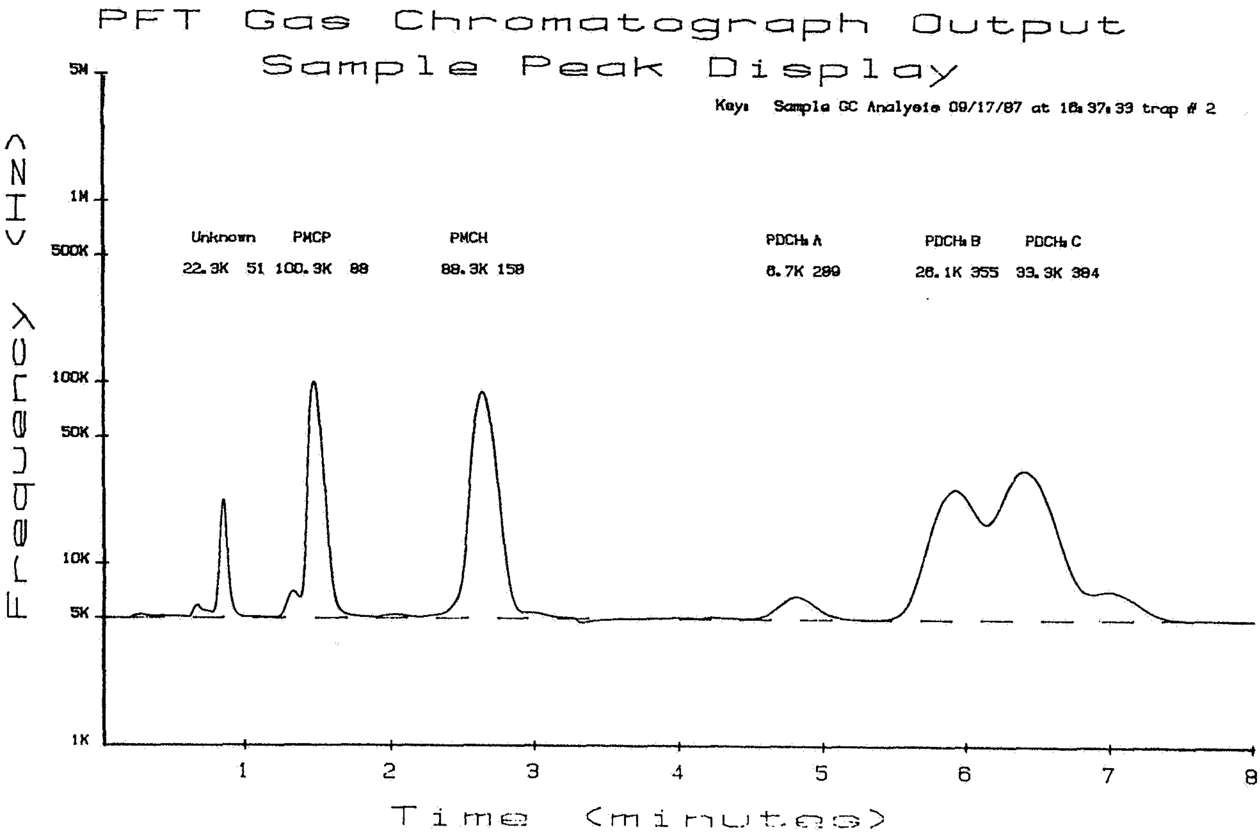


Figure 1. Sample chromatogram showing peaks from three different PFT gases: PMCP, PMCH, PDCH.

The PFT analysis system is calibrated by measuring the peak height response of each of the gases over a range of gas volumes. Calibrations are presently performed for volumes from 5 to 500 pico liters. If necessary the range could be expanded or shifted down by a factor of 40. A typical calibration curve for the three gases is displayed in figure 2. The data are fit to a third order polynomial equation using a weighted least squares regression technique. The difference between the sample volume and that computed from the calibration equation is seldom greater than 3%. The calibration of the system typically drifts a few percent from day to day. To adjust for this drift three CATSs, with known volumes of tracer gas (reference CATS), are analyzed with each rack of field CATS. The difference between the known and assumed volumes are used for a linearly proportional adjustment of the calibration curves. Our tests have shown the drift to be proportional over the entire calibration range.

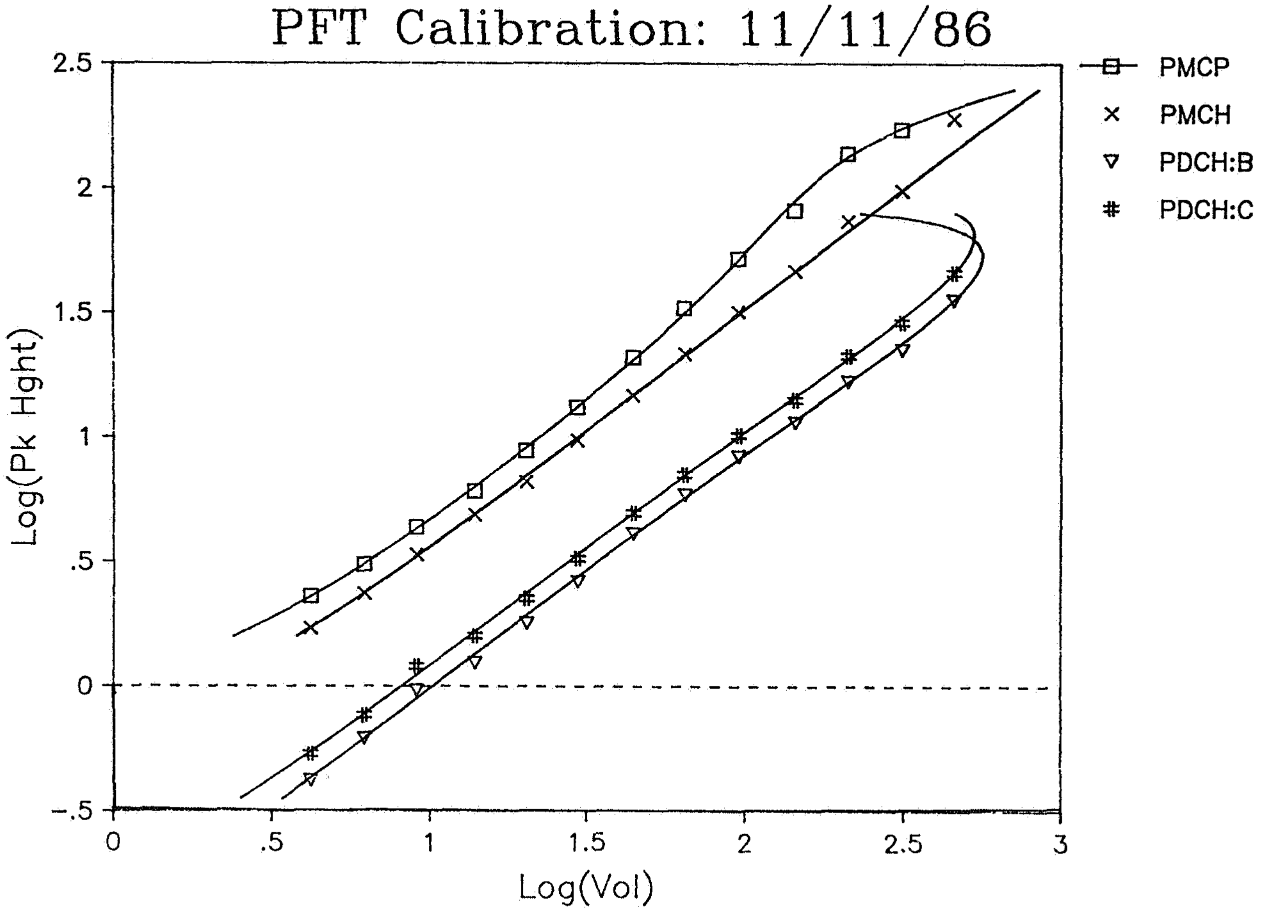


Figure 2. Typical calibration curve for PFT gases. The curve fit is a third order polynomial.

The calibration samples and reference CATS are constructed by flowing a calibration gas of known concentration through a CATS for a specified time at a known rate. The accuracy of the timing mechanism and flow measuring device is less than or equal to 1%. Unfortunately, commercially produced calibration gases of high accuracy are not available. In order to establish the PFT gas concentrations in the calibration cylinder, a series of calibration gas exchanges have been conducted with BNL. Additional standards were made at Princeton using the gas emitted by sources located in a sealed flask placed in a constant temperature bath. The standards were produced by flowing air through the flask at a constant, measured rate and collecting the air in a sample bag. With this method, the concentration of the sample bag is equal to the tracer gas source rate divided by the air flow rate. The GC measurements from the BNL gas, the sample bags, and the calibration cylinder have been compared to determine the concentration of the cylinder. From the range of values obtained in this process, it is belived that the accuracy of the PFT gas concentrations in the cylinder is approximately 8%.

This section has presented the errors associated with each piece of equipment of the PFT system. In addition to these errors there is also an error due to the nonnuiformity of the concentration in the zone. This error is chosen to be either the standard deviation of the CATS measurements in the zone or 5% - whichever is greater. Given the uncertainties of the variables in the flow equation, the uncertainty of the each air flow rate can be approximated by the Euclidean summation of the uncertainty due to each variable in the flow rate equation[7]. Using this method the uncertainty of the infiltration rates in the occupied house ranged from 15 to 20% for the downstairs, 17 to 55% for the upstairs, and 14 to 24% for the whole house.

3.0 DESCRIPTION OF TEST HOUSES

3.1 Unoccupied House

The unoccupied house is a bi-level, single-family residence located northwest of Washington, D.C.. The house is heated with a heat pump warm air system. There are supply vents in each zone of the house and the two return vents are located upstairs. Infiltration measurements in this structure have been described in previous AIVC publications, including a companion paper in this conference[8,9]. The CCTG system was installed to measure infitration in the downstairs and five separate upstair zones. For the purposes of this study the flow rates in the five upstair zones have been added together and are designated as the single upstair zone.

The PFT gases were released by placing two PMCH emitters in the downstairs and five PDCH emitters in the upstairs. The concentration measurements were obtained using three CATS in the downstairs and six to seven upstairs. The temperature in the upstairs and downstairs was measured and recored on a separate data acquisistion system. The average temperatures over the sample period are used to adjust the tracer emission rates.

3.2 Occupied House

The occupied house is a single story ranch house with basement located in central New Jersey. It is heated with a heat pump, oil furnace backup, warm air system. The basement is unfurnished and not purposely heated, i.e., all supply and return vents are located upstairs. The total volume of the two levels is 767 cubic meters. The house is part of a seven-home radon study[10] and is designated as house #5 in the figures. As part of the radon study, side-by-side CCTG and PFT air flow measurements have been conducted for nine consecutive months.

The CCTG system has been installed to measure infiltration in seven upstair zones and two downstair zones. Similar to the unoccupied house, the separate zones in the upstairs and downstairs have been combined and infiltration measurements are reported for these two zones of the building. For the PFT measurements the house was also treated as a two zone building. PMCH was released in the basement using three emitters and three PDCH emitters were distributed upstairs. The concentration measurements were carried out using three CATSs upstairs, three downstairs, one replicate downstairs, and one blank (i.e. unexposed) downstairs. The temperatures in the two zones were recorded on a separate data acquisition system and the average temperatures over the sample period are used to adjust the tracer emission rates.

4.0 FIELD TEST RESULTS

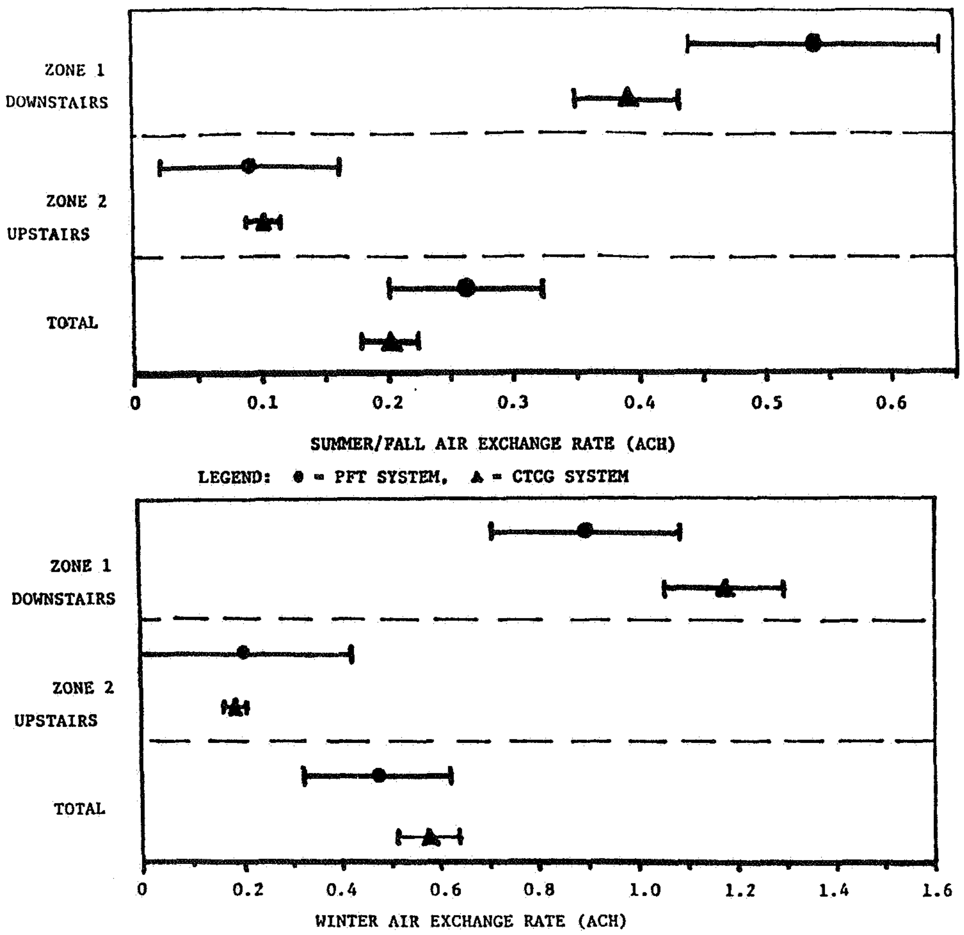
4.1 Unoccupied House

The simultaneous PFT and CCTG measurements were performed on two separate occasions. The first test was conducted from August 21st, 1986 to September 9th. The second test started January 14th, 1987 and ended January 22nd. Since the CCTG system was interrupted every second day to perform interzone tests and the GC was not always functioning properly, the CCTG data does not span the entire time of the PFT measurements. For the first period the CCTG measurements cover 66% of the total time and they cover 77% of the second.

A comparison of the CCTG and PFT data for both time periods is displayed in figure 3. The measured average infiltration rates for the two separate zones and whole house are shown along with the corresponding uncertainties. For all of the values the uncertainties of the two methods overlap. This indicates that there are no major discrepancies between the two methods. From this limited data set (with incomplete coverage by the CCTG method), it is difficult to draw any conclusions about the tendency of the PFT method to measure lower values than the CCTG method.

4.2 Occupied House

The PFT measurements from November 1986 to May 1987 have been analyzed. These 15 tests span time periods from one to three



PFT/CCTG COMPARISON FOR UNOCCUPIED
TEST HOUSE

Figure 3. Results of the CCTG and PFT measurements for the two test periods. The error bars indicate the uncertainties of the measurements.

weeks. The CCTG system was operating in the house for 10 of the test periods. The results reported here include eight periods when the CCTG system was operating for at least 85% of the period. On average, the CCTG data covers 93% of the PFT period.

A comparison of the infiltration measurements of the two methods is displayed in figure 4. The data show that the PFT measurements are consistantly lower than those by the CCTG method. Figure 5 displays the same comparison for the whole house data with error bars indicating the uncertainty of the measurements (note - one of the data points is off scale and has the value: CCTG - 1.30, PFT- 0.21). Unlike the results from the unoccupied house, in only one of the eight measurements does the uncertainty explain the difference between the two methods.

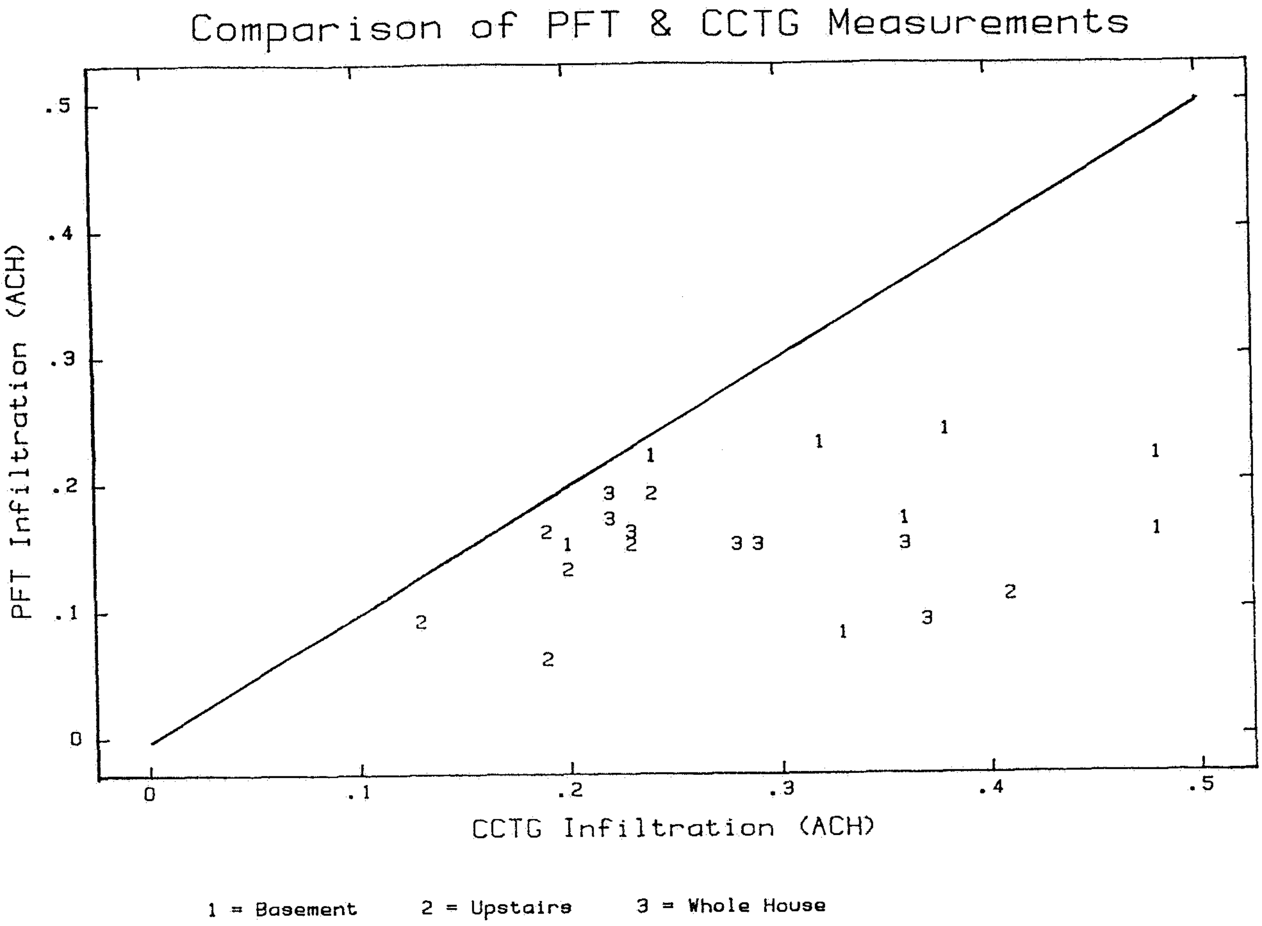


Figure 4. Results of the CCTG and PFT measurements for the eight test periods. The data include the infiltration measurements for the basement, upstairs, and whole house.

A possible explanation for this difference is that the occupants of house #5 are causing large fluctuations in the infiltration rate during some of the periods. Figures 6 and 7 display the time history of the CCTG measurements in house #5 for the eighth and twelfth periods. During the twelfth period there appears to be a fairly regular pattern of airing each afternoon. At these times the infiltration in the basement often increases by a factor of ten over its normal value (note - data above 1.0 are not shown on the graph). In comparison, the infiltration values shown in period eight do not fluctuate as strongly or as regularly.

From the analysis presented in section 2.2, it is expected that the relative magnitude of the fluctation will effect the level of underprediction of the PFT method. For the following analysis the standard deviation of the infiltration rate divided by the mean (normalized standard deviation - NSD), as computed from the CCTG data, is used as a measure of the fluctuation. This variable is plotted against the percent underprediction of the PFT method (the

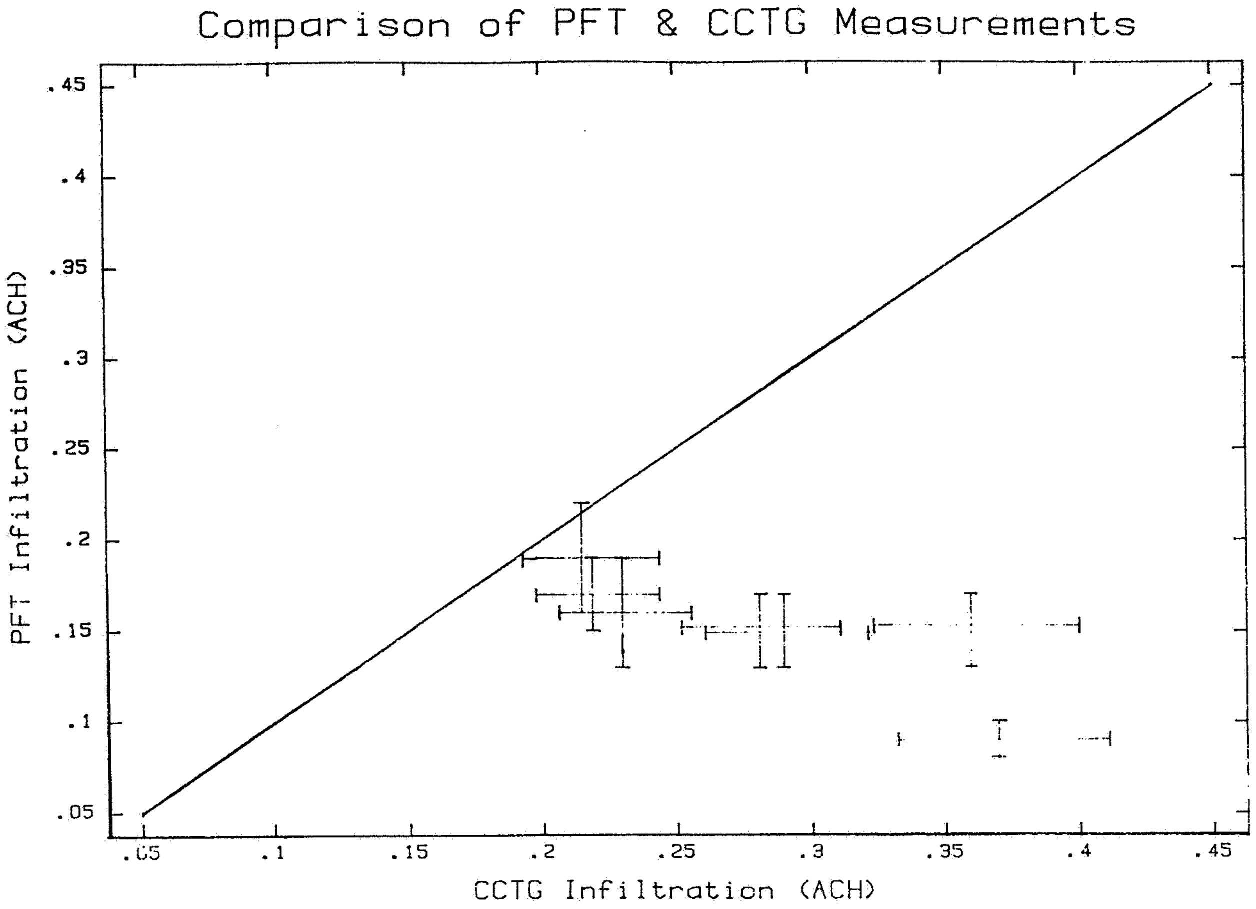


Figure 5. A comparison of the two methods for the whole house data. Error bars are included as a representation of the uncertainty of the measurements.

measurement by the CCTG method minus that by the PFT method divided by that by the CCTG - all multiplied by 100) in figure 8. The results show that there is a general trend of greater underprediction with larger deviations in the flow rate. However, there is quite a bit of scatter in the data that is not explained by the NSD.

The expected magnitude of the underprediction error can be more accurately determined from the CCTG time history data. These data are used with the single zone tracer gas equation to simulate the tracer concentration for the PFT method. The simulation is performed using the whole house data and treating the house as a single zone with one tracer gas being emitted. A two zone simulation is not possible since the CCTG system does not typically measure interzone flow rates. The constant tracer source rate is divided by the average simulated concentration to compute the simulated PFT measurement. The simulations were performed using the CCTG data from the eight measurement periods. A comparison of the percent underprediction of the measured PFT flow rate and those from the simulated rates is displayed in figure 9. The plot shows that there is a good correlation between

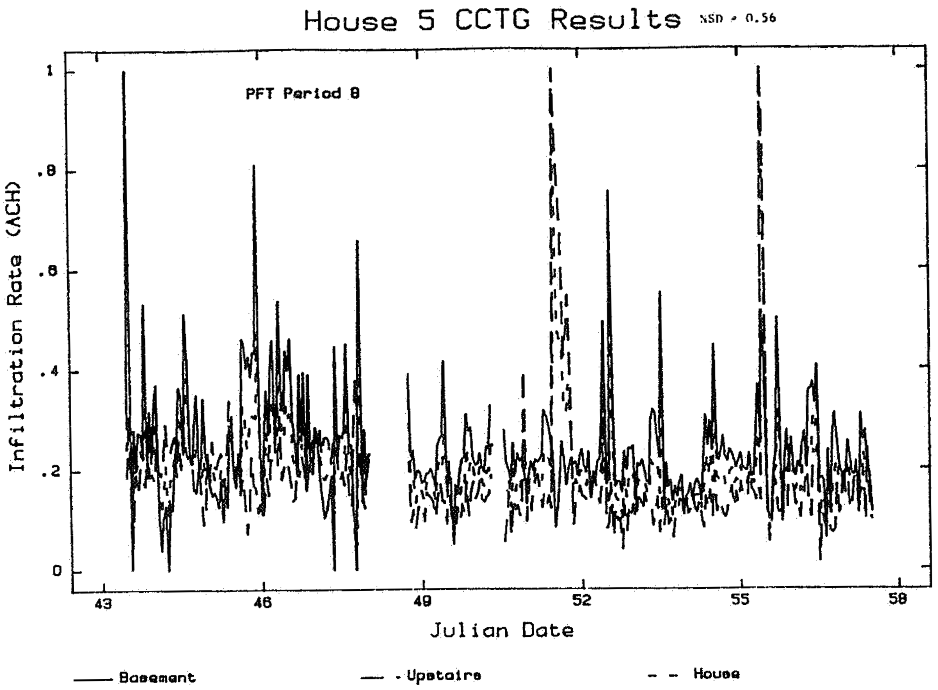


Figure 6. CCTG measurements of the infiltration during a winter measurement period. This period had the lowest NSD (0.56).

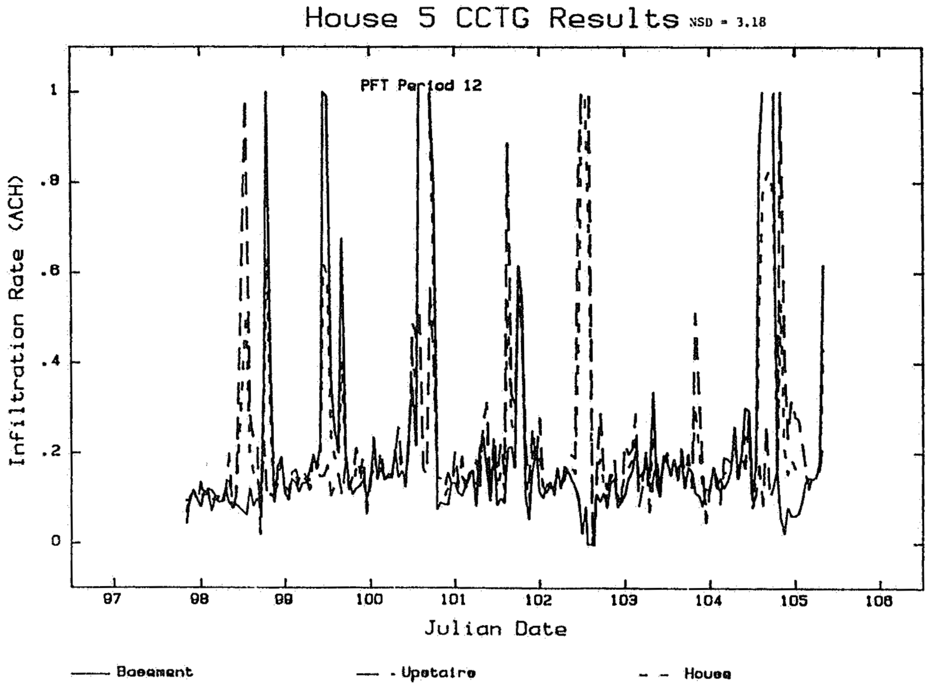


Figure 7. CCTG measurements of the infiltration during a warm weather measurement period. This period had the highest NSD (3.18) and the most evident airing.

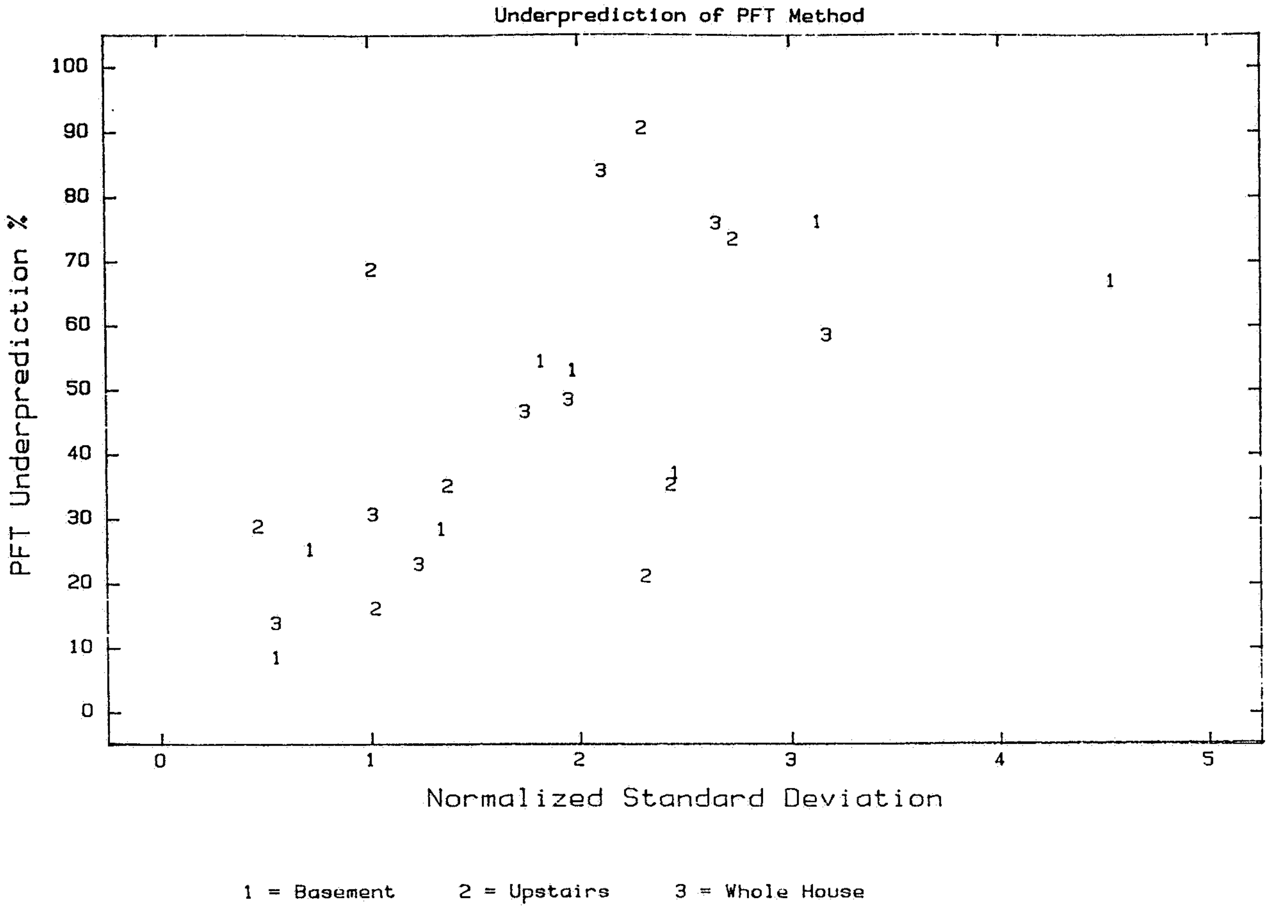


Figure 8. Variation of the percent underprediction of the PFT method with the relative magnitude of the infiltration rate fluctuation. The fluctuation is measured by the normalized standard deviation of the infiltration as reported by the CCTG method.

the measured and simulated underprediction. The strong relationship between the measured and simulated values indicates that the variation in the flow rate is responsible for much of the underprediction of the PFT method. However, the measured error is consistantly greater than the simulated error. This bias could be due to either the simplified nature of the simulation (one zone instead of two with interzones flows) or a bias in the two measurement systems.

The results of the simulations show that the underestimation error of the PFT method is large when there are strong fluctuations in the flow rate. However, in some instances the error is as low as 5%. The four periods with the largest simulated percent underprediction (32 to 78%) occurred during the spring when the average outdoor temperatures varied from 12 to 20°C. The high levels of NSD (1.8 to 3.2) and large, periodic excursions in the infiltration (see figure 7) indicate occupant airing during this warm weather. Thus, variation in the infiltration as a result of

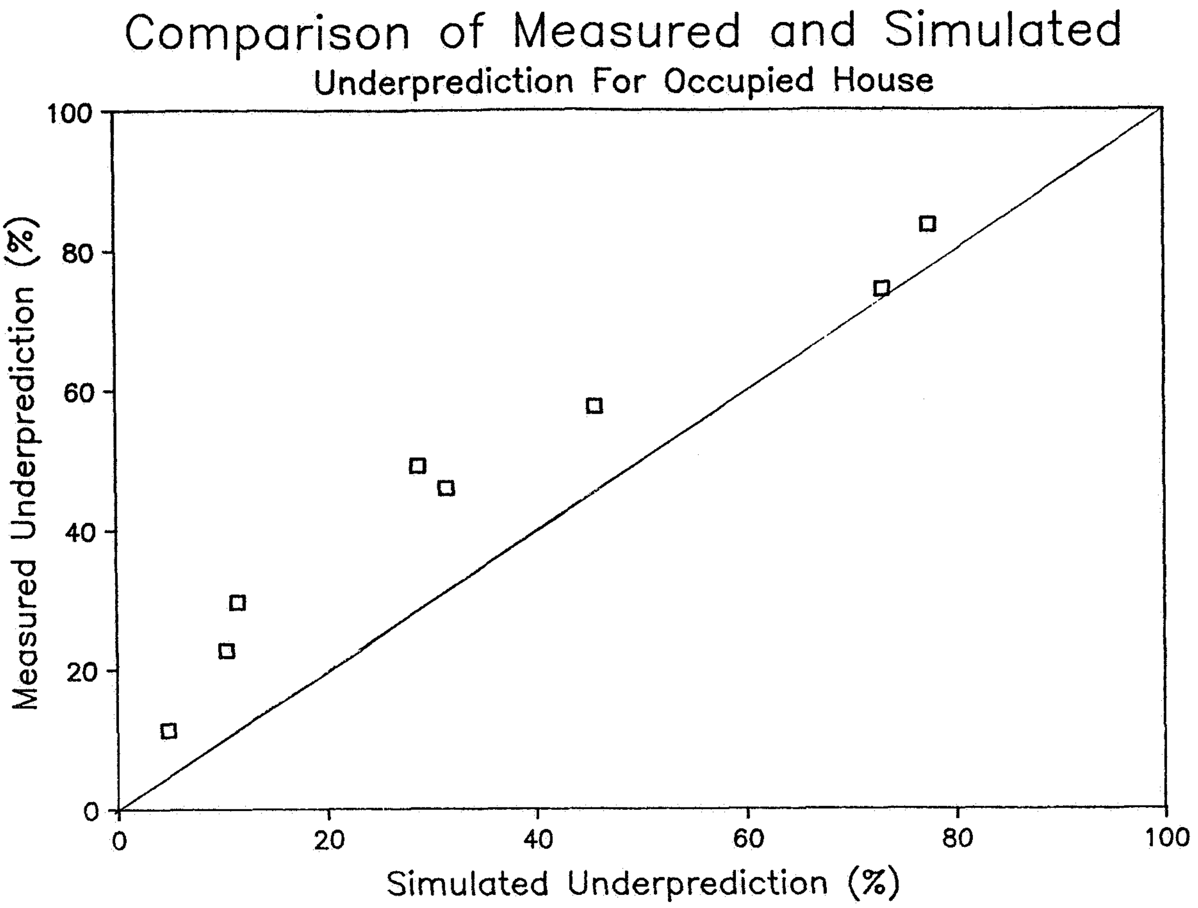


Figure 9. A comparison of the measured to simulated percent underprediction for the eight test periods.

occupant airing, and not changes in the weather, is causing large errors in the PFT measurements. The periods with the smallest error (5 to 29%) occurred during the winter when the average outdoor temperature varied from -1 to 5°C. The lower NSDs (0.6 to 2.0) and fewer infiltration excursions (see figure 6) indicate that airing is still present, but to a lesser degree, in the cold weather. The reduced airing corresponds to underprediction errors less than 30%. In summation, the data show that regular occupant airing can result in PFT underestimation errors greater than 30% but that infiltration fluctuations due to weather with only small amounts of airing result in errors between 5 to 30%.

5.0 CONCLUSIONS

The PFT approach has proven to be an efficent way to conduct field measurements of air infiltration rates in multi-zone buildings. Multiple measurements can be performed in many houses relatively easily. The laboratory analysis equipment is complex, but after the system became operational it operated reliably. The inherent errors of the PFT equipment and non-uniform mixing in a building corresponded to uncertainties ranging from 14 to 24% for the whole house infiltration measurements in the occupied house. The substantial, periodic airing that occurred during warm weather resulted in the PFT method producing underprediction errors greater than 30%. During periods when the infiltration fluctuation was due to weather changes and small amounts of airing the underprediction error ranged from 5 to 29%.

ACKNOWLEDGEMENTS

The authors wish to thank the U.S. Department of Energy for the support for this research which is presently funded through Lawerence Berkeley Laboratory. We wish to acknowledge the interest and help of Kevin Teichman, DOE Contract Monitor and Max Sherman, LBL Contract Monitor in this area of research. The PFT work of Russel Dietz and his associates at BNL, and their assistance throughtout our study, has made the project possible. At Princeton, we wish to thank Tony Lovell for his work on the programming and analysis associated with the PFT and CCTG systems.

REFERENCES

1. DIETZ, R.N., GOODRICH, R.W., COTE, E.A., and WEISER, R.F. "Detailed description and performance of a passive perfluorocarbon tracer system for building ventilation and air exchange measurements, Measured Air Leakage of Buildings, ASTM SP 904, (Eds. Trechsel and Lagus), 1986, pp. 203-265.

2. BOHAC, D.L., HARRJE, D.T. and NORFORD, L.K. "Constant concentration infiltration measurement technique: an analysis of its accuracy and field measurerments", Proceedings of the Conference on Thermal Performance of the Exterior Envelopes of Buildings III, ASHRAE SP 49, Atlanta, GA, 1986, pp. 176-200.

3. BOHAC, D.L. and HARRJE, D.T. "Improving the accuracy of a constant concentration tracer gas system", Proceedings of the 6th AIC Conference Ventilation Strategies and Measurement Techniques, Air Infiltration and Ventilation Centre, Great Britian, Doc AIC-PROC-6-85, 1985, pp. 25.1-25.23.

4. BOHAC, D.L. "The use of a constant-concentration tracer gas system to measure ventilation in buildings". Princeton University/CEES Report No. 205, 1986.

5. DIETZ, R.N., GOODRICH, R.W., COTE, E.A., and WIESER, R.F. Brookhaven National Laboratory, 1985, Report BNL 36327.

6. D'OTTAVIO, R.W., GOODRICH, R.W., and DIETZ, R.N. "Perfluorocarbon measurement using an automated dual-trap analyzer", Environmental Science and Technology, 20, 1986, pp. 100-104.

7. BECKWITH, T.G., BUCK, N.L., and MARANGONI, R.D. Mechanical Measurements. Reading, Massachusetts: Addison-Wesley, 1982.

8. HARRJE, D.T., BOHAC, D.L. and NAGDA, N.L.
"Air exchange rates based upon individual room and single cell measurements", Proceedings of the 6th AIC Conference-Ventilation Strategies and Measurement Techniques, Air Infiltration and Ventilation Centre, Great Britian, Document AIC-PROC-6-85, 1985, pp. 7.1-7.14.

9. HARRJE, D.T., BOHAC, D.L. and FORTMANN, R.C.
"Measurement of seasonal air flow rates in an unoccupied single family house", Proceedings of the 8th AIVC Conference-Research and Application, Air Infiltration and Ventilation Centre, Great Britain Document AIVC-PROC-8-87, 1987.

10. SANCHEZ, D.C., HUBBARD, L.M., HARRJE, D.T. and TURK, B.H.
"The use of diagnostic measurements to enhance the selection and effectiveness of radon mitigation for detached dwellings, Proceedings from Indoor Air '87, Institute of Water Soil and Hygiene, Berlin, W. Germany, Vol. 2, 1987, pp. 370-376.

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

PAPER S.5

THE EFFECT OF VAPOUR BARRIER THICKNESS ON AIR TIGHTNESS

JØRN T. BRUNSELL

Norwegian Building Research Institute
Forskningsveien 3 B
Postboks 123
0314 OSLO 3, NORWAY

THE EFFECT OF VAPOUR BARRIER THICKNESS ON AIR TIGHTNESS

Abstract

Laboratory measurements have shown that when pressure differences are applied across wall and roof elements, the majority of the pressure drop takes place across the vapour barrier. Similarly, field measurements have shown that the majority of the leakage in Norwegian buildings occurs at the joints in the vapour barrier, at wall/floor joints, around penetrations of the vapour barrier and through holes in the vapour barrier. Prior to 1980, the standard vapour barrier in Norway was 0.06 mm thick polyethylene sheeting. However it was suggested that the use of thicker material could reduce the number of holes in the vapour barrier created during construction so in 1980 the use of 0.15 mm thick sheet was initiated and this is now the standard.

This paper reports on a comparative study of the air leakage performance of these two vapour barrier thicknesses. The study considered 10 identical single family houses, five of which were constructed using 0.06 mm polyethylene and five of which used 0.15 mm. Air infiltration measurements were carried out on completion of the houses and repeated four years after construction. The results show that the houses with 0.06 mm film were on average about 17% more leaky than the houses with the 0.15 mm film when they were new.

Background

90% of the people in Norway live in single family houses and 95% of these are built of timber frame construction. In order to make the houses more energy efficient we have looked at different ways of making the envelope more airtight so that the ventilation rate can be controlled by the occupants. Laboratory measurements have shown that when pressure differences are applied across wall and roof elements, the majority of the pressure drop takes place across the vapour barrier. Field measurements of air tightness accompanied by thermography measurements have shown that the majority of the leakage takes place at the joints in the vapour barrier, especially at the wall/ceiling joints. Leaks are also often seen around penetrations of the vapour barrier and through holes in the vapour barrier.

Norwegian housebuilders used to use 0.04 mm or 0.06 mm thick polyethylene film as the vapour barrier in timber frame constructions. However about 1980 0.15 mm thick polyethylene film was introduced to the building market with the aim of reducing the number of holes made in the vapour barrier during construction. It was also expected that the joints in the polyethylene should be tighter with a thicker film.

Method

To verify these predictions 10 identical single family houses were built. They each have 1 1/2 storeys and a basement giving a total floor area of 260 m^2, are heated by electricity using individually thermostated, wall mounted panel heaters and have mechanical ventilation using a balanced system with heat recovery, see figures 1a - 1d. The normal ventilation rate is 100 m^3/h but can be varied up to a maximum of 250 m^3/h. In 5 of the houses 0.06 mm polyethylene film was used and in the other 5, 0.15 mm film was used. All the building details were discussed with the architect, the developer and the carpenters before construction started, in order to find out how the building details which affect air tightness were planned. The final solutions were chosen by the architect and the developer with the aim that the construction details should be similar for all the houses.

Meetings were arranged with all the carpenters before construction started where they were informed about the project, why and how to build airtight houses, the building regulations and about how to measure airtightness.

During the construction we visited the building site several times both to see how the vapour barrier was installed and to interview the carpenters about the installation of the film.

After construction we measured the airtightness of the houses using fan pressurization in conjunction with thermography measurements.

After 4 years the measurements were repeated. At the same time we interviewed the occupants and questioned them about draughts, the ventilation system and whether they had carried out any alterations to the house since the last measurements which could affect the airtightness. In addition we read the electricity meters.

Results

During the construction period no difference could be seen in the number of holes or other damage which could be attributed to the difference in the thickness of the polyethylene film.

The carpenters said that one disadvantage of the thick film was that it was heavier, however, they thought that the greater strength was an advantage.

The airtightness measurements which were carried out on completion showed that the average n_{50} value for the houses with the thick film was 2.9 ach compared with 3.4 ach for the houses with thin film, see figure 2. After 4 years the numbers were 3.2 ach and 3.6 ach respectively, see figure 3.

Thermography measurements showed many different leaks in each of the 10 houses. We were, however, not able to discover any difference in the leakage distribution between the two groups of houses. We found leaks in the vapour barrier joints, e.g. between walls and roofs and in roofs, see figures 4 and 5, and also between different building components where one or both did not have a vapour barrier, e.g. between walls and windows and between walls and intermediate floors, see figures 6 and 7.

In the questionnaire only one occupant complained about draughts saying that there were draughts around the doors and windows. However 70% of the occupants were dissatisfied with the mechanical ventilation system complaining that it had insufficient capacity, that it was noisy and that the heat recovery system seemed inefficient.

The annual total electricity consumption for each house is shown plotted against its air tightness in figure 8. The average annual electricity consumption for the group of houses with 0.15 mm foil is 29800 kWh compared with 30800 kWh for the houses with 0.06 mm thick foil.

Discussion

The fan pressurization measurements carried out when the houses were new showed that the houses with the thin film were on average about 17 % more leaky than the houses with the thick film . After 4 years this difference had apparently decreased to 9 %. This reduction can be due partly to changes carried by the occupants which could have affected the airtightness. It may also be due to the effects of thermal movement.

The standard of building will, of course affect the results. The intention was to let each construction crew build one house with each of the two polyethylene film thicknesses but in practice this was only the case with 6 of the houses. The remaining 4 were built by other construction crews. However the variation in airtightness of houses built by the same crews appeared to be of the same order as the variation between different crews. There are however other factors that could influence the results e.g. which of the houses was built first, or the weather conditions during the construction of the vapour barrier.

The Norwegian building regulations require that the n_{50} value shall be equal to or less than 4.0 ach. This regulation was introduced in 1981. However air tightness measurements made on new single family houses before and after 1981 show significantly higher values than 4.0 ach on average. The low average of the n_{50} value for the houses in this project, 3.2 ach, may thus indicate that the results are influenced by the purpose of the project. The construction of the houses in this study is no less complex than that for the other houses measured so this cannot explain the low leakage.

There appears to be poor correlation between the total electricity consumption in the houses and their airtightness. The spread in individual consumptions is also large but this is to be expected because the total electricity consumption, which includes not only space heating but also water heating, cooking, lighting and power is greatly dependent on the occupants. Part of the spread may also be due to the fact that some of the houses used wood for space heating in addition to electricity, but there was insufficient information to include this in the calculation of the total energy consumption. The group of houses with 0.06 mm thick foil does have a slightly higher average total electricity consumption (3% higher) than the group of houses with 0.15 mm thick foil.

In order to access the cost effectivness of using 0.15 mm thick foil rather than 0.06 mm thick foil the average air infiltration rates for the two groups of houses need to be known. Work carried out previously at NBI (see ref.1) used a computer programme called ENCORE to calculate a relationship between the airtightness and the annual energy consumption for ventilation of dwellings. Using meteorological data for a standard year (1964) for Oslo the predicted energy loss over the heating season due to infiltration for an average dwelling with different values of airtightness is shown in figure 9. From this graph it can be seen that the use of 0.15 mm foil rather than the 0.06 mm foil results in a reduction in the calculated infiltration heat loss for the heating season of about 300 kWh/100m^2. Thus for the test house (floor area 260 m^2) the saving is about 760 kWh. At a current cost of 0.35 NoK/kWh the energy costs are thus reduced by about 270 NoK/yr. Current prices for the 0.15 mm and the 0.06 mm foil are 2 NoK/m^2 and 5 NoK/m^2 respectively. This means that the additional cost of using 0.15 mm thick foil on a test house (300 m^2 total foil) is about 900 NoK . The additional cost for the 0.15 mm thick foil is thus recovered in approximately 3.5 years.

Conclusions

The results from our study show that the 5 houses with 0.06 mm polyethylene as the vapour barrier are on average 17 % more leaky than the 5 houses built with 0.15 mm film. The n_{50} values are 2.9 ach and 3.4 ach respectively

After four years the majority of the houses were less airtight with the houses with 0.15 mm film showing an increase in n_{50} value of about 10% compared with an increase of about 7% for the houses with thin film. The houses with thick foil are thus now, on average, only 10% more airtight than those with thin foil.

Direct comparison of the 2 sets of results is however difficult because some of the owners have made changes to their houses which could affect the airtightness. Increased leakage may also be due to thermal movement.

The current Norwegian Building Regulations require an n_{50} value of not more than 4 ach. The average for the houses in the study at 3.2 ach was well within the regulations. This leakage is actually low compared with other measurements on new single family houses and this indicates that the nature of the project and the efforts to make all the participants aware of air tightness may have influenced the results.

The polyethylene sheet thickness did not affect the position of leaks in the houses as far as could be seen using thermography. It also had little effect on the building process and both thickness were equally acceptable to the construction workers.

Only the total annual electricity consumption of each of the houses was measured and this showed only poor correlation with airtightness. The average consumption for the two groups of houses was similar with the houses with thicker sheet having marginally lower consumption, but the individual consumptions showed considerable spread (±15%).

Using a theoretically calculated relationship between airtightness and energy consumption for infiltration, the direct payback period for the thicker polyethylene sheeting was calculated to be about 4 years, which is short compared with the lifetime of the building. The change to 0.15 mm thick polyethylene sheeting thus appears to be cost effective.

ACKNOWLEDGEMENTS

This work was supported by The Royal Norwegian Council for Scientific and Industrial Research. The project was also supported by The Norwegian Plastics Federation.

The author would like to thank Rosemary Rawlings for her assistance in preparing this paper.

REFERENCES

1. Brunsell, J.T.
   Teoretisk beregning av luftlekkasjenes betydning for energiforbruket og ventilation i småhus. Intern arbeidsrapport nr. 229, Norges Byggforskningsinstitutt Oslo 1981.

2. Norwegian Standard 8200. Air tightness of buildings. Test Method.

3. Bankvall, Claes G. Forced convection. Technical Report 1977:21, Revised April 1979. Swedish Testing Institute, Borås.

Figures 1 a and 1 b
Views of the test houses

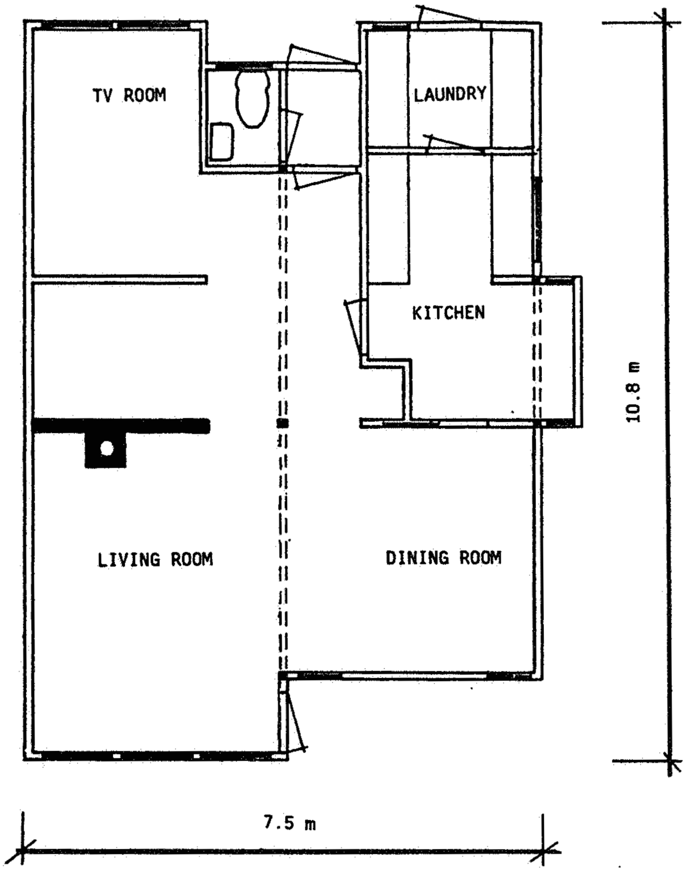


Figure 1 c
Ground floor plan

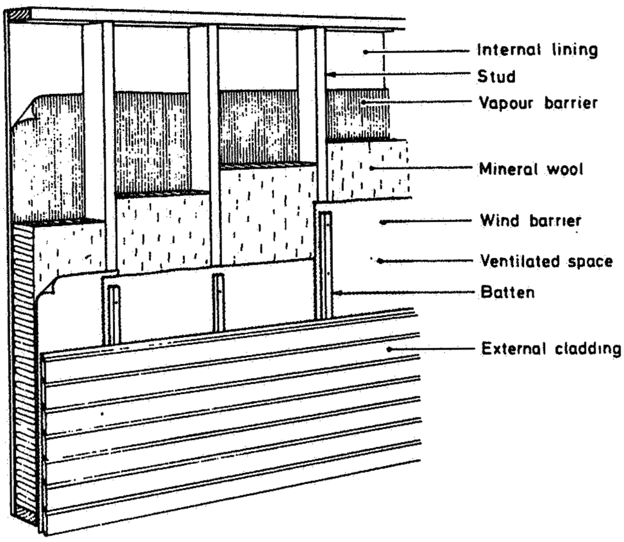


Figure 1 d
Section showing the timber frame wall construction

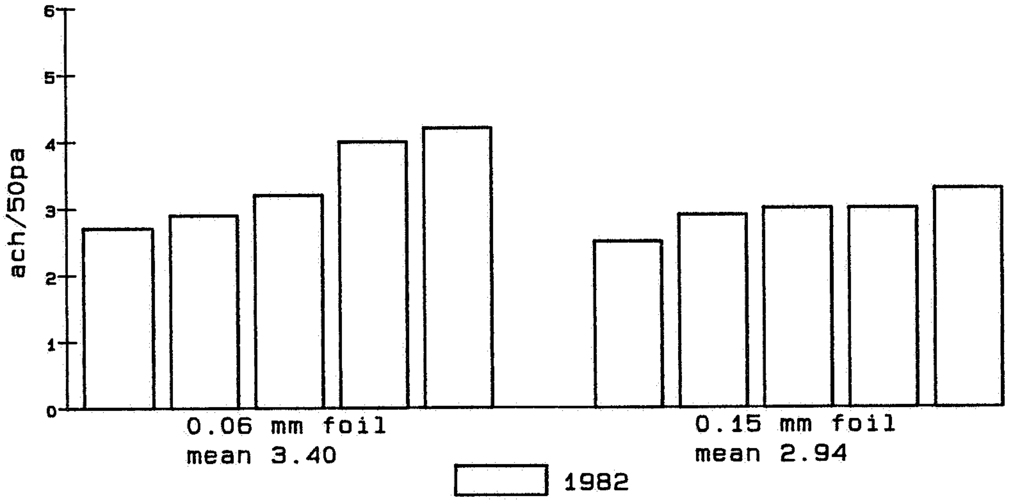


Figure 2
Effect of foil thickness on air tightness

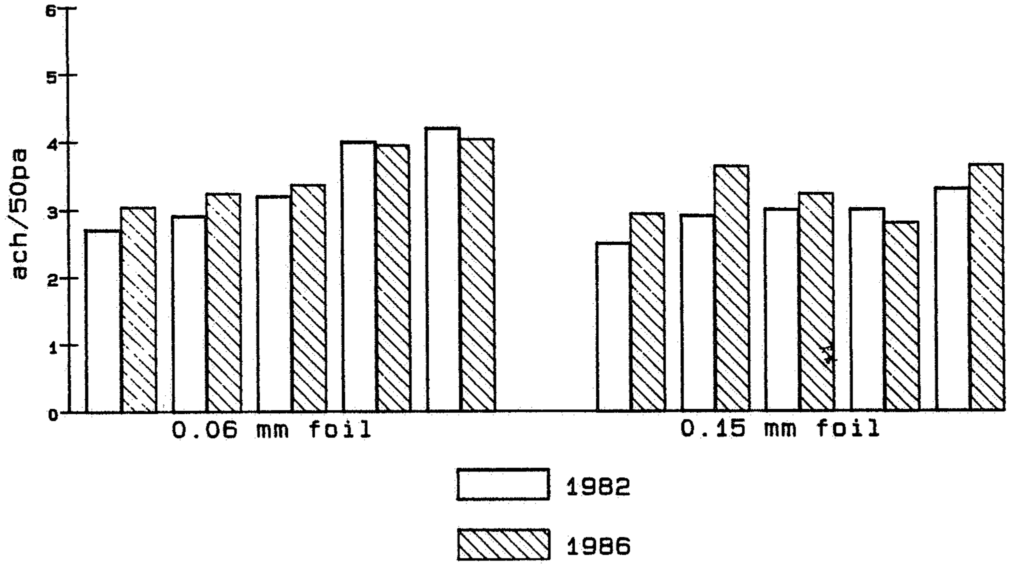


Figure 3
Effect of foil thickness on air tightness
comparison of 1982 and 1986 measurements

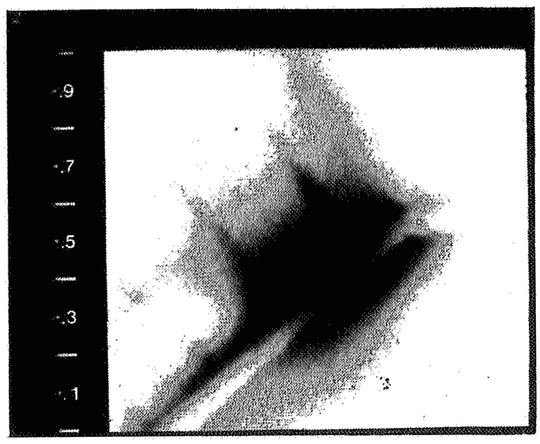


Figure 4
Leak at a vapour barrier joint between a wall and a sloping roof

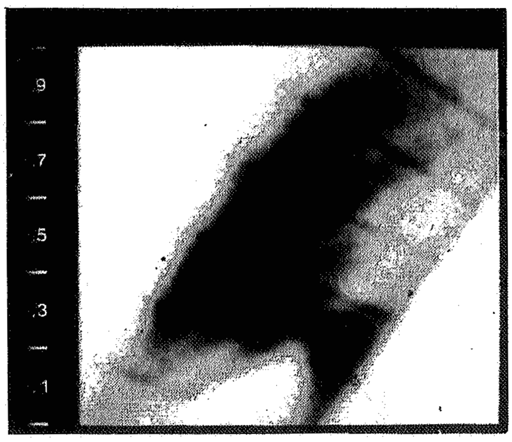


Figure 5
Leak at a vapour barrier joint in the roof

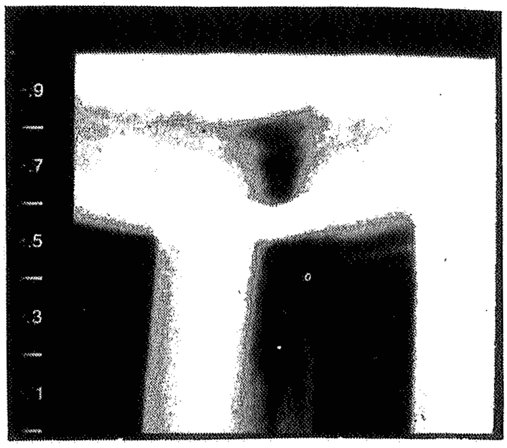


Figure 6
Leak between a window and a wall

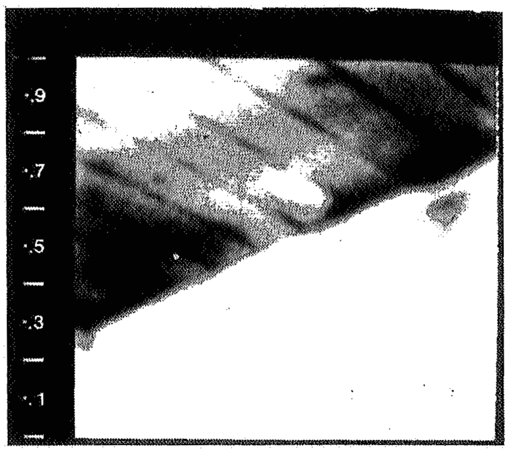


Figure 7
Leak between a wall and an intermediate floor

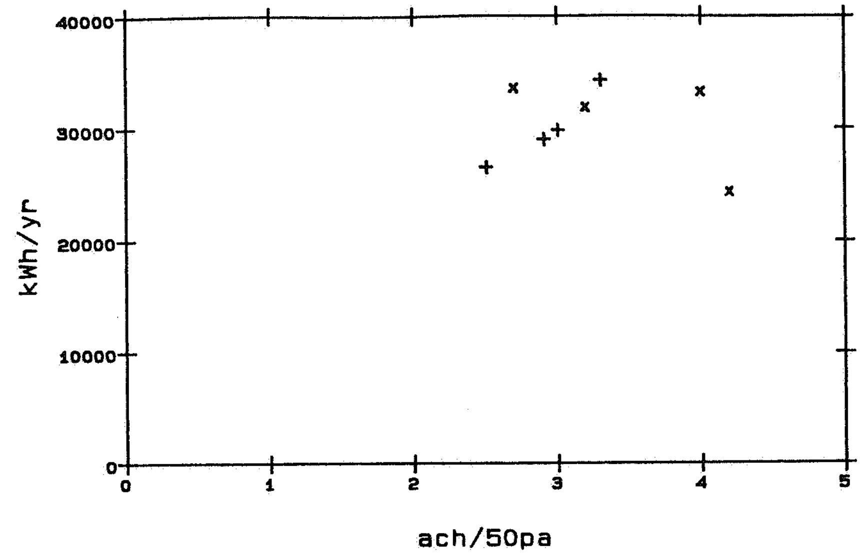


Figure 8
Total annual electricity consumption
vs. air tightness

x 0.06 mm
+ 0.15 mm

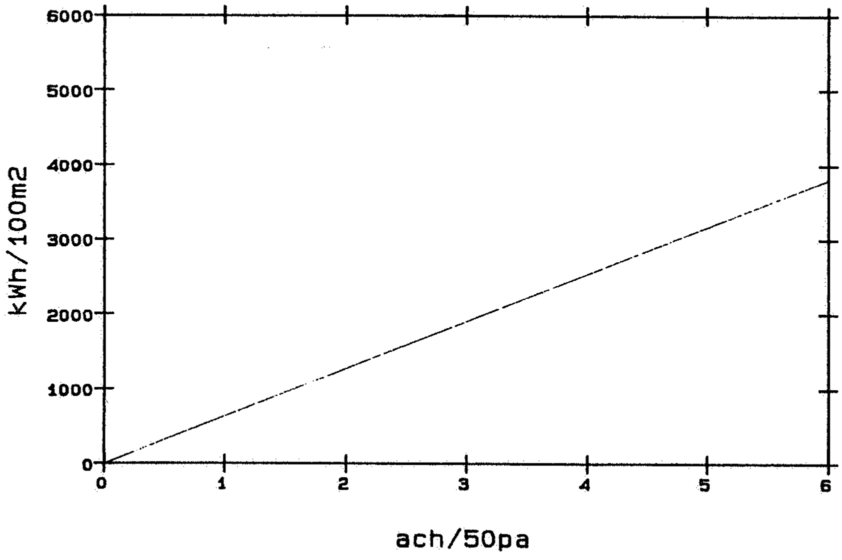


Figure 9
Average annual infiltration energy loss vs. air
tightness for housing in Oslo

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

PAPER S.6

SIMULATION OF CO_2 CONCENTRATION FOR DETERMINING AIR CHANGE RATE

TH. BAUMGARTNER, D BRÜHWILER

EMPA
Abt. Bauphysik
Ueberlandstrasse
CH-8600 Duebendorf
Switzerland

ABSTRACT

The CO_2-concentration of room air provides an indicator for the air quality in spaces without smokers. A classroom with mechanical ventilation has been evaluated for eighteen months using such a technique. These measurements were made within the framework of the research project Gumpenwiesen. A model to calculate the CO_2 concentration as a function of occupancy, activity level of the occupants and air change rate was developed. It was validated using the measurement data. The daily profile of CO_2 concentration and the duration of time when the limit of 1500ppm is exceeded can be predicted. The prediction can be made for any time step and any room. The model is useful as a planning tool for fixing the necessary air change rates for occupied rooms.

1. MINIMUM OUTSIDE AIR SUPPLY RATE

The CO_2-Concentration is a measure of room air quality. The maximum level of CO_2-concentration in room air for hygienic reasons (non smoking area) is given by Prof. Wanner (ETH Zurich) for classrooms as 1500 ppm (Ref. 1). The minimum air supply rate per person can be calculated by using the following formula, where the CO_2-production per person is dependent on the activity of the person.

$$V = \frac{C}{Kzul - Ka} 10^3 \qquad (1)$$

V= Minimum outside air supply rate in m3/h person
C= CO_2-production in l/(h person)
Kzul= max. allowed CO_2-concentration in the room air (ppm)
Ka= CO_2-Concentration in the outside air (300 ppm)

The calculated minimum outside air rate for rooms, where smoking is not allowed, are given in Table 1 for two CO_2-concentration levels.

Activity	CO_2-Production 1/h person	Outside Air Supply Rate for CO_2 max. 1500 ppm m3/h person	 max. 1200 ppm m3/h person
resting	12	10.0	13.3
sitting	15	12.5	16.7
light work	23	20.2	25.6
medium work	30	25.0	33.3
hard work	>30	>25.0	>33.3

Table 1: Minimum outside air supply rate for non smoking rooms (Ref. 2)

2. INSTANTANEOUS CO_2-CONCENTRATION IN A ROOM

In rooms where incoming air is perfectly mixed with room air, the instantaneous CO_2-concentration in the room air can be calculated using the following formula:

$$Kt = Ka + (KO-Ka)\, e^{-nt} + \frac{Ctot\,(1 - e^{-nt})}{n\, I}\, 10^{6} \qquad (2)$$

Kt= CO_2-Concentration in the room air at time t (ppm)
Ka= CO_2-Concentration in the outside air (300 ppm)
KO= CO_2-Concentration in the room air at time 0 (ppm)
Ctot= CO_2-production in the room (m3/h)
n= air change rate (1/h)
I= room air volume (m3)
t= time difference (h)

3. CO_2-VARIATION IN THE MEASUREMENT ROOM

In one of the classrooms of the measured building "Gumpenwiesen", the CO_2-concentration was monitored using a gas analyser during the 18-month measurement period. A typical profile for a day is shown in figure 1. The measured and calculated CO_2-concentrations can also be compared in this figure. The agreement between the two curves shows, that its possible to calculate the CO_2-concentration in the room air at any given time, if one knows the parameters on which it depends (perfect mixing provided):

- number of people
- length of occupancy
- CO_2-production per person (activity)
- air change rate (natural and mechanical ventilation)
- room volume

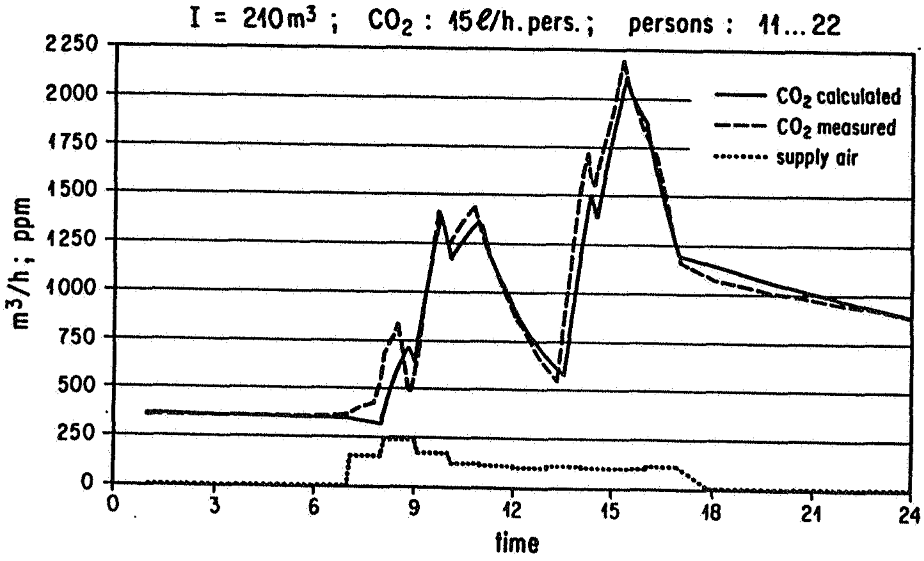


Figure 1: Comparison of measured and calculated CO_2-concentrations for the 13th May 1986.

The cumulative frequency distribution of the the hourly maximum CO_2-concentration in the measurement room is shown in figure 2. When the room air supply system was on, and more than one person was in the room, then the 1500 ppm maximum level was exceeded 30.7 % of the time. The outside air supply of 9 m3/h per person is too small (following table 1: 12.5 m3/h per person is required).

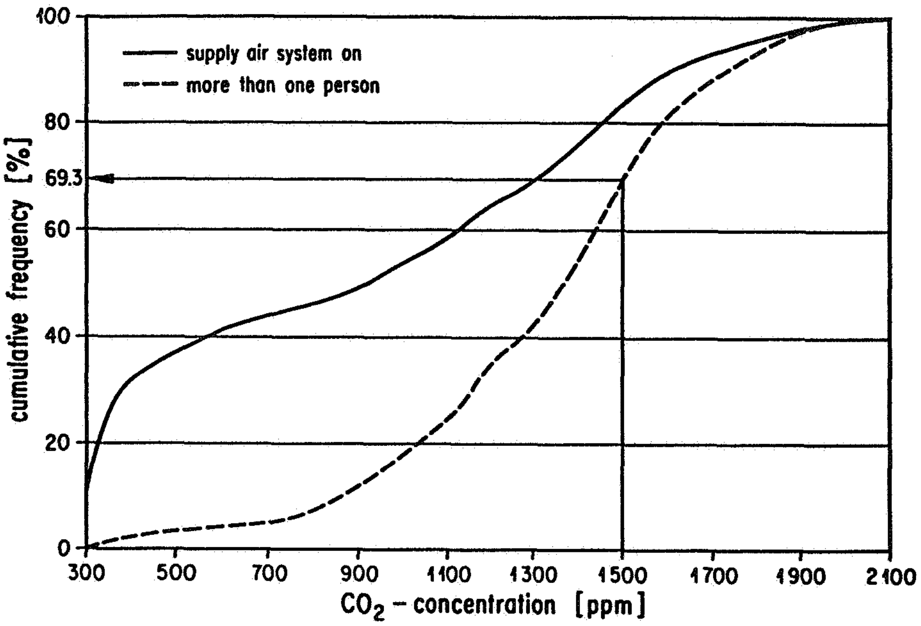


Figure 2: Cumulative frequency distribution of the the hourly maximum CO_2-concentration in the measurement room

The required conditions in the classroom are shown in figure 3 with the occupancy schedule for the room shown in figure 4. The maximum CO_2-concentration of 1500 ppm was never exceeded, if the fresh air intake was 11.2 m3/h person. Due to the breaks, the hourly average of fresh air intake needs not be as high as given in table 1.

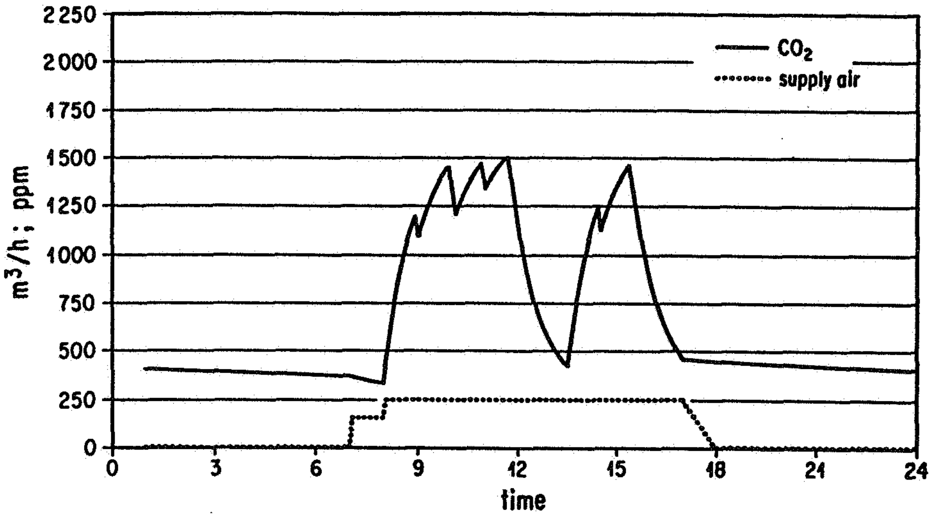


Figure 3: Calculated CO_2-concentration (outside air supply rate: 11.2 m3/h person)

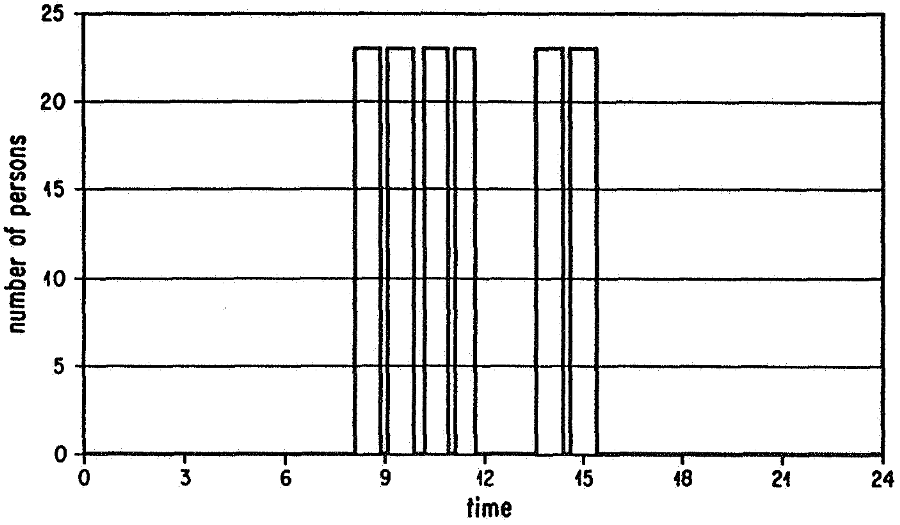
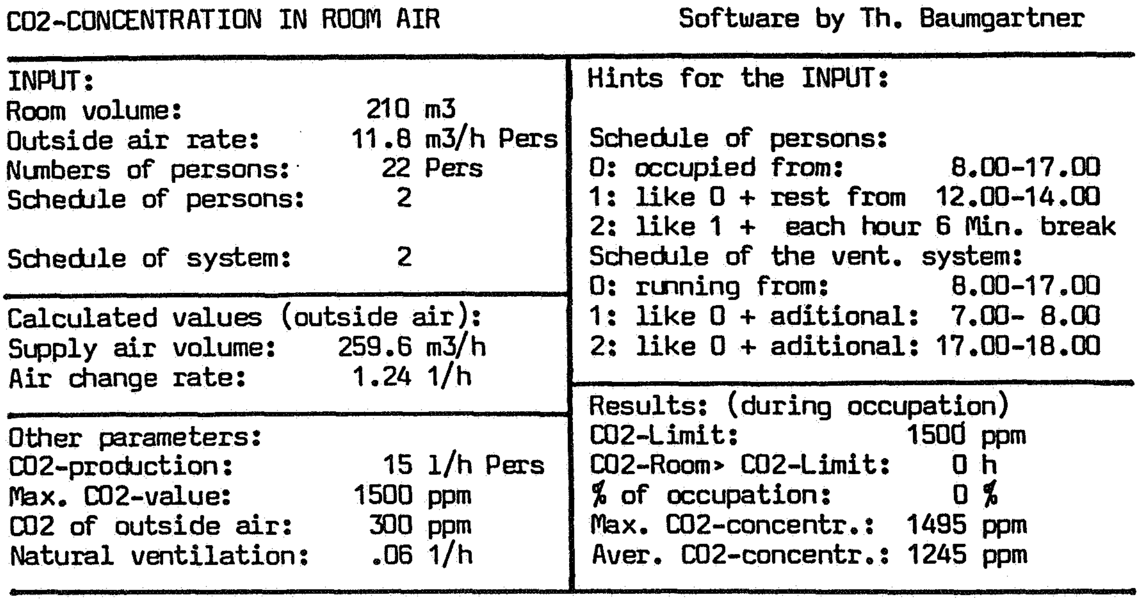


Figure 4: Occupation schedule for figure 3.

4. COMPUTER PROGRAM

The formula (2) was put into a spreadsheet program using a time step of six minutes. With this program it is possible to obtain a realistic view of the CO_2 variation quickly and easily. Especially in rooms where a large number of people is coming and going, the model can be used, to reduce the outside air supply rate.

The software is already used in Switzerland for different purposes.



```
CO2-CONCENTRATION IN ROOM AIR                    Software by Th. Baumgartner
-----------------------------------------------------------------------------
INPUT:                                   | Hints for the INPUT:
Room volume:               210 m3        |
Outside air rate:         11.8 m3/h Pers | Schedule of persons:
Numbers of persons:         22 Pers      | 0: occupied from:         8.00-17.00
Schedule of persons:         2           | 1: like 0 + rest from   12.00-14.00
                                         | 2: like 1 +  each hour 6 Min. break
Schedule of system:          2           | Schedule of the vent. system:
-----------------------------------------| 0: running from:          8.00-17.00
Calculated values (outside air):         | 1: like 0 + aditional:  7.00- 8.00
Supply air volume:       259.6 m3/h      | 2: like 0 + aditional: 17.00-18.00
Air change rate:          1.24 1/h       |------------------------------------
                                         | Results: (during occupation)
-----------------------------------------| CO2-Limit:               1500 ppm
Other parameters:                        | CO2-Room> CO2-Limit:        0 h
CO2-production:             15 1/h Pers  | % of occupation:            0 %
Max. CO2-value:           1500 ppm       | Max. CO2-concentr.:      1495 ppm
CO2 of outside air:        300 ppm       | Aver. CO2-concentr.:     1245 ppm
Natural ventilation:       .06 1/h       |
-----------------------------------------------------------------------------
```

Table 2: Sample input of the spreadsheet program

5. CONCLUSION

In this paper a model was presented to calculate the variation with time of CO_2-concentration in perfectly mixed room air, provided that occupancy, activity level, air change rate and room volume are known. The results of the model were compared with measurements in a mechanically ventilated classroom. The model provides a tool to determine minimum outside air supply rates for rooms with a significantly fluctuating occupancy. This air supply rate is smaller than the one calculated with standard methods. In the future the model may as well be used for other pollutants where the production rate varies rapidly with time.

6. REFERENCES

(1) Wanner H.U., Fecker I, Personal Communication
(2) Handbuch der Klimatechnik, Bd.I, p. 95,
C.F. Müller Verlag, Karlsruhe 1986

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

PAPER S.7

ESTIMATION OF AIR INFILTRATION IN MULTI-STORY BUILDINGS USING WIND TUNNEL TESTS

P. GRABAU and A.G. DAVENPORT

The Boundary Layer Wind Tunnel Laboratory
The University of Western Ontario
Faculty of Engineering Science
London, Ontario, N6A 5B9
Canada

SYNOPSIS

When carrying out pressure tests of models of multi-story buildings in The Boundary Layer Wind Tunnel, the external mean and RMS pressures are measured at 400 to 800 different locations over the building surface. The tests are originally carried out in order to determine the net wind loads for the design of cladding and glazing, but the results can also be used to estimate the internal pressures, and then calculate the air infiltration. Two mathematical models are used to estimate the wind-induced air infiltration in three multi-story buildings. One of the mathematical models is used to estimate the infiltration in the case that the internal pressure is optimally controlled (i.e.when the mean differential pressures all over the building surface equal zero) and the only infiltration will be that due to turbulence. The importance of including the turbulence in infiltration calculations is discussed. The effectiveness and potential advantages of carrying out these studies is referred to as well as the limitations presented by current practices.

1. MODEL AND BUILDING DESCRIPTIONS

The three buildings in question are of different shapes but of similar heights. The surroundings are different as well, roughly they experienced three different exposures to the wind: exposed, intermediate and built-up. Photographs of the models are shown in Fig.1 and Fig.2.

A) The first building is located at a lake shore, and only one other high-rise building is located close to it, so it is exposed. In full scale it rises to 136 meters, and the plan is shaped almost like a four-leaf clover. (Pressure taps are not shown in photographs of building A)

B) The second building is square with cut-off corners. The corners are increasingly cut off near the top. It rises to a full scale height of 184 meters and it is located on a lake shore but a number of high-rise buildings are located north of the building. The terrain is later referred to as intermediate.

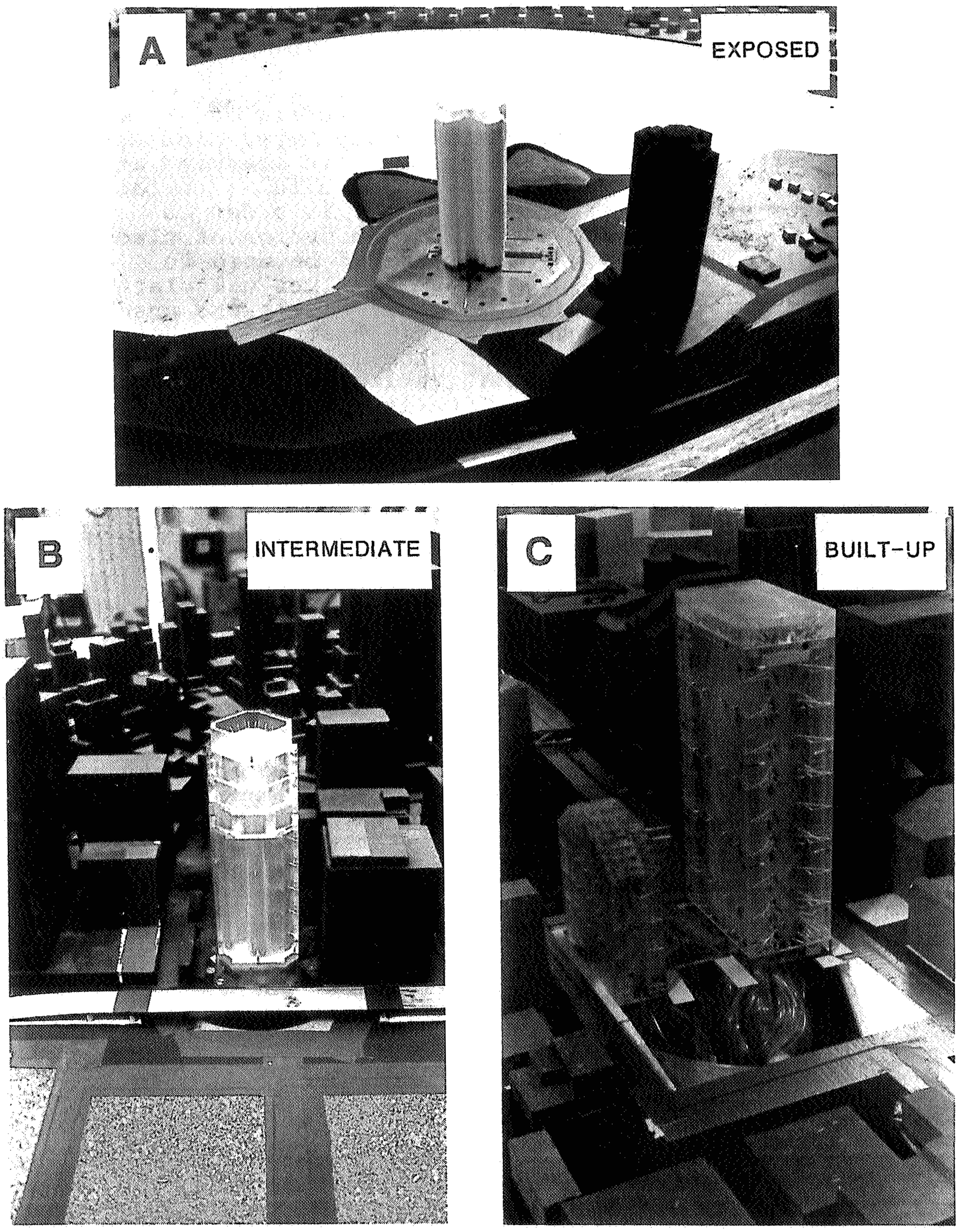


FIG.1 PHOTOGRAPHS OF THE THREE WIND TUNNEL MODELS

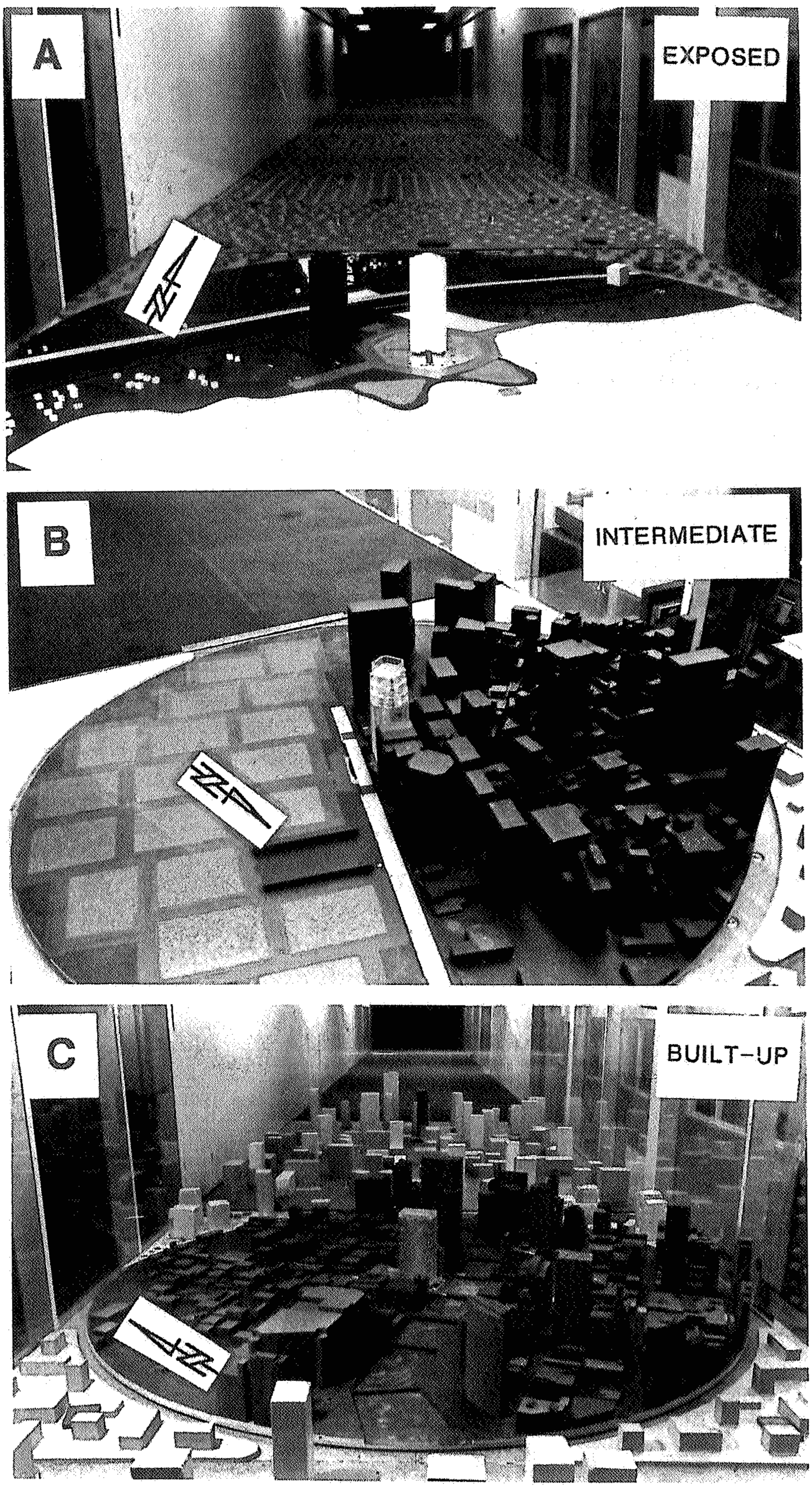


FIG.2 PHOTOGRAPHS OF THE THREE WIND TUNNEL MODELS WITHIN THE PROXIMITY MODELS

C) The third building tested has a full scale footprint of 38 x 65.5 meters and rises to a height of 147 meters. It is surrounded by high-rise buildings, so the terrain is referred to as built-up. (Only the tallest of the two buildings in Fig.1C was used in this study).

2. TEST PROCEDURE

Models of the three multi-story buildings have been tested in The Boundary Layer Wind Tunnel Laboratory at The University of Western Ontario, London, Ontario, Canada, in order to determine the accelerations, deflections and moments of the buildings. The net wind loads acting on the building used in the design of the cladding and glazing were also determined. The test results of the latter are used to calculate air infiltration rates. Models of the buildings in question were built in detail at a scale of 1:500 in plexiglass and equipped with pressure taps for measuring the mean and the root-mean-square (RMS) values of the external pressures at a large number of locations over the surfaces of the buildings. These measurements were taken at 10 degree intervals for a full 360 degree range of azimuths. The model of the immediate surroundings included all major buildings within a full scale radius of 610 meters. The overall textures of the upstream terrains were modelled but not the detailed geometry.

3. INSTRUMENTATION

Measurements of wind-induced surface pressures at a point are accomplished by allowing the surface pressure to act on a transducer which provides an electrical analogue of the pressure. The electrical signal is then processed using standardized instrumentation techniques and digitized to allow on-line analysis by a small computer and peripherals.

In practice, the transmission of surface pressure to the transducer is complicated in two ways. First, there are usually a large number of measuring positions requiring the use of multiple pressure switches - in this case scanivalves - to provide a reasonable trade-off between a large number of transducers and a lengthy testing time. Second, the model is generally too small to allow the pressure switches and transducers to be very close to the measuring locations. The resulting use of long lengths of pneumatic tubing leads to modification of the pressure at the transducer compared to that at the model surface.

These problems are dealt with as follows: pressure taps on the model are connected pneumatically to one of several scanivalves, each capable of handling 48 different taps. Each scanivalve contains a pressure transducer to which individual taps are connected on computer command. The pneumatic connection between model and scanivalve is typically 1/16'' ID plastic tubing containing a restricting insert of small bore at a specific point along its length. The function of the restrictor is to add damping to the resonant system made up of the pressure tube and the connecting volume adjacent to the pressure transducer. The resulting pressure system with two-foot long tubes responds with negligible attenuation or distortion to surface pressure fluctuations with frequencies up to about 100 Hz. Although some response is obtained for signals of several hundred Hertz, these higher frequencies suffer increasing attenuation.

The on-line digital data acquistion system, consisting of a small computer and peripherals, simultaneously samples the signals from each of the pressure transducers at a rate of about 500 times per second for sixteen inputs. Typically, sampling is continued for a period of up to about a minute in real time during which the computer records, for each input, the maximum and minimum values that occur, and computes the mean and the RMS values. Other statistics such as probability distributions can also be gathered. The reference dynamic pressure, usually measured in the free stream above the boundary layer, is monitored similarly. At the end of the sampling period, the measured maximum, minimum, mean and RMS pressure for each channel are converted to pressure coefficients by dividing each by the reference dynamic pressure. These are then stored on disk for later analysis. In addition to the sampling and on-line calculation, the computer controls the experimental hardware such as the stepping of the scanivalves, the rotation of the turntable on which the model is mounted and the wind speed.

4. THE MATHEMATICAL MODELS

Tamura and Shaw[4] and Shaw[5] developed some valuable information on the leakage of Canadian buildings using measurements of the flow into buildings from a fan pressurization system. They found the leakage proportional to $c(\Delta p)^n$ where Δp is the pressure difference, c an empirical flow coefficient and n an empirical flow exponent. The flow coefficient, c, was found to have a mean and range of 0.018 ± 0.010

[m/s/(kPa)$^{-0.65}$]. These values were found from the testing of 8 high-rise buildings. The flow exponent, n, can vary over the range 0.5 to 1.0, but it appears to converge on a value of 0.65. In the following the value of c is set to 0.018 [m/s/(kPa)$^{-0.65}$], and the value of n is set to 0.65. The three mathematical models used in this study, are derived from this expression and the model to calculate total infiltration described by Davenport and Surry[3] :

$$Q_{in} = \int_A \int_{z_1}^{\infty} c(r)\{\Delta p(r,z)\}^n \, f_z(z)dz \, dA(r)$$

where the fluctuations of the pressure are described in statistical terms by a probability density function $f_z(z)$ that can be taken as Gaussian. The parameter z is a random variable with mean zero and standard variation of unity, and z_1 is the value of z at which $\Delta p = 0$. The flow coefficient, c(r), is a function of the position, r, since the leakage is, in practice, not uniformly distributed.

4.1 The internal pressures

The time average internal pressure coefficients for distributed leakage are found by using the continuity condition $Q = 0$, and the two first terms of the Taylor expansion as described by Davenport and Surry[3] :

$$C_{pi} = E(C_p) - m \, RMS(C_p) \int_{-\infty}^{\infty} \theta \ln|\theta| \, f_\theta(\theta)d\theta$$

in which the reduced pressure term is represented by

$$\theta = (C_p - E(C_p))/RMS(C_p).$$

$E(C_p)$ is the expected value of the external mean pressure coefficient, and it is a first approximation to C_{pi} and the second term gives a correction usually of around 10 %. The parameter $m = 1 - n$ and $\theta \ln|\theta|$ is a weighting function.

4.2 Model 1

In this model the turbulence is not included in the infiltration calculations but only the mean differential pressures. The velocity pressure is $q = 1/2\ \rho\ V^2$ where ρ is the density of air and V the mean velocity, and when expressing Δp by $q\ \Delta C_p$ and when n is the number of pressure taps, the equation for the total leakage flow into the building is:

$$Q_{in} = c\ q^{0.65} \sum_{i=1}^{n} A_i\ \Delta C_p{}^{0.65} \quad (\text{for } \Delta C_p > 0)$$

where A_i is the tributary area and the summation is done for those areas where $\Delta C_p > 0$ only.

4.3 Model 2

In this model the turbulence is included, and the equation is

$$Q_{in} = c\ q^{0.65} \sum_{i=1}^{n} A_i \int_0^{\infty} z^{0.65}\ f_z(z)dz$$

where

$$f_z(z) = (1/(\mathrm{RMS}(C_p)\sqrt{2\pi}))\ \exp[-0.5(z-\ \Delta C_p/\mathrm{RMS}(C_p))^2].$$

4.4 Model 3

This model is the same as model 2, but the mean differential pressure coefficients (ΔCp) are all set equal to 0, so the model simulates the infiltration corresponding to the lowest possible air change rates, when the internal pressure is controlled, but not fluctuating. In other words the only infiltration is that due to the turbulence.

$$Q_{in} = c\ q^{0.65} \sum_{i=1}^{n} A_i \int_0^{\infty} z^{0.65}\ f_z(z)dz$$

where

$$f_z(z) = (1/(\mathrm{RMS}(C_p)\sqrt{2\pi}))\ \exp[-0.5(z-0/\mathrm{RMS}(C_p))^2].$$

4.5 Infiltration and Exfiltration Estimates

The calculations of the internal pressure coefficients are not exact. In order to obtain a better estimate of the infiltration into the building the following is done. First the infiltration is calculated as indicated above and then the exfiltration is calculated by reversing the sign of the differential mean pressure coefficients, and then recalculating the infiltration. The mean of these two is taken to be the best estimate of the infiltration. The difference is not found to be significant though.

5. RESULTS FROM THE THREE MATHEMATICAL MODELS

In Fig.3 are the results from model 1 and model 2 for gradient wind speed equal to 10, 20 and 30 m/s. The overall influence of including the turbulence does not seem very significant, but including the turbulence seems always to result in slightly higher infiltration rates. When Building B was subjected to winds from the north, the inclusion of turbulence resulted in more than twice as much infiltration. This is a significant difference,though. The results of model 3 are shown in Fig.4 for the same wind speeds as those looked at in the previous models. In order to determine how much the infiltration rates will decrease, the results from model 2 are shown again. It is, of course, impossible to control the internal pressure so that it will equal the external mean pressure at all points of the exterior wall, but by individual pressure control in all rooms, one can come close. The results from model 3 is, therefore, the absolute minimum air change rates we can obtain by internal pressure control. Since the infiltration rate always seems to be at least half as much for model 3 as for model 2, a better air barrier system might be the way forward rather than a better pressure control. None of the models above includes the stack effect, which is a significant factor for high rise buildings. The results show that we can expect only a minor reduction in the overall wind-induced infiltration rate in the case of a building located in a built-up area. For wind coming from sea or lake, we can expect to halve the infiltration rate.

6. AN EXAMPLE OF A WIND CLIMATE

Since the overall infiltration rates can vary by a factor four or more due to changes in wind direction alone, the annual heat losses and heat gains for a building will be very dependent on what the predominating wind direction is for the area in question. The wind climate for Columbus, Ohio is taken as an example. There is a predominating gradient wind direction between 225 and 270 degrees (Southwest to West). The wind data from records in the period 1960 to

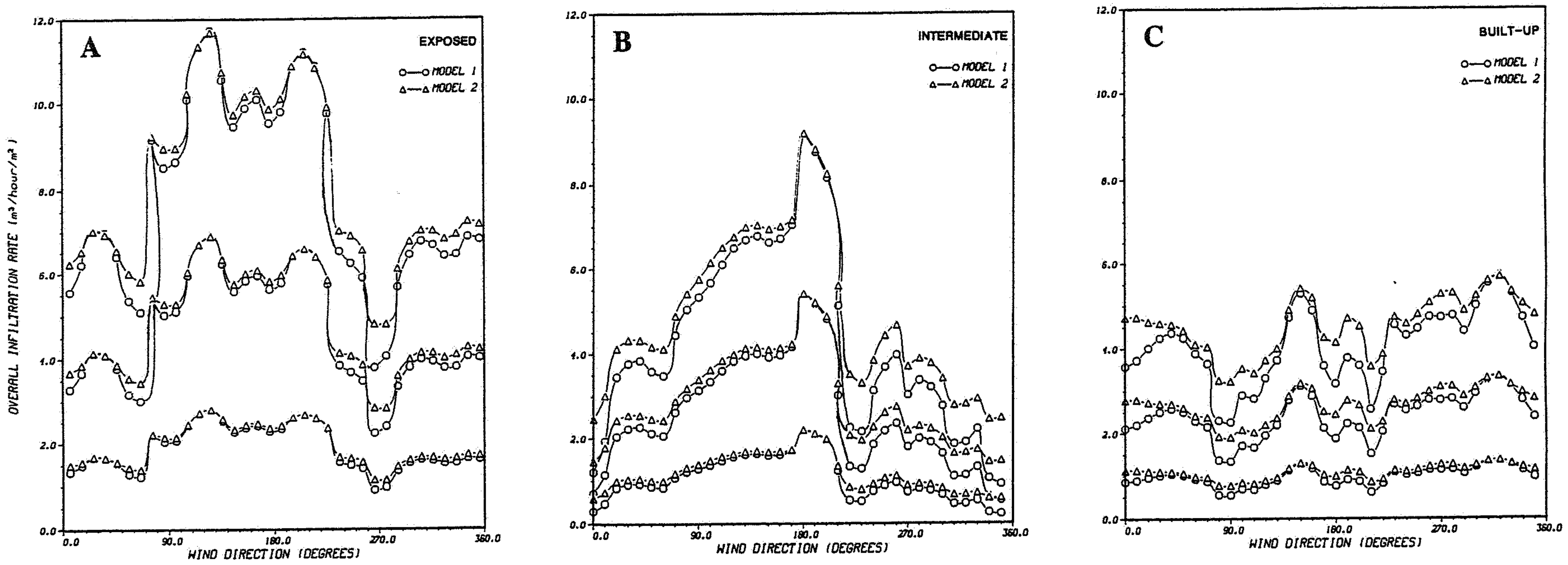


FIG.3 THE VARIATION OF OVERALL INFILTRATION RATES WITH GRADIENT WINDSPEED.

THE THREE CURVES CORRESPOND TO WIND SPEEDS OF 10, 20 AND 30 m/sec.

THE TURBULENCE IS INCLUDED IN MODEL 2 BUT NOT IN MODEL 1

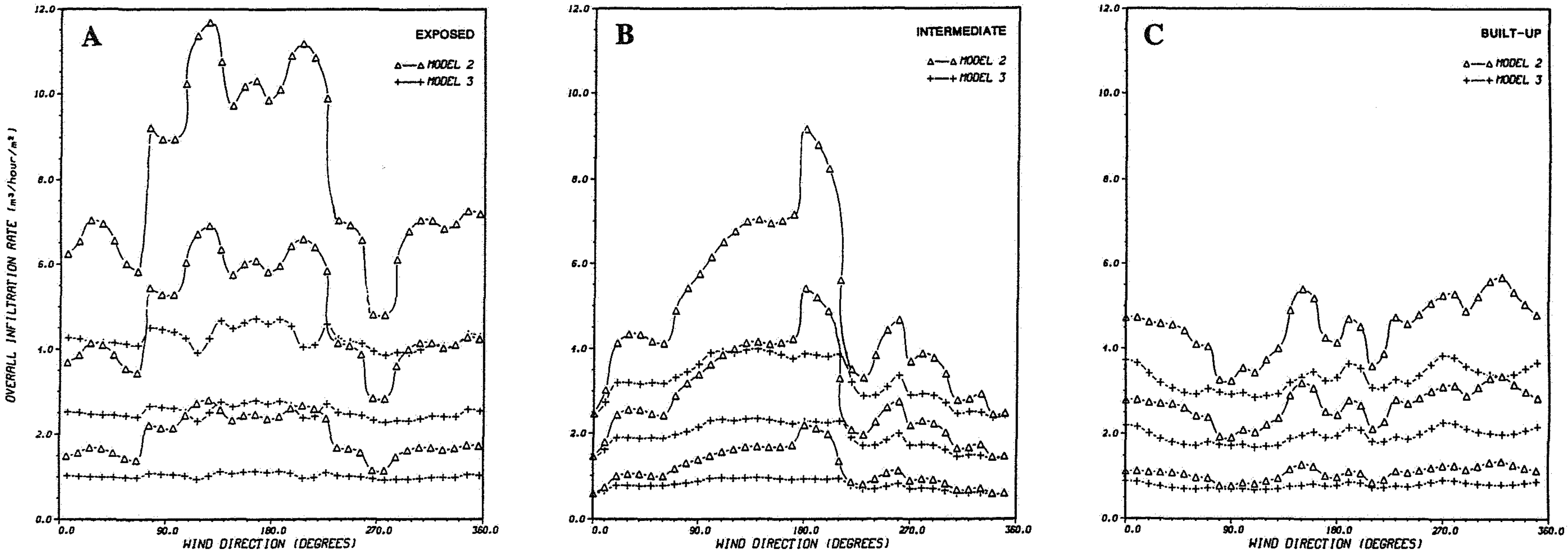


FIG.4 THE VARIATION OF OVERALL INFILTRATION RATES WITH GRADIENT WIND SPEED. THE THREE CURVES CORRESPOND TO WIND SPEEDS OF 10, 20 AND 30 m/sec. MODEL 3 INDICATES THE LOWEST RATE POSSIBLE WHEN CONTROLLING THE INTERNAL PRESSURE. IN MODEL 2 THE INTERNAL PRESSURE IS NOT CONTROLLED

1978 are fitted to a Weibull distribution as described by various authors (ex. Conradsen et al[1]and Davenport[2]) and Fig.5 illustrates the resulting distribution. P(>Vg) = the probability of exceeding the hourly mean gradient wind speed, Vg, within an azimuthal sector of 10 degrees.

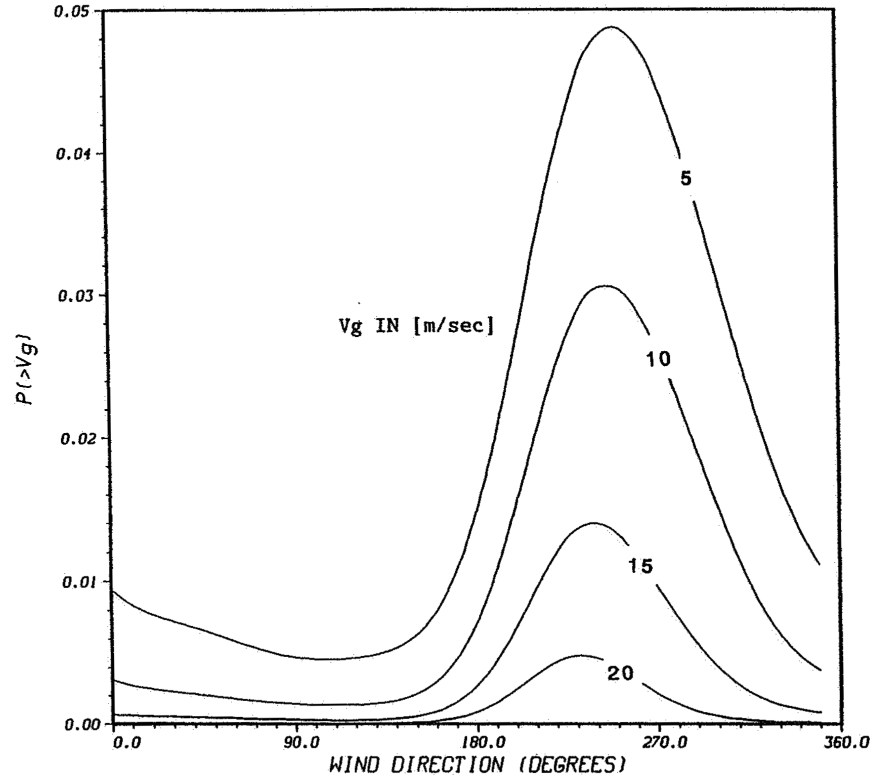


FIG.5 PROBABILITY OF EXCEEDING THE HOURLY MEAN GRADIENT WIND SPEED, Vg, AS INDICATED, WITHIN AN AZIMUTHAL SECTOR OF 10 DEGREES FOR COLUMBUS, OHIO

The results from the infiltration calculations (model 2) are combined with the probability distribution in Fig.6. Also in Fig.6 are the same results but with the probability distribution turned 180 degrees. The probability distribution is seen to be the most dominating factor. Since most of the air infiltration will take place on the wind ward walls, more heating and cooling is needed in certain areas of the building. Designing HVAC systems in high-rise buildings, by including informations as those in FIG.6, could be beneficial.

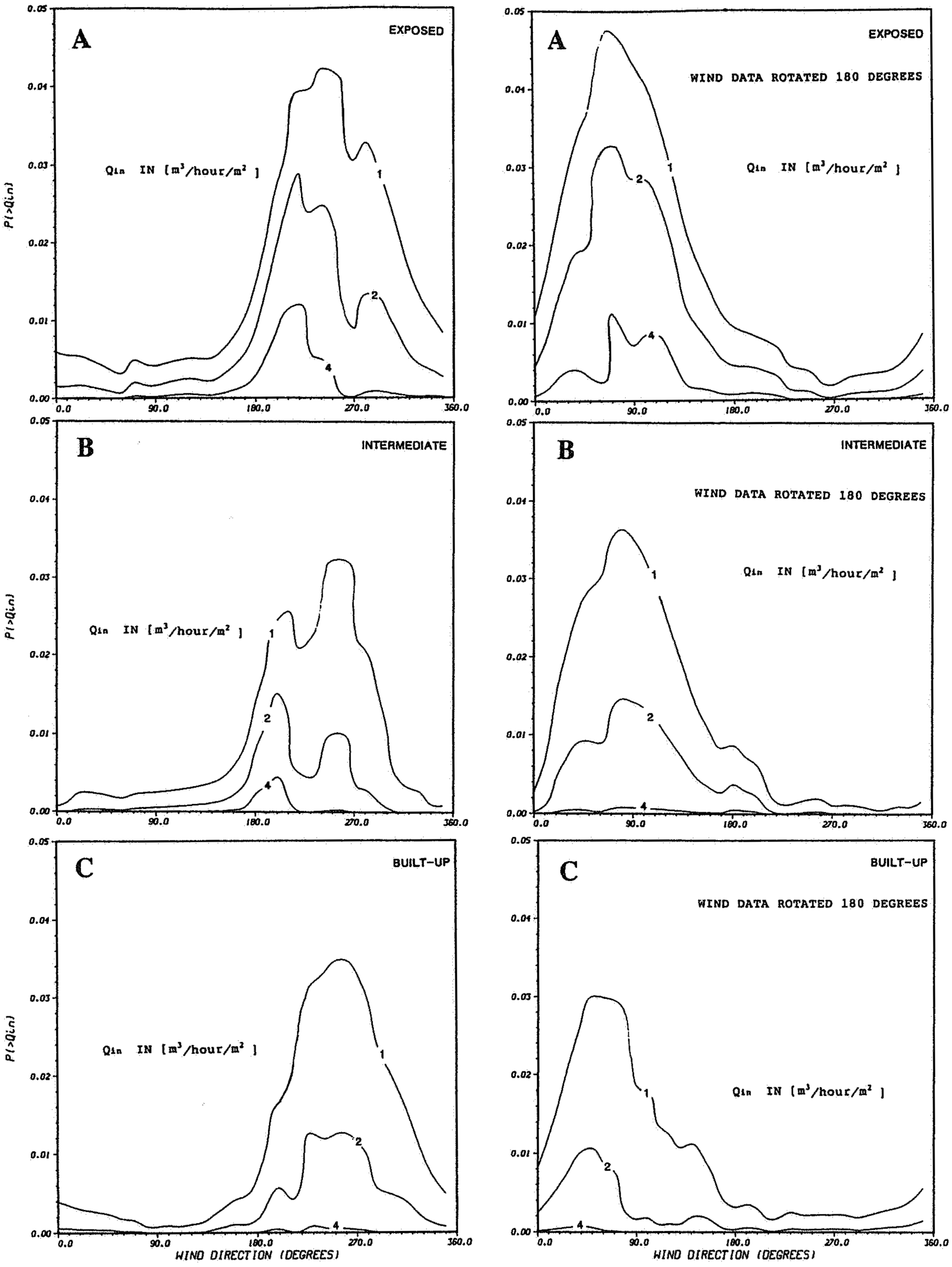


FIG.6 PROBABILITY OF EXCEEDING THE HOURLY MEAN INFILTRATION RATES AS INDICATED (BY CONTOURS 1, 2 AND 4) WITHIN AN AZIMUTHAL SECTOR OF 10 DEGREES, WHEN USING THE WIND SPEED DISTRIBUTION IN FIG.5 AND THE SAME DISTRIBUTION TURNED 180 DEGREES

7. CONCLUSIONS

Wind induced overall infiltration rates on a high-rise building can vary by a factor of four or more for different wind directions due to difference in exposure.

Estimating overall infiltration rates from mean differential pressures only, will result in a slight underestimate.

A simple approach to internal pressure control would, under some circumstances, reduce the wind induced air changes by roughly half.

Information on the wind speed and direction and the infiltration likely to result can be exploited using zone heating and cooling to improve the efficiency of the HVAC system.

8. REFERENCES

1. Conradsen, K., Nielsen, L.B. and Prahm, L.P., "Review of Weibull Statistics for Estimation of Wind Speed Distributions",Paper, Journal of Climate and Applied Meteorology, Vol. 23 No. 8 Aug. 1986, pp 1173-1183.

2. Davenport, A.G.,"The Dependence of Wind Loads on meteorological parameters", Theme paper, Wind Effects on Buildings and structures, International Research- seminar, Ottawa, Canada, september 11-15, 1967. Proceedings, Toronto, University of Toronto Press, 1968, Vol. 1. pp. 19-82.

3. Davenport, A.G. and Surry, D.,"The Estimation of Internal Pressures Due to Wind With Application to Cladding Pressures and Infiltration", Paper, Air Infiltration Center - Wind Pressure Workshop, Brussels, Belgium, 21-22 March 1984.

4. Tamura, G.T. and Shaw, C.Y.,"Studies of Exterior Wall Air Tightness and Air Infiltration of Tall Buildings",ASHRAE Transaction, Vol 82, Part 1, New York, 1976.

5. Shaw, C.Y.,"Air tightness: Supermarkets and Shopping Malls", ASHRAE Journal, Vol. 23, March 1981.

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

PAPER S.8

THE MOISTURE LOAD IN DWELLINGS AS A FUNCTION OF THE LAYOUT OF THE ROOMS SHOWN BY GROUND PLANS

PROF. DIPL.-ING. H. TRÜMPER, DIPL.-ING. K. HAIN

Universität Dortmund, Abteilung Bauwesen, Postfach 50 05 00,
D-4600 Dortmund 50, West-Germany

SYNOPSIS

Measurements in some dwellings show differences of the absolute humidity as a function of the kind of ventilation (only natural or mechanical exhaust air or balanced ventilation) and the position of the single rooms, especially of the bedrooms. Therefore is investigated into the expected moisture transport in two different ground plans.

The main humidity production is in the kitchen and bathroom. If kitchen and bathroom are on the outer side, the dwelling is loaded with this moisture through the main wind direction. This counts especially for bedrooms, because through this moisture load on the day there can appear peaks in the night.

By the right layout of these rooms in the ground plan you can relieve the dwelling of moisture load as far as possible.

If kitchen and bathroom are in the interior of the dwelling, only the effectiveness of the natural or mechanical exhaust air counts for the transport of moisture. By the right construction of the exhaust air, this air can reduce the moisture even in the living- and bedrooms.

1. INTRODUCTION

The National German building code only say that a dwelling`s ventilation has at least to be guaranteed by natural cross ventilation. In fact, also before this code was set up, there has always been a regard for dwelling ventilation in the way that every room of an apartment could be provided with supply air coming through opened or not airtight closed windows or out of other rooms in the dwelling, respectively.

The last two decades show a development in building construction favorizing smaller dwellings, especially apartments of a size of 30 - 40 m^2. Additionally those apartment buildings were economically constructed as blocks with ground plans of depth up to 15 m. In the interior of the dwelling windowless sanitary rooms like bathroom and W.C. are situated. Consequently, first we had to accept bathroom and toilet as interior and windowless rooms; finally - with the late edition of the building code - we have come to kitchens, situated in the dwelling`s centre and without windows, too.

However, these rooms now being windowless an additional ventilation according to the building code becomes necessary. This code, written down in DIN 18 017, describes a shaft ventilation with natural air draught or an additional supporting ventilator.

The efficiency of this system for the interior rooms depends on:

- a sufficient natural air draught trough the shaft
- the operation time of the possibly installed ventilator in the day`s course
- the amount of air which is additionally provided as supply air out of these rooms which still have natural cross ventilation

Experience shows that those shaft ventilation systems - in possible combination with ventilator - for the interior rooms have also improved the ventilation of the whole dwelling in general.

In case of a greater amount of exhaust air load arousing from many visitors to the user, people smoking or an exagerated heating up of the rooms a sporadic ventilation by a wide opening of the windows for a short time is still absolutely necessary, though.

The basic ventilation by the exhaust system reaches an air change rate of 0,3 - 0,5 per hour. A ventilation by window opening comes up with an air change rate of 1,5 - 3,0 per hour depending on the wind (direction and velocity) and the opening time of the windows.

In the last 10 years the function of the ventilation systems for the interior sanitary rooms turns more bad, because the construction of new windows becomes more airtight as well in new buildings as in older buildings through reconstruction. Therefore there are only little possibilities for the air to come through the envelope and the cross ventilation doesn`t exist in a adequate proportion.

2. PROBLEMS OF VENTILATION CONCERNING A THREE ROOM DWELLING, PARTIALLY FINANCED WITH GOVERNMENT SUBVENTION

The apartment consists of three rooms, dining place and kitchen and interior bathroom and toilet.

Figure 1 shows a ground plan with cross ventilation according to west - east direction. With the wind coming most often from southwest till northwest one can expect that the stream of natural air will take its way from dining place, kitchen and living room over the floor into parents` and children`s room. The points of exhaust ventilation in kitchen, bathroom and toilet will be even more efficient, if during periods of high load of exhaust air this air is drawn off additionally by a mechanical system. Even if this mechanical aid is used just temporarily, an air stream from the bedrooms to the ventilation points as a sort of supply air for the interior rooms can arouse.

In case of changing wind direction or an insufficient or even missing ventilation in bathroom, W.C. and kitchen, it can happen - as shown by the turned around arrows in figure 1 - that the supply air stream is led from bedrooms to the living area.

The figure 2, a) - c), presents a cut through the ground plan of figure 1, showing the possible air streams through the rooms. The minimum demand of the national building code is a shaft ventilation system with natural air draught in bathroom and W.C. There is no definite rule for the kitchen as long as being provided with windows - here through the dining place - but experience recommends at least the same treatment for the kitchen as for the interior sanitary rooms.

The function of exhaust ventilation with only natural air draught mainly depends on the length of the shaft and the difference in density between inside and outside air.

The stream of supply air as well as the stream going through the dwelling, which implies also the continous stream of exhaust air to the ventilation points, is in the meantime ruled by wind direction, wind intensity and by the pressure difference as described in figure 2 for the cross ventilation. The consequence of wind calm is stagnation of the streams.

The figures 3 and 4 show in addition to the possible air streams the corresponding humidity streams. As long as cross ventilation reached the level of the air change rate 1,0 - 2,0 per hour, humidity was just regarded secondarily. With air change rates now being 0.3 - 0.5 per hour only, we have to concentrate our special regard on humidity streams, though, since there load has increased through new windows. Wrong behaviour of the users may influence a possible damage to the building by condensation of humidity with a final development of mould growth.

So far, in figures 1 - 4, we saw today`s technical possibilities concerning exhaust ventilation for those cases in which one wants to fulfill just the minimum demand of our building code.

The exhaust ventilation guarantees a constant standard of hygienics in the rooms without influence on or consideration of the building`s heating. Exhaust air will be drawn off with its complete heat capacity depending on the room temperature respectively. This means that all the time a certain amount of heat will get lost to the atmosphere. Consequently we always have to substitute the infiltration heat loss arousing from this type of ventilation system.

2.1 Order of natural exhaust shaft ventilation

The figure 5 presents in a cut through a building the function of a natural exhaust shaft ventilation. The shafts having the heights h_1 = 5,00 m and h_2 = 8,00 m.

The tables of figure 6 present values of the supply air stream by window rabbets as a function of several a-values.

In figure 7 values of air volume transport through shafts are plotted as a function of outdoor temperature range from - 10 °C up to + 20 °C and of wind velocity at 4 m/s in the diagram and are given in the table.

The values of the tables in figure 6 and 7 show that, for instance, the stream of supply air in the line with wind velocity of 4 m/s will be with an a-value of 1,0 = 1,24 m^3/h,m. Presuming a total length of 15 m for the window rabbets of the apartment, considered in the ground plan of figure 1, and furthermore presuming the outside air stream coming from one side with positive pressure only, an amount of 19 m^3/h of outside air as supply air for the dwelling will result.

The ground plan in figure 1 comprehends for kitchen and for bathroom and toilet one shaft each. For a sufficient exhaust ventilation of the dwelling an air change of 2 x 60 m^3/h = 120 m^3/h is necessary.

2.2 Summary

The outdoor temperature ranging at + 5 °C and below and the wind velocity reaching 4 m/s those two shafts described in figure 5 cannot guarantee the necessary air change.

Our experience proved that in such a constellation either additional window opening or support by a ventilator, which has to be operated at least temporarily, are necessary to keep up the minimum conditions.

2.3 Streams of air and humidity in a dwelling with kitchen and bathroom on the outside

In figure 1 kitchen, bathroom and toilet were arranged as interior rooms. The kitchen, however, designed as kitchen-dining room can receive window air and light from the dining place with the need of a shaft ventilation system.

Now in figure 8 we see a ground plan in which both kitchen and bathroom are lying on the outside, so they have windows. Therefore the necessary air change can be provided by opening the window only.

Values concerning the ground plan in figure 8 of supply air stream, which depends on the wind conditions, and values of humidity streams are given in figure 9.

Supply air finds its way into kitchen, bathroom, parents` bedroom and then loaded with humidity and wasted air it streams as exhaust air through living room and children`s room to the envelope of the building with the negative pressure.

Figure 10 shows the change in wind direction and followingly in pressure a situation results, in which exhaust air stream and humidity stream as well have changed, too, according to the new direction.

Both figures 9 and 10 prove that in this dwelling there will always be a certain disturbing load of humidity and several odours. Figure 9 reveals the somewhat inconvenient situation, especially for the users of living- and children`s room as far as the air conditions are concerned.

2.4 Streams of air and humidity in a dwelling with mechanical ventilation

Considering the haft ventilation above, it was mentioned that in case of an insufficient function of natural draught an additional ventilator becomes necessary.

The shafts in the ground plan of figure 1 being equipped with exhaust ventilators one can reach, presuming a sufficient arousel of negative pressure, a supply air stream through the window rabbets on all sides and not only on the side of the building with the positive pressure.

Looking back to the figures 3 and 4, 9 and 10, we realize that there we had an effective stream of supply air on the side with positive pressure, only.

Completing the ground plan of figure 1 by installation of ventilators we find the air and humidity streams presented in figure 11.

The supply air streaming into the apartment takes the exhaust and humidity load out of the living-, parents`- and children`s room over to the ventilation points in the kitchen and in the bathroom and toilet, where it is drawn off.

There is no possibility that - as with the natural shaft ventilation system - exhaust air may stream from the sanitary rooms back over to the living area. However, we cannot exclude the eventual necessarity of an additional window ventilation in terms of sporadic ventilation in those cases of an overflow of exhaust air, for instance many visitors or smokers being in the rooms. If it is made use of this sporadic ventilation, there again we have to cope with the disadvantage of exhaust air being exchanged between the rooms.

So far we have proved that the mechanical exhaust ventilation compared to just natural air draught leads to a considerable improvement of air and humidity values in a dwelling.

That situation of a mechanical exhaust ventilation can be improved even more by installation of a balanced ventilation.

The figure 12 presents, refering to the ground plan of figure 1, the arrangement of a balanced ventilation system, comprehending a mechanical exhaust and a mechanical supply ventilation as well. Air and humidity streams shown in figure 12.

The whole volume of air stream is 180 m^3/h for supply and exhaust air respectively. This means an air change rate of 0,8 per hour for the dwelling.

		supply air		exhaust air
	normally	switch over		
rooms		day	night	
	m^3/h	m^3/h	m^3/h	m^3/h
living room	60	80	40	--
dining room	40	60	20	--
kitchen	--	--	--	100
children`s room	40	20	60	--
parent`s room	40	20	60	--
bathroom	--	--	--	50
toilet	--	--	--	30
amount	180	180	180	180

The table shows the volumes of the streams related to the several rooms.

A reduction of the volumes of air stream during the night period may be performed by appropriate mechanical or electrical connections.

In the summer month the mechanical supply ventilation can be switched off also during day time while it is then substituted by window ventilation.

Besides the fact that balanced ventilation will guarantee a continuous drawing off of humidity and exhaust load, there is the possibility to combine it with a heat recovery.

2.5 Values of humidity measured in dwellings with different ventilation systems

The diagrams of figure 13 present values of absolute humidity in the course of four consecutive days in January. The values were measured in two dwellings with the type of ground plan shown in figure 1, both having shaft ventilation in bathroom and toilet, however, no one in the kitchen.

One can well perceive the different behaviours of the users concerning the window opening. The apartment 3. floor left has the highest values of absolute humidity, so one may conclude that there had been little window ventilation by the users.

The living room has relatively low values of humidity. Users affirmed our presumption that the room most likely had been used rather seldom.

The curves of figure 14 show values of absolute humidity measured in two dwellings, one of which was equipped with mechanical exhaust ventilation - 1. floor left - the other one with balanced ventilation - 2. floor right.

Since these measurements have been taken at the same time as those shown in the diagram before we can compare them under the aspect of absolute humidity values.

All rooms being provided with balanced ventilation obviously showed the lowest values of absolute humidity.

The dwelling with mechanical exhaust ventilation only has higher values than the one mentioned before with the balanced ventilation; however, its values in the bedrooms are still found to be lower than those given in diagram of figure 13, where we had natural shaft ventilation only.

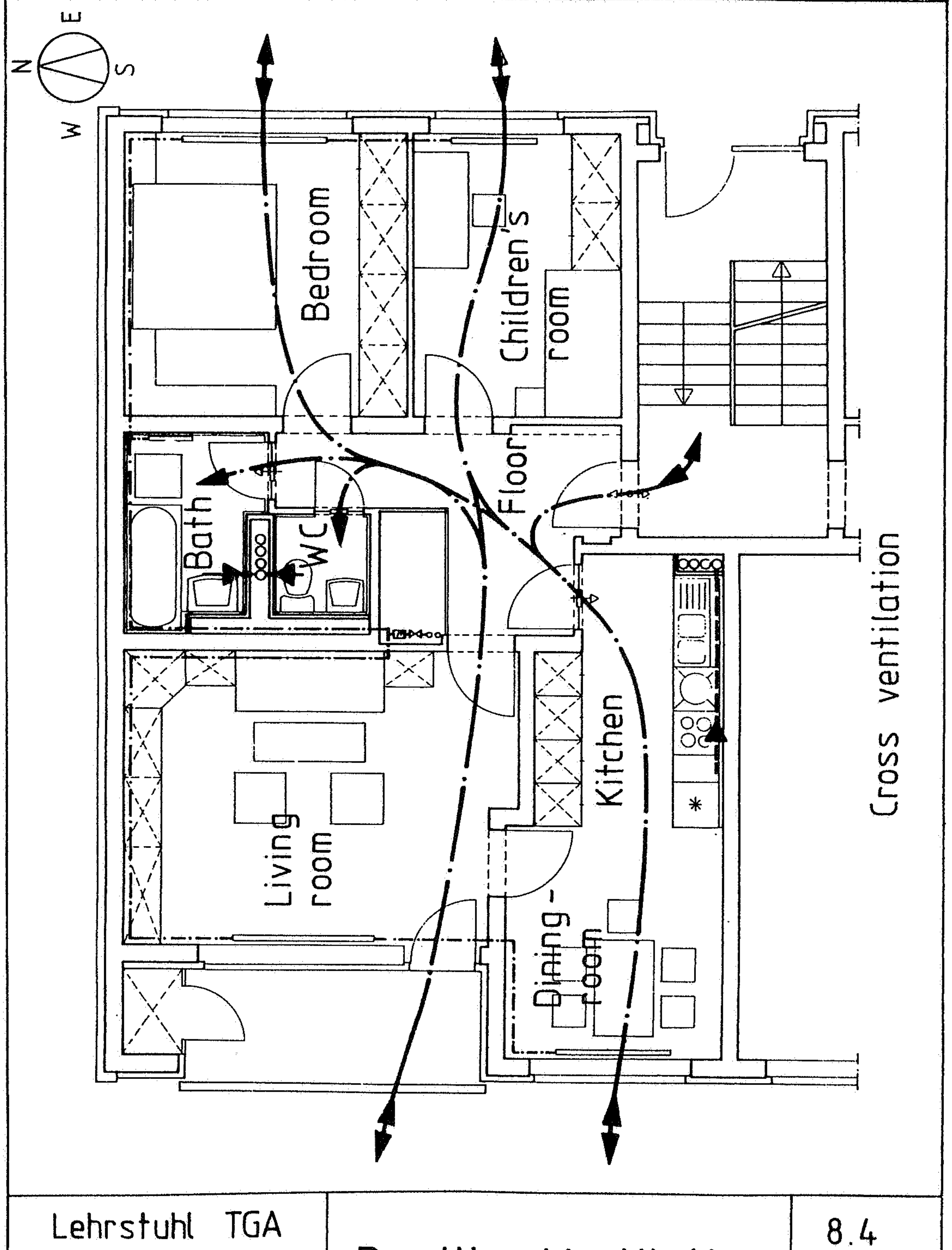
3. CONCLUSION

The previous pictures and diagrams proved that values of air and humidity streams can obviously be looked upon as a function of the different ventilation systems the dwellings are equipped with.

Furthermore user`s behaviour has a certain influence on the curves of absolute humidity in the different rooms within the same apartment as well to be perceived from the example shown in figure 13.

We should emphasize that especially in those bedrooms which were ventilated rather and therefore showing high values of absolute humidity in consequence, there was in spite of double glassed windows a condensation and mould growth to be seen.

The balanced ventilation as described in figure 12 should be installed in buildings because of hygienic and energetic reasons as well as to avoid humidity problems.

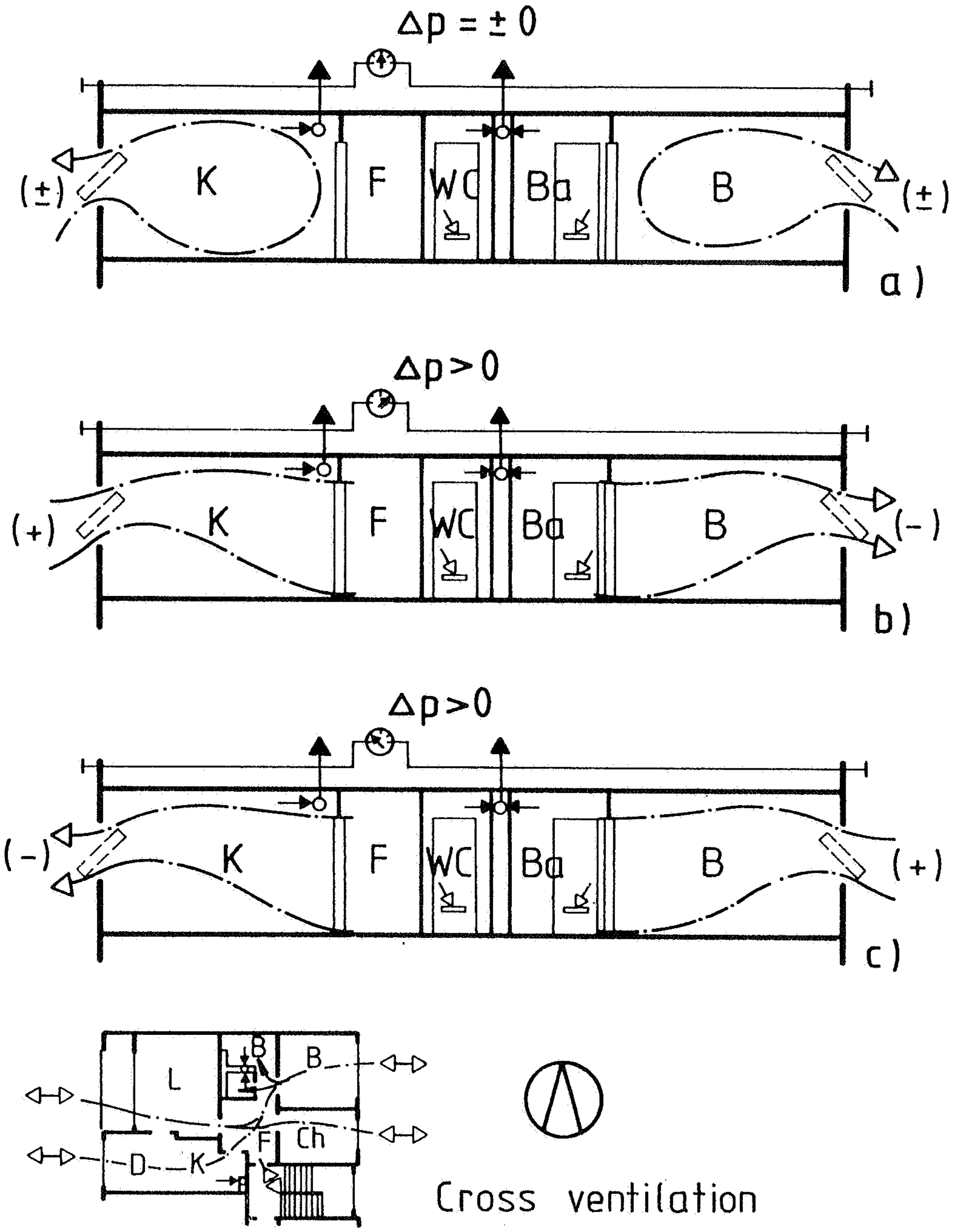


Lehrstuhl TGA
Uni Dortmund
1987

Dwelling Ventilation

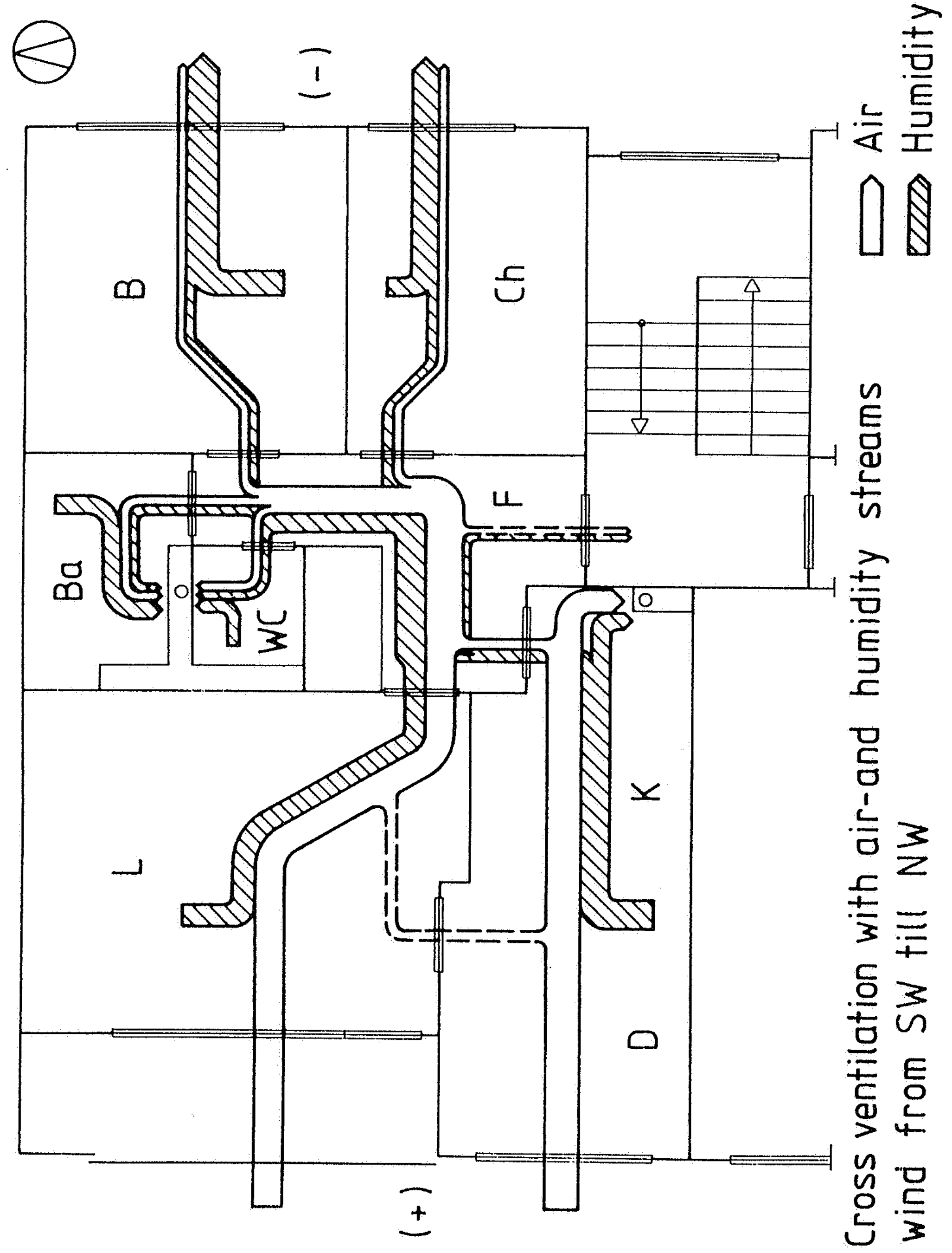
8.4

Bild 1



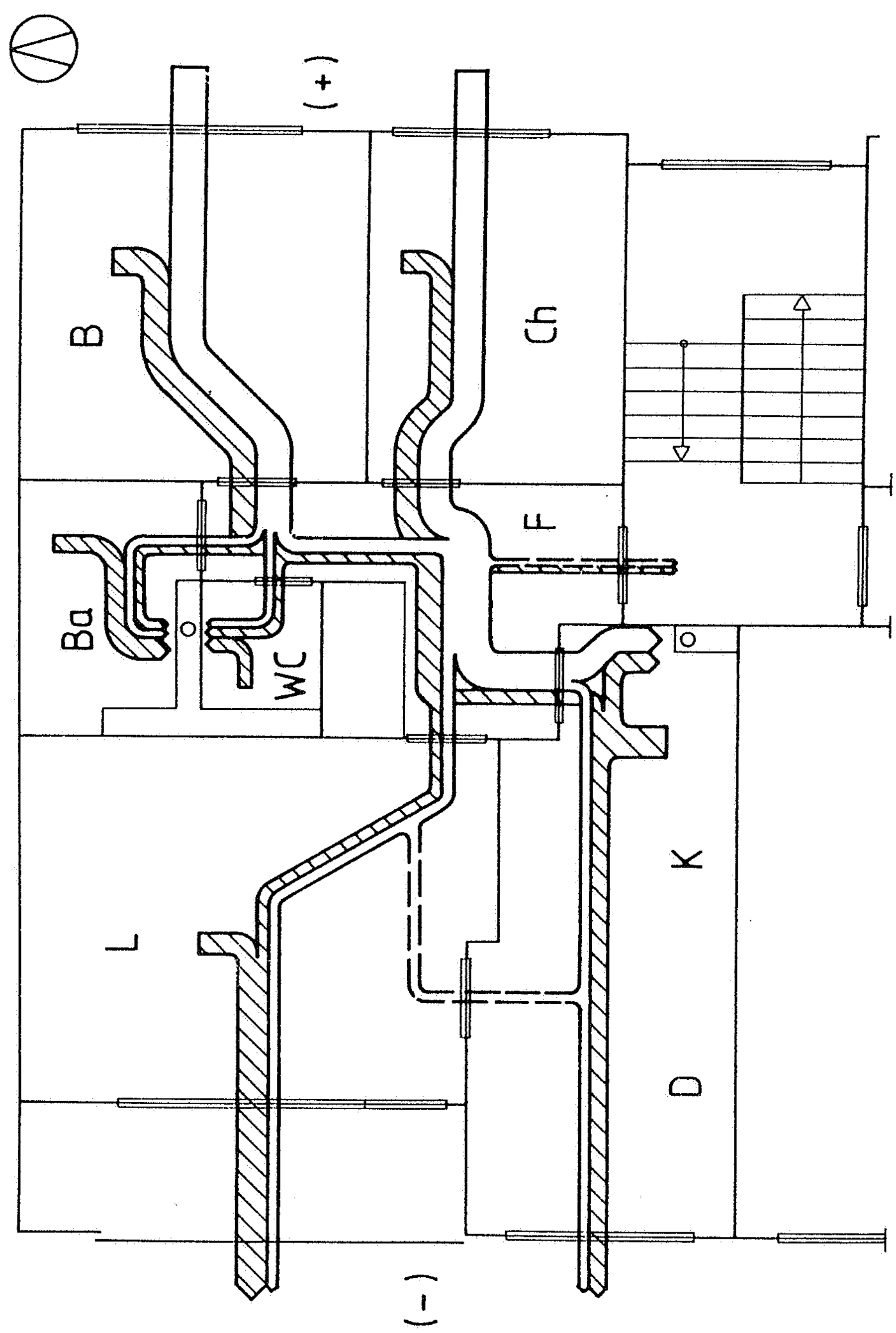
Cross ventilation

Lehrstuhl TGA Uni Dortmund 1987	Dwelling Ventilation	8.4 Bild 2



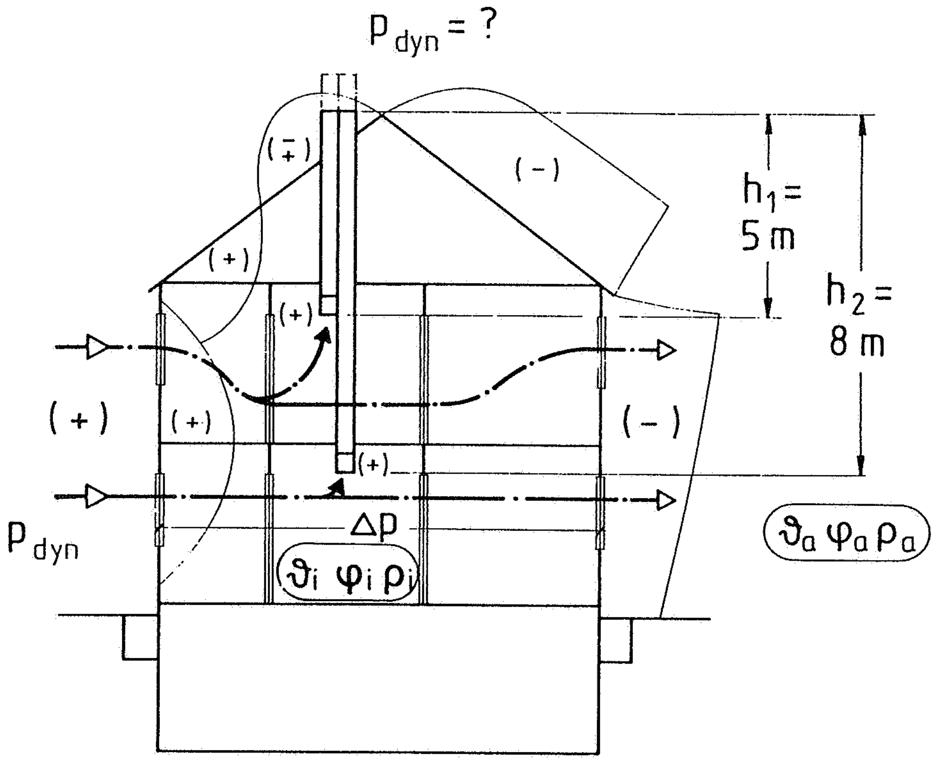
Cross ventilation with air-and humidity streams
wind from SW till NW

Lehrstuhl TGA Uni Dortmund 1987	Dwelling Ventilation	8.4 Bild 3



Cross ventilation with air-and humidity streams
wind from SE till NE

Lehrstuhl TGA Uni Dortmund 1987	Dwelling Ventilation	8.4 Bild 4



$v = 4\,m/s\,;\quad \rho_{0\,°C} = 1{,}29\ kg/m^3$

Lehrstuhl TGA
Uni Dortmund
1987

Dwelling Ventilation

8.4

Bild 5

$$H = h \cdot g \, (\rho_a - \rho_i) \text{ in Pa}$$

ϑ_o °C	ϑ_i °C	φ_a %	φ_i %	ρ_a kg/m³	ρ_i kg/m³	H_1 Pa	H_2 Pa
− 10	22	90	50	1,34	1,19	7,36	11,77
± 0	22	90	50	1,29	1,19	4,91	7,85
+ 15	22	70	50	1,22	1,19	1,47	2,35

$$p_{dyn} = \frac{v^2 \cdot \rho}{2} \; ; \; \Delta p = \frac{4}{3} p_{dyn} \quad \text{in Pa}$$

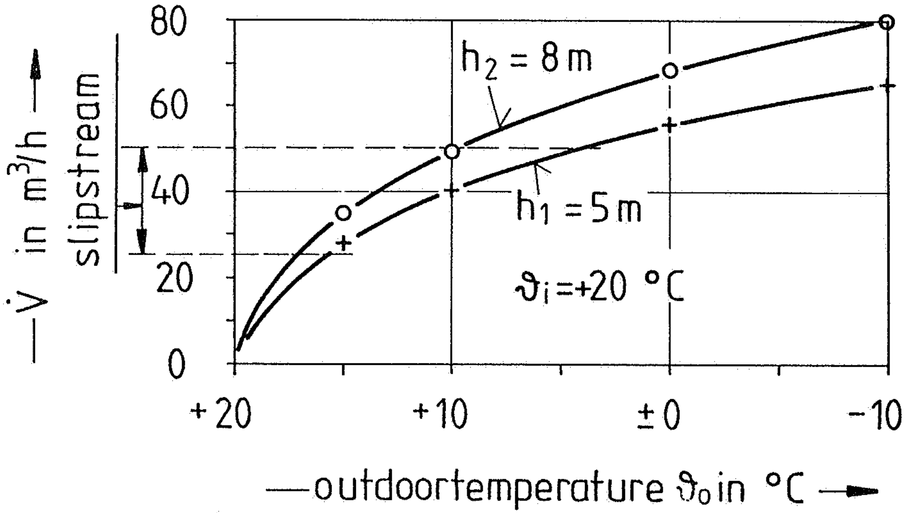
v m/s	p_{dyn} Pa	Δp Pa	$\dot{V}/l$ m³/mh a=1,0*	$\dot{V}/l$ m³/mh a=2,0*
1	0,65	0,87	0,20	0,39
2	2,58	3,44	0,49	0,98
3	5,81	7,75	0,84	1,69
4	10,32	13,76	1,24	2,47
5	16,13	21,51	1,67	3,33
6	23,22	30,96	2,12	4,25

$* : \text{in} \; \frac{m^3}{h \cdot m \cdot (daPa)^{2/3}}$

nach DIN 18 055 Ausgabe 10.81

Lehrstuhl TGA Uni Dortmund 1987	**Dwelling Ventilation**	8.4 Bild 6

ϑ_o °C	H_1 Pa	v_1 m/s	$\dot{V}_1$ m³/h	H_2 Pa	v_2 m/s	$\dot{V}_2$ m³/h
−10	6,72	1,28	64,5	10,75	1,62	81,6
±0	4,32	1,09	54,9	6,90	1,35	68,1
+10	2,11	0,78	39,3	3,38	0,97	48,9
+15	1,30	0,55	27,7	1,65	0,69	34,8



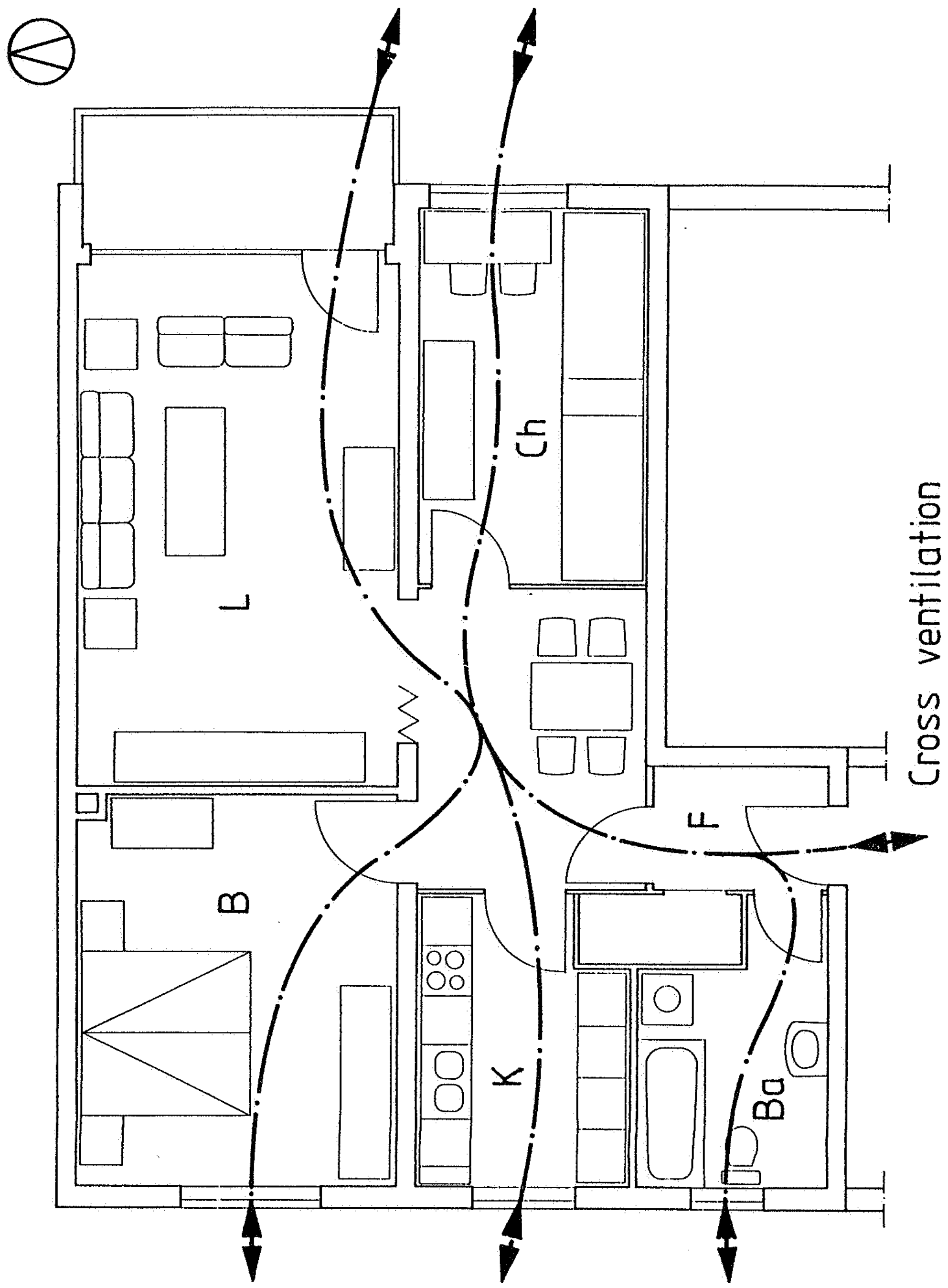
p_{dyn} ≈ 10 Pa ; Δp ≈ 13,3 Pa
□ = 0,014 m² = 100 / 140

Lehrstuhl TGA
Uni Dortmund
1987

Dwelling Ventilation

8.4

Bild 7

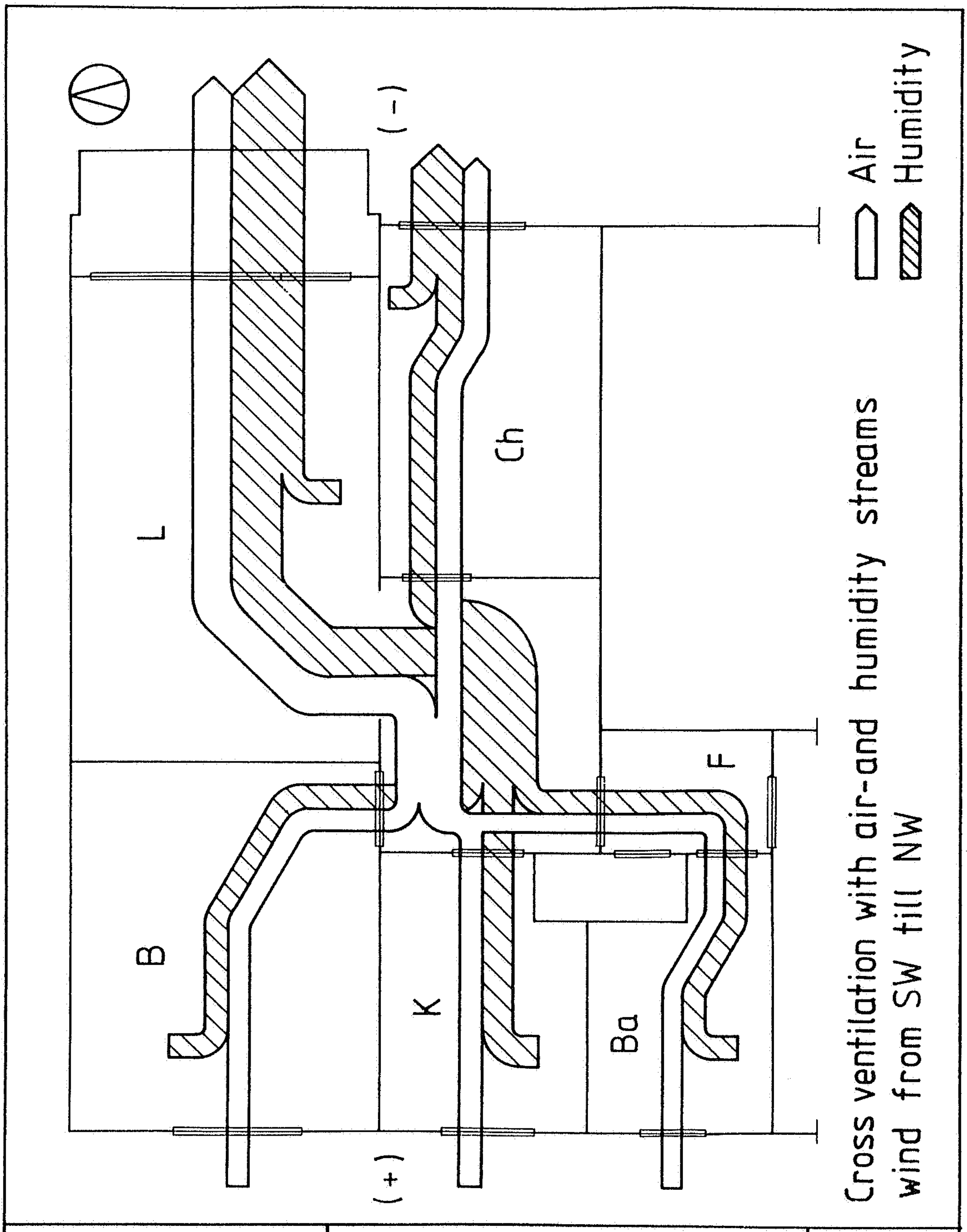


Lehrstuhl TGA
Uni Dortmund
1987

Dwelling Ventilation

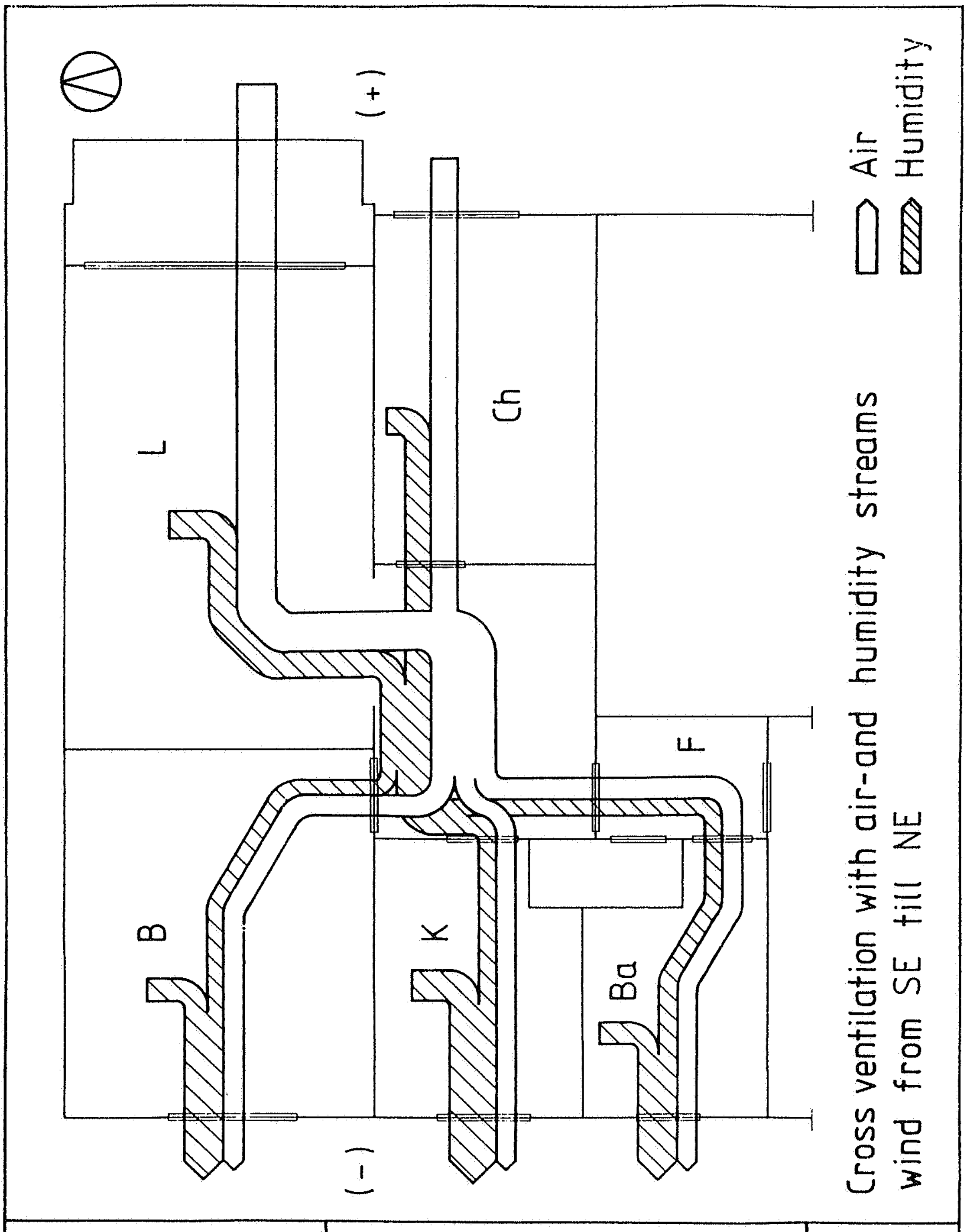
8.4

Bild 8



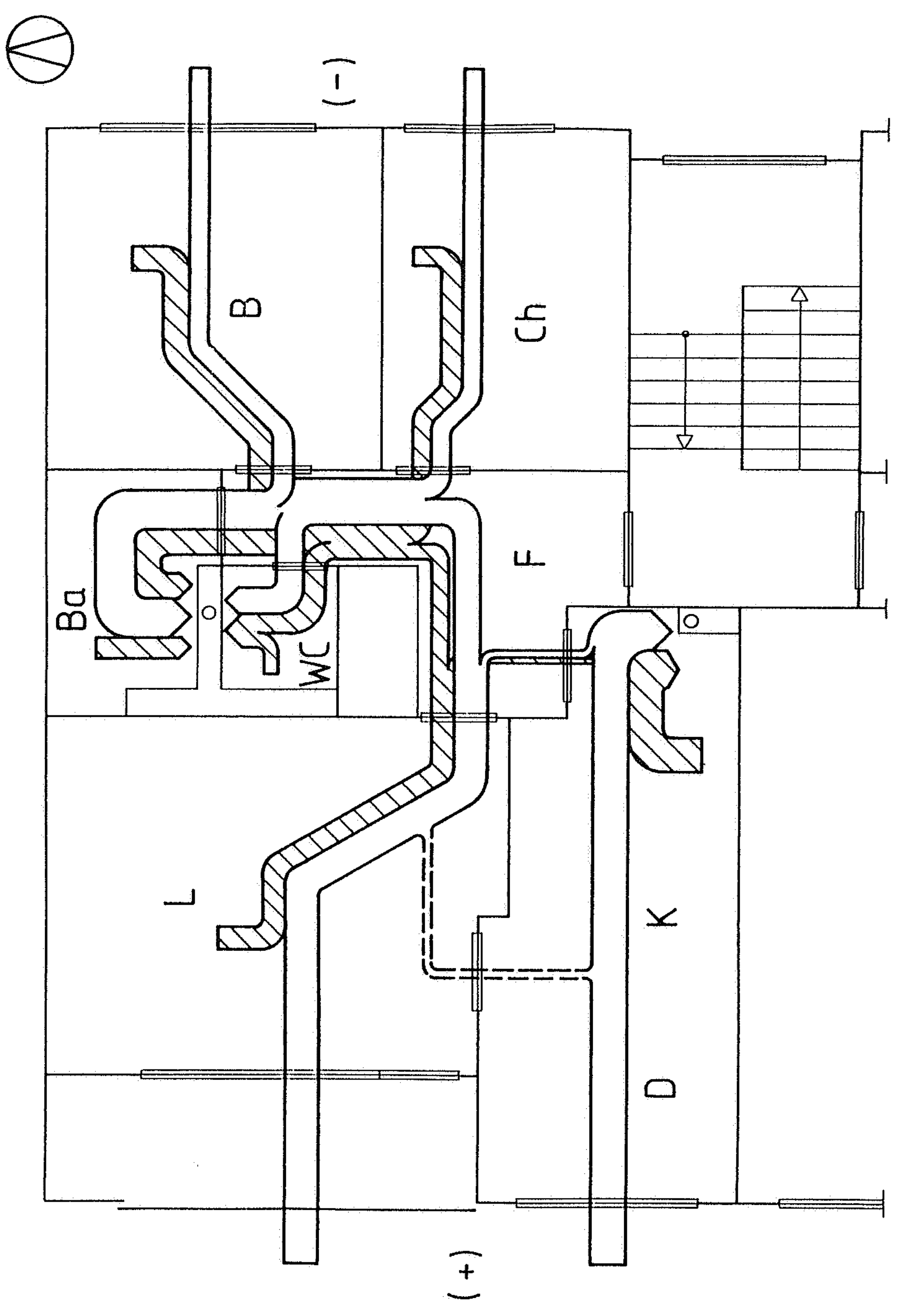
Cross ventilation with air-and humidity streams
wind from SW till NW

Lehrstuhl TGA Uni Dortmund 1987	Dwelling Ventilation	8.4 Bild 9



Cross ventilation with air-and humidity streams
wind from SE till NE

Lehrstühl TGA Uni Dortmund 1987	Dwelling Ventilation	8.4 Bild 10



Shaft ventilation with air-and humidity streams
wind from SW till NW

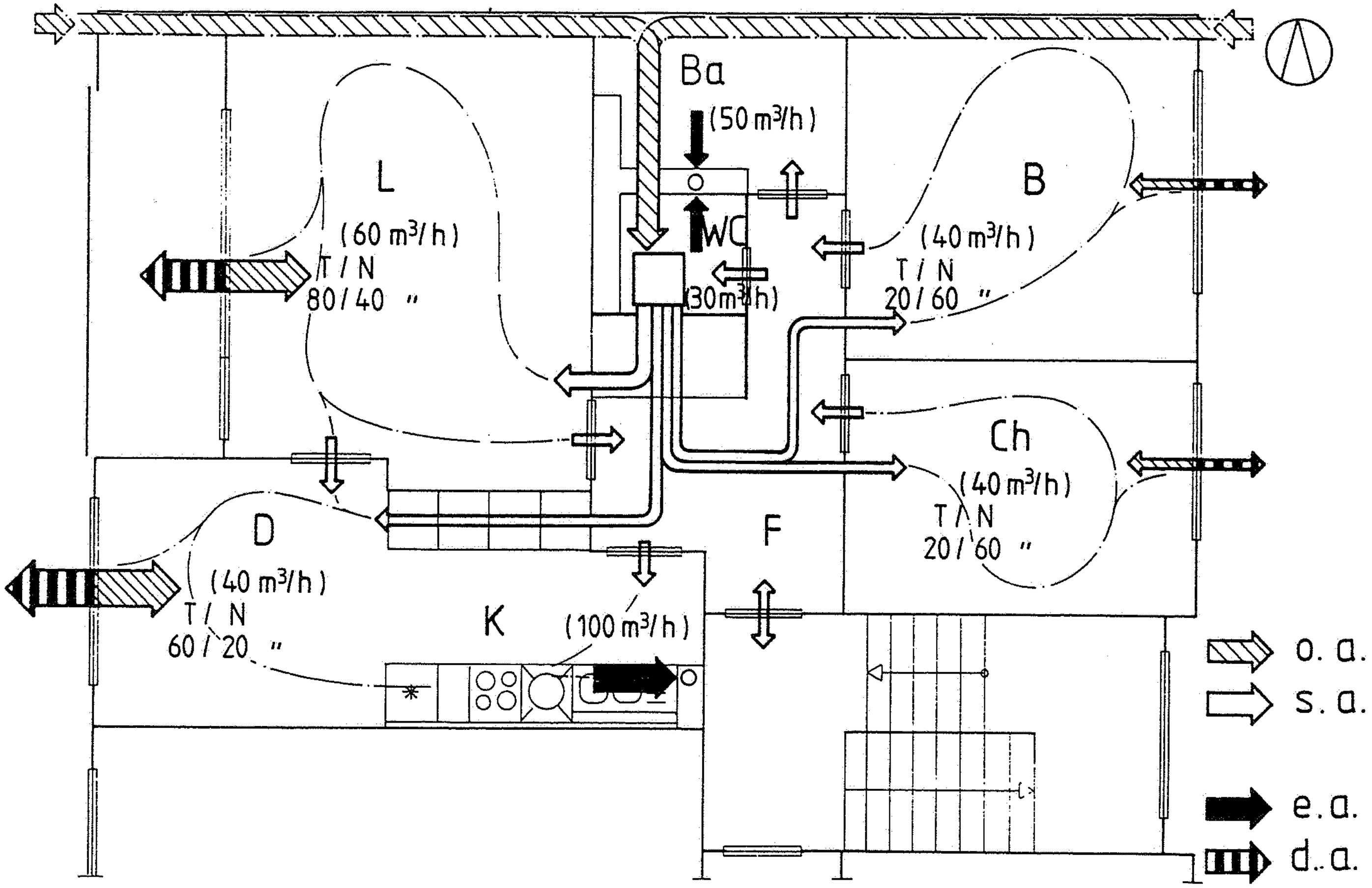
Lehrstuhl TGA
Uni Dortmund
1987

Dwelling Ventilation

8.4

Bild 11

Dwelling Ventilation



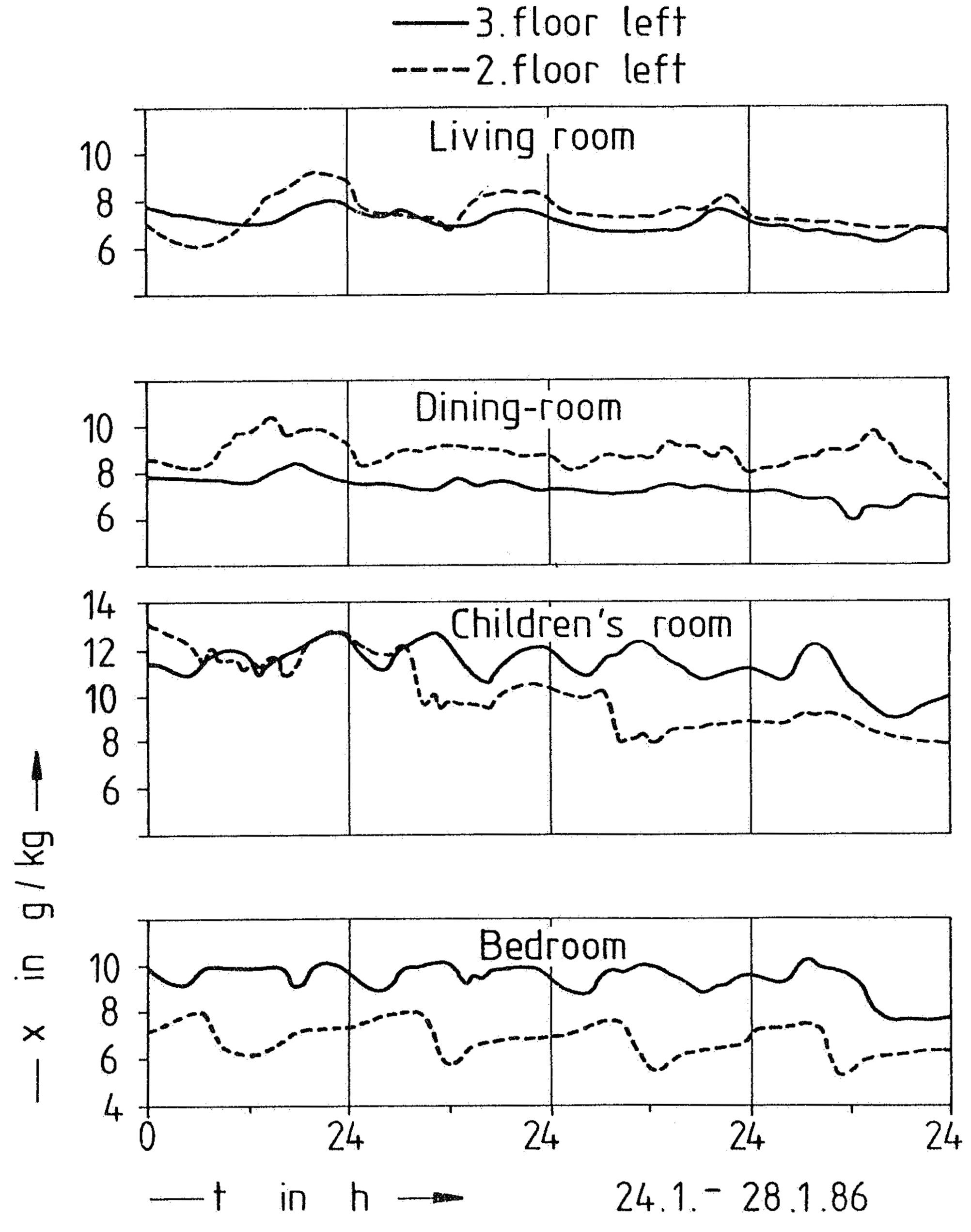
Balanced ventilation

Lehrstuhl TGA
Uni Dortmund
1987

8.4

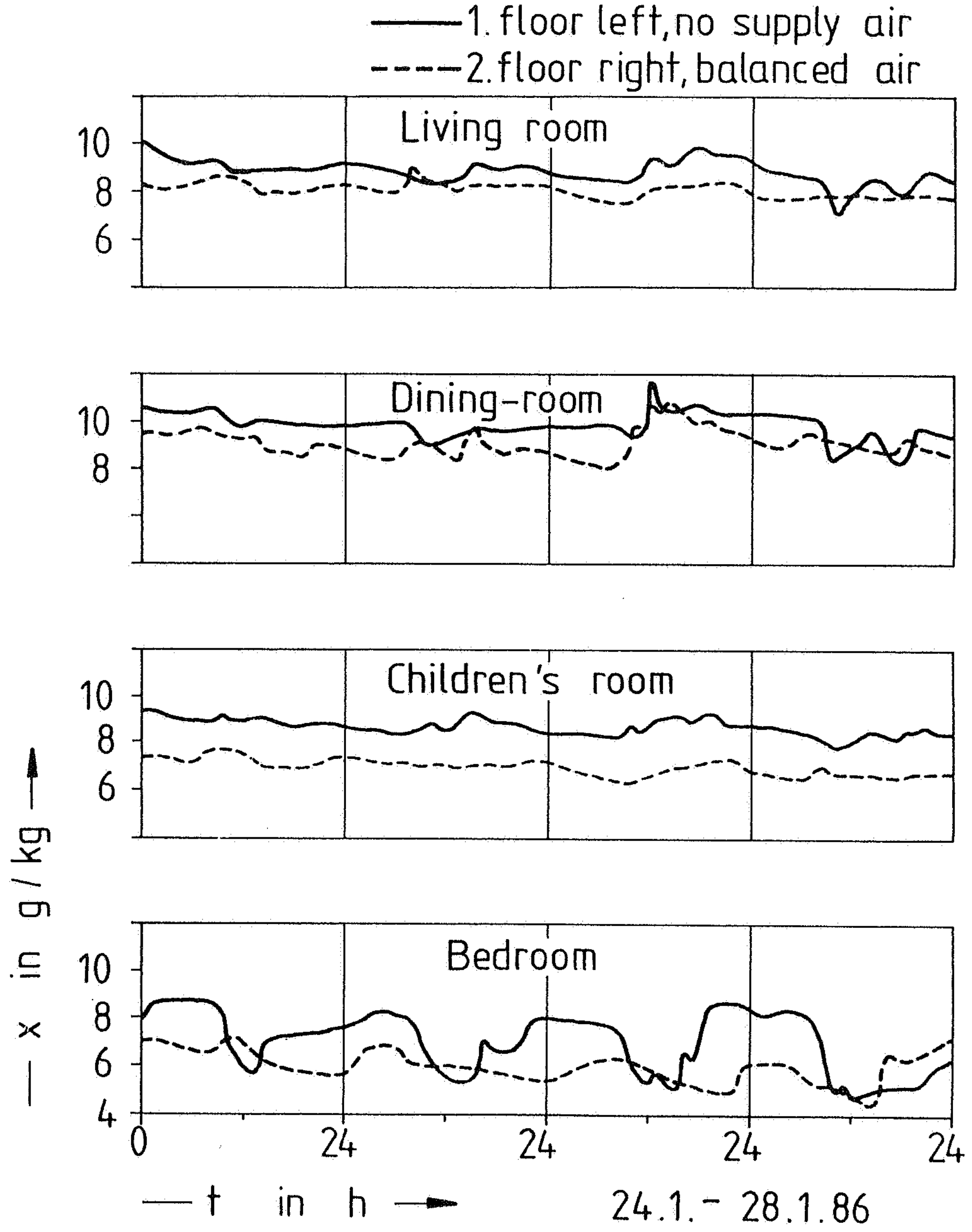
Bild 12

Absolute Humidity Residential building "B"



Lehrstuhl TGA Uni Dortmund 1987	Dwelling Ventilation	8.4 Bild 13

Absolute Humidity Residential building "A"



Lehrstuhl TGA
Uni Dortmund
1987

Dwelling Ventilation

8.4

Bild 14

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

PAPER S.9

PREVENTION OF MOISTURE DAMAGE BY VENTILATION OF THE FOUNDATION

LARS-ERIK HARDERUP,JOHAN CLAESSON,CARL-ERIC HAGENTOFT

Department of Building Technology, Lund Institute of Technology
Box 118,S-221 00 Lund,Sweden

1. SYNOPSIS

Rising moisture from the ground has caused quite a lot of damage on foundations of Swedish buildings, in particular for the type concrete slab on the ground. Some of these constructions may be repaired by mechanical ventilation, for example below the floor or below the concrete slab , if there is an air-permeable layer below the slab.

Summarized results from a few field studies and tests, which have been going on for a period of 2-3 years, are reported. Different methods with mechanical ventilation systems have been found to work quite well so far, i.e. under two and a half years of experience, provided that the air flow is well distributed over the whole area exposed to the ground.

The temperatures immediatly below the slab is an important factor for the condensation. The time-dependent, two-dimensional thermal process in the ground, coupled to the convective heat transfer in the air-permeable layer, is simulated by a computer model. Preliminary results from the field measurements showed that it was necessary to take into account the heat of evaporation in order to get better agreement between calculations and field measurements.

A few results from parameter studies are reported. The influence of air flow intensity, inlet air temperature, climate, thermal insulation thickness, thermal properties of the ground and moisture supply to the inside air and from the ground is discussed.

2. LIST OF SYMBOLS

L= length of the house, m
B= width of the house, m
λ= thermal conductivity of the soil, W/m°C
ρc= volumetric heat capacity of the soil, $J/m^3{}^\circ C$
T_o^{mean}= annual outdoor mean temperature, °C
T_o^{amp}= amplitude of outdoor temperature, °C
λ_{ec}= thermal conductivity of the insulation, W/m°C
d_{ec}= thickness of thermal insulation, m
Q_a= air flow intensity from mechanical ventilation, m^3/h
T_i= indoor temperature, °C
T_a= air flow temperature, °C
v_o^{max}= maximum outdoor vapour concentration, kg/m^3
v_o^{min}= minimum outdoor vapour concentration, kg/m^3
Δv_i^{max}= maximum moisture supply to the inside air, kg/m^3
Δv_i^{min}= minumum moisture supply to the inside air, kg/m^3
Z= resistance to water vapour migration, s/m

3. EXPERIENCE FROM FIELD MEASUREMENTS

A lot of relatively new Swedish buildings, founded with concrete slab on the ground, suffer from moisture damages. Therefore, a lot of different repairing methods have been developed in recent years. In many of these methods, mechanical ventilation in some form is an important factor.

3.1 Mechanical ventilation below the concrete slab

In order to ventilate an air-permeable layer below a concrete slab, different kinds of system have been developed. In many of these, holes are drilled through the concrete slab at the central part of the building. Fans are installed in connection to the holes. They force air through the air-permeable layer below the concrete slab. This air flow will prevent rising moisture from the ground to enter the concrete slab. In some of these systems, the fans are installed to give a positive pressure in the layer. As the fans are installed at the central parts of the building, the air is forced to move to the foundation walls, where it leakes out through drilled holes to the outdoor air. Other mechanical systems of this type creates a negative pressure in the permeable layer below the concrete slab. Indoor air is sucted into the air-permeable layer through holes which have been drilled through the concrete slab near the outer walls of the building. In a one-family residential house, it is usually sufficient to install a single fan at the center of the house. See Figure 1. The Swedish National Testing Institute has performed some field measurements on this type of system.

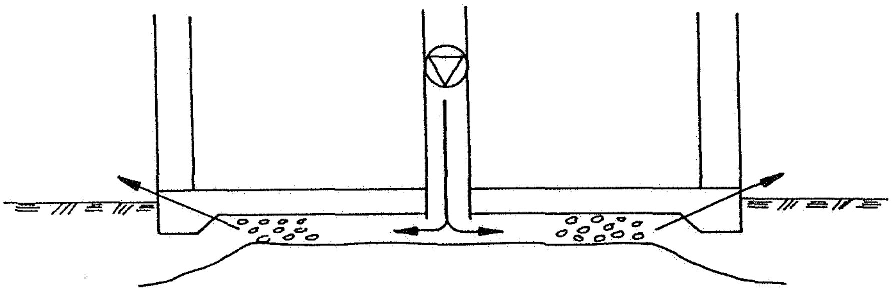


Figure 1: Ventilation under the slab with air flowing from the center to the sides.

Another system, with holes along two opposing sides is shown in Figure 2. The air flow in the air-permeable layer below the concrete slab is one-dimensional. We have followed such a system since its installation in June,1986. Indoor air from different parts of the building is pumped into the layer of lightweight expanded clay aggregate below the concrete slab at one gable end of the building and sucked out from the other gable end. In order to obtain a reasonably even distribution of the air stream below the concrete slab, evenly spred holes have been drilled through the foundation walls at the gable ends. Outside these holes there is a thermally insulated air channel which is connected to a fan at each gable end. Temperature measuring points have been installed in the upper- and lower parts of the ventilated layer below the spine wall. These temperature measurements, combinded with other measurements, are used in order to test the numerical model described below.

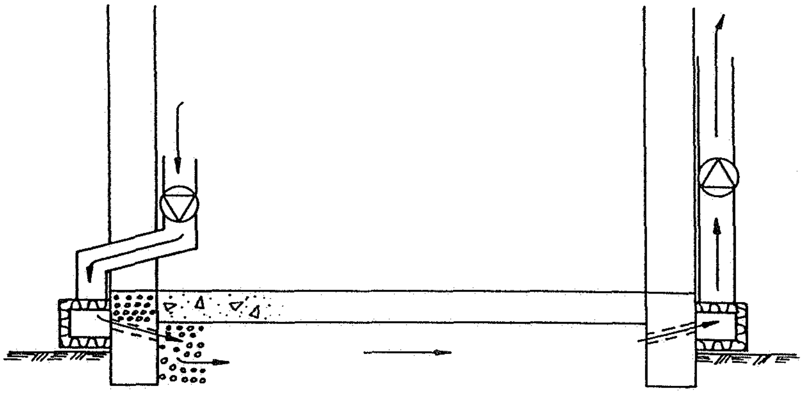


Figure 2: Ventilation under the slab with one-dimensional air flow from side to side

The measurements have just been finished, and no final conclusion regarding the installation has been reached. At this time, the experiences can be summarized in the following way:

- The relative humidity has decreased considerably in the lightweight expanded clay aggregate layer below the whole building. The concrete slab has also dried out, both near the gable ends and in the central part of the house.
- An advantage of this system compared to many other similar systemes, is that it should give an even distribution of the air flow below the whole concrete slab, provided that the foundation walls are fairly airtight.

3.2 Mechanical ventilation above the concrete slab

Methods of ventilating the space between a concrete slab and a joist floor construction in order to dry out wooden parts of the floor have been used in many Swedish houses during the last years. It is a comparably cheap method that has shown more positive effects than were expected only a few years ago.

We have made measurements for two one-family residential houses with joist floor on concrete slab in the south of Sweden. A centrally placed exhaust air fan has been installed in the houses combined with air supply devices at the outer corners. See Figure 3. The inlet to the exhaust air fan tube is placed immediatly above the concrete slab in the joist floor and the outlet is placed in the roof of the building.

In both of the houses, the mechanical ventilation system has caused a drying of the wooden parts of the floor. The effect has varied somewhat due to the fact that different parts of the floor are ventilated to lesser or greater degree. The surface of the concrete slab has also dried out.

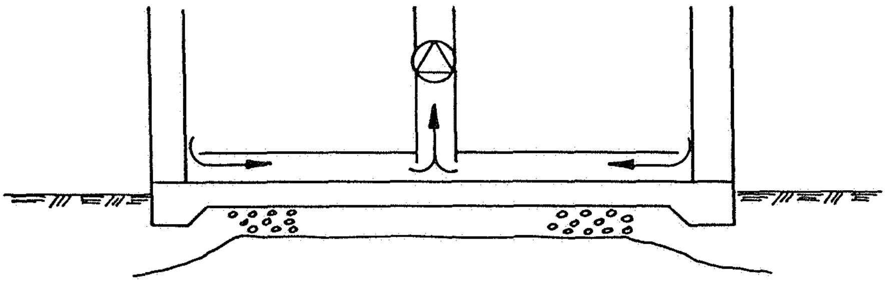


Figure 3: Ventilation above the concrete slab with air flowing from the sides to the center.

Mathematically this system can be described in exactly the same way as the systems with a centrally placed fan for ventilation of an air-permeable layer below the concrete slab.

3.3 Conclusions

The experiences this far indicate that, in many situations, mechanical ventilation is a succesful way to repair concrete slab foundations with moisture problem caused by rising moisture from the ground.

A disadvantage is that it is impossible to get full control of the air flow pattern.

It is a relatively cheap method. It can be installed in a short time and with small disturbance to the inhabitants.

Ventilation of the layer below the concrete slab is practically impossible, if the layer is to air tight.

Sewer pipes and other installations that have been placed in the ventilated layer will disturb the air flow pattern in a negative way.

The mechanical ventilation of the foundation must always be in use.

The mechanical ventilation should improve the quality of the indoor climate for a house with natural ventilation only.

There remains risks for condensation in the ventilated layer, if the indoor air has a high relative humidity, if there is a considerable temperature fall near the foundation walls, or if the moisture supply from the underlying ground is very big combined with low ventilation intensity.

4. NUMERICAL MODEL

The heat flow in the ground, below and around a building is three-dimensional and time-varying. The model described here concerns the two-dimensional case for a vertical cross-section. The heat flow in the ground is simulated using conventional explicit forward differences. The mesh size increases outwards and downwards to adiabatic boundaries far away. The outdoor temperature at the ground surface, the outdoor vapour concentration and the moisture supply to the indoor air varies during the year.

The vertical space below the house becomes, in the two-dimensional case, a channel along the x-axis. Let T_a(x,t) be the air temperature along the channel. The convective-diffusive heat balance for the air is:

$$K_+ (T_+ - T_a) + K_- (T_- - T_a) - \rho_a c_a q_a \frac{\partial T_a}{\partial x} = 0 \tag{1}$$

Here K_+ (W/m°C) is the conductance between the indoor temperature T_+ and the air, and K_- the conductance to the centre of the first cell in the ground with the temperature T_-(x,t). The air flow rate is q_a(t) ($\mathrm{m_a^3/ms}$). We neglect horizontal heat conduction in the air and the capacity term ($\rho_a c_a \frac{\partial T_a}{\partial t}$). There is evaporation or condensation of moisture, which is determined by the difference between the moisture content in the air and at the ground surface. In the model we assume that the ground is saturated and that the resistance to water vapour migration Z (s/m) between the ground surface and the air in the ventilated layer is constant. A mass balance along the channel between evaporation/condensation and convective moisture flow gives the evaporation rate $g(x,t)$ ($\mathrm{m_w^3/ms}$). The corresponding latent heat of evaporation must be accounted for in the heat balances. In the model, this heat enters in the balance of the first cell layer, which is exposed to the air channel.

The temperature field in the ground is calculated for time-step after time-step. At each step, equation 1 is solved analytically in the following way. We introduce the average temperatures T_m and the length l:

$$T_m = \frac{K_+ T_+ + K_- T_-}{K_+ + K_-} \tag{2}$$

$$l = \frac{\rho_a c_a q_a}{K_+ + K_-} \tag{3}$$

Equation 1 becomes:

$$\frac{\partial T_a}{\partial x} = -\frac{1}{l}(T_a - T_m) \tag{4}$$

The quantities l and T_m are piece-wise constant for each cell, $x_i \leq x < x_{i+1}$. The temperature along the cell becomes:

$$T_a(x) = T_{m,i} + (T_a(x_i) - T_{m,i})\, e^{-(x-x_i)/l_i} \qquad x_i \leq x \leq x_{i+1} \tag{5}$$

The inlet temperature to the air channel is given. The outlet temperature becomes the inlet temperature to the next cell, and so on.

5. PARAMETER STUDIES

The model is currently used to investigate how different parameters influence the temperature- and moisture distribution in the air-permable layer above or below a concrete slab. The model with its one-dimensional, or linear air flow, is applicable to the field measurement for the case shown in Figure 2.

The other types with a central hole give a more complicated two-dimensional air-flow pattern. We are currently working with this case. The two-dimensional air flow in the ventilated space must first be calculated. Then, there is a convective-diffusive heat balance with a more complicated convective term in equation 1.

Before the results from the parameter study are presented, it should be mentioned that the model that describes the moisture flow and the moisture distribution in the air-permeable layer is rather simple. We assume that the air flow is confined to one distinct level in the air-permeable layer. In most of the calculated cases we assume that this level is situated in the middle of the expanded clay aggregate layer below the concrete slab.

A basic case used in the discussions below, has the following data:

Basic case:

L =15.6 m
λ =1.0 W/m°C
T_o^{mean}=8.0 °C
λ_{ec} =0.12 W/m°C
Q_a=50.0 m^3/h
v_o^{max}=$10.9 \cdot 10^{-3}$ kg/m^3
Δv_i^{max}=$3.0 \cdot 10^{-3}$ kg/m^3
Z=360 s/m

B =8.0 m
ρc =$1 \cdot 10^6$ J/m^3°C
T_o^{amp}=8.6 °C
d_{ec}=0.2 m
T_i=T_a=22.0 °C
v_o^{min}=$3.9 \cdot 10^{-3}$ kg/m^3
Δv_i^{min}=$1.0 \cdot 10^{-3}$ kg/m^3

All cases below are compared at the end of January when the differences between the cases are largest. The differencies can generally be seen during the whole year, but they are not so pronounced in other seasons when the outdoor air temperature is higher.

Figure 4 shows the computed temperature along the air channel in three cases: 1. without ventilation, 2. with ventilation and without evaporation/condensation , 3. with ventilation and evaporation/condensation.

5.1 Temperatures without taking into account evaporation/condensation

Firstly, we will in this section study the thermal behaviour, and, in particular, the air temperature of the ventilated layer, without evaporation/condensation. The parameter studies presented in this section concern variations from the basic case

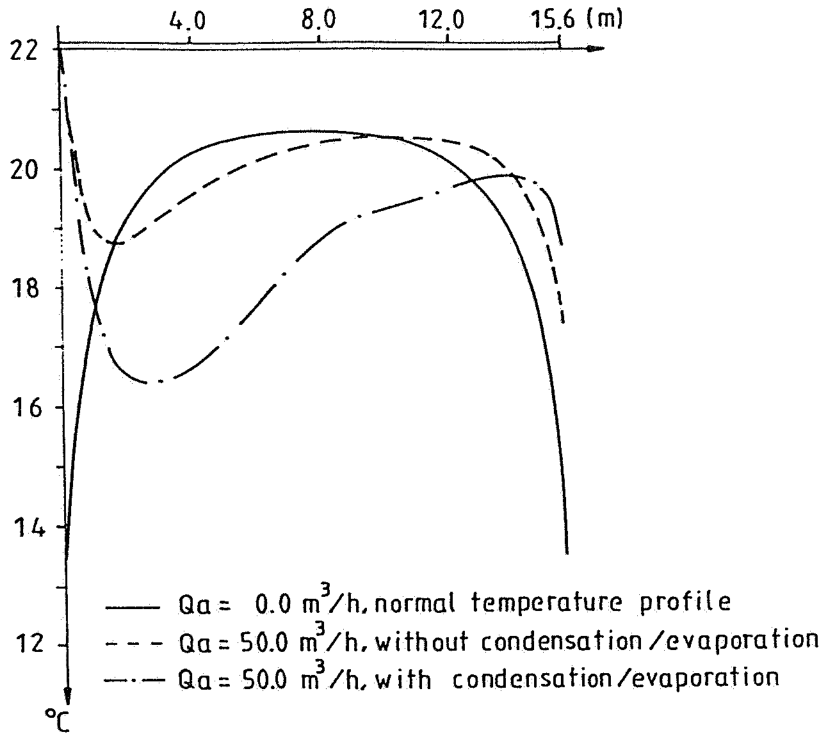


Figure 4: Temperature along the air channel.

without evaporation/condensation.

Basic case compared to natural temperature distribution without air flow
The temperature increase with more than 1 °C in the first 1.5 meter from both gable ends. The largest temperature increase occurs below the foundation walls.

Increased air flow rate (Q_a *= 100* m^3/h*)*
A considerable increase in temperature is obtained near the inlet gable end. A very low air flow rate of 5 m^3/h results in approximately undisturbed conditions.

Increased inlet air temperature (T_a *= 32 °C)*
This gives a considerable temperature increase from the inlet gable to the middle of the house.

Colder outdoor climate (north of Sweden)
This gives a decrease of 0.5-1.5 °C.

Thicker thermal insulation (d_{ec} *= 0.4 m)*
The effect is small near the foundation walls. Below the central part of the concrete slab, the temperature decreases by at most 1.3 °C.

Thermal insulation outside the gable ends (width=0.8 m, R=1.0 m^2*°C/W)*
This gives a rather small increase of the temperature. The maximum increase is of 0.5 °C near the inlet gable end.

Increased thermal conductivity in the ground (λ *= 3.5 W/m °C)*

This gives a considerable temperature decrease, with a maximum of 2.5 °C. This can be noticed except near the inlet gable end.

Thermal insulation of the foundation walls at the gable ends ($R = 0.5\ m^2 {}^\circ C/W$)
The effect on the temperature in the layer, is negligible.

Air flow along the bottom of the air-permeable layer
This means that the air is in direct contact with the ground below, while,in the basic case, the flow is positioned to the middle of the layer. This results in a temperature decrease of several degrees centigrade, about 4 °C near the gable ends.

5.2 Temperatures when evaporation/condensation is taken into account

Basic case including evaporation/condensation
Water from the ground will evaporate near the inlet gable end. This results in a temperature decrease. The temperature gradually approaches the temperatures of the basic case without evaporation/condensation, as the flowing air becomes saturated. Near the outlet gable end, the temperature becomes somewhat higher, compared with the basic case, which means that condensation is taking place. The parameter studies presented in this section concerns variations from this basic case with evaporation/condensation.

Increased air flow rate ($Q_a = 100\ m^3/h$)
If the air flow rate is doubled the temperature decreases near the inlet gable end. The increase in temperature when the saturated air moves towards the outlet gable end is also reduced.

Colder outdoor climate (north of Sweden)
A colder climate results in lower vapour concentration of the outdoor air. In this case we get the same behaviour as in the basic case, but the effect of the latent heat release is larger.

Thicker thermal insulation ($d_{ec} = 0.4\ m$)
The local maximum in temperature near the outlet gable end is decreased with approximately 1 °C.

Higher resistance to water vapour migration from the ground ($Z = 16500\ s/m$)
This will result in lower moisture supply from the underlying soil, and an ensuing smaller influence from the latent heat.

5.3 Vapour concentration in the air-permeable layer

Basic case
The vapour concentration increases continiously until about 2 m from the outlet gable end where it decreases somewhat due to condensation.

Higher heat conductivity of the natural soil (λ=2.0 W/m° C)
Approximately the same form of the vapour concentration curve is obtained but on a lower level due to the lower temperature level.

Increased air flow rate (Q_a= 100 m^3/h)
The vapour concentration increases of a lower rate along the layer, and the decrease near the outlet is reduced.

Colder outdoor climate (north of Sweden)
The only difference from the basic case is that the level of the vapour concentration curve lies about 1.0 g/m^3 lower.

Thicker thermal insulation (d_{ec}= 0.4 m)
The shape of the curve does not change, but the level is 1-2 g/m^3 lower.

5.4 Comparison between field measurements and calculations

The measured temperatures in the air-permeable layer differ somewhat from the calculated ones. The gradients along the flow direction near inlet and outlet become larger in the calculations, and the level is about 1-2°C too high. Part of the differences can probably be explained by uncertainties in the parameter values, in particular for thermal conductivity of the soil, thermal conductivity of the ventilated layer, air flow, outdoor climate and measuring errors. Another uncertainty is the distribution of the air flow in the air-permeable layer. The model assumes a perfectly linear flow, which is evenly distributed over the inlet/outlet gable ends.

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

PAPER S.10

THE EIGHTH AIVC CONFERENCE
SUMMING UP

M J HOLMES

Ove Arup Partnership
13 Fitzroy Street
London
W1P 6BQ

Thank you for asking me to sum up. The opinions I am about to present are personal, and from the point of view of a consulting engineer, but not one directly involved in day-to-day design work. I may upset some of you, and apologise beforehand, but I must reflect what I believe to be the implications of the papers presented.

It would seem that the papers can be grouped under four headings:

Measurement
Prediction
Design
The positive aspects of ventilation - passive heat recovery.

Taking each of these in order:

Measurement Techniques

After 15 years or so it would seem that we are still in the development stage; certainly there is still no compact instrument available to the consulting engineer for the accurate measurement of infiltration rates. The impression I get is that there is, as yet, no general agreement on the best way to measure air change. One reason for this may be a lack of rigour during the development phase of the methods - especially in the attention paid to error analysis. I do recognise that the purpose of the measurements has also changed from the determination fairly high air change rates related to energy, to detecting low figures that might give rise to air quality problems, and of course, from empty to occupied buildings. In some cases I get the impression that if using the equipment results in what appears to be a reasonable figure for air change (anywhere between 1 and 5) then this proves that the technique and apparatus are sound.

The development of simple methods, PFT's and bag sampling is important so that the practicing engineer can give his client a good idea of the performance of an existing building. In this case the objective will often be to confirm that the building is not too leaky - precise values will not be very important, possibly ± 0.25, or even 0.5 air changes may be good enough.

I anticipate that many of these problems will be solved with the publication of the AIVC Measurement Techniques Guide next year.

Calculation Techniques

Whilst there was not too much emphasis on this aspect this time it is obviously still a topic of great interest - as was shown by the interest in the demonstrations during the Poster session. The main talking points appear to be:

Validation
Simple vs Complex Models

It is clear that unless methods for validation are available, arguments over techniques are not very relevant. As I see it only two forms of validation need to be considered.

1) Will the method reproduce a standard (probably manual) design calculation?

2) Reproduction of measured data.

The first, whilst applicable to many computerised design methods is probably not valid (yet?) with respect to ventilation and infiltration calculations. To reproduce experimental results implies that suitable data (together with error assessments) are available. The task of providing such data sets should not be underestimated as they must contain all relevant parameters and be demonstrated as suitable for validation checks. I would suggest that a central record of validated data sets be created; this is obviously a task for the AIVC.

The simple vs complex argument can only be relevant if the data input to simple methods is also simple, the availability and application of suitable hardware for the more complex technique are certainly no longer a discussion point. In general it can be said that even with the most sophisticated computer programs the data preparation and checking time exceeds the run time. This is true for what may be the ultimate infiltration model - computational fluid dynamic codes.

I think one encouraging trend in the development of prediction techniques is the introduction of statistical methods in an attempt to reproduce variations found in practice. I am sure that there will be more papers on this approach at future AIVC conferences. Again validation is important and it will be interesting to see how the predictions check against some of the large sample surveys now being carried out.

Design (Control of the internal environment)

The best way to get acceptable air quality throughout a building is to ensure appropriate quantities of fresh air are delivered to each occupied space and not to rely on random factors such as weather and windows (cracks). The design of suitable systems is trivial for engineers familar with design of commercial buildings, however, it appears that those who only have experience of dwellings have some difficulty in accepting such concepts. There is therefore, a need to educate the industry and to demonstrate the need for and advantages of good ventilation design. The general public should be made aware of this need. To do this it will be necessary for the AIVC to prepare information suitable for publication in national newspapers. Research is of little value unless the results find their way into everyday life.

The Positive Aspects of Ventilation and Infiltration

It is very interesting to learn that the building can be used as a passive heat recovery device so that not all the energy used to heat infiltrating air is lost to the surroundings. The measurements required to validate the theory are quite difficult and consequently great care is required if meaningful results are to be obtained. Again a case for a rigorous examination of errors, as emphasised in the discussion of dynamic insulation which appears to be a very interesting development.

Finally we need to be aware of differences between countries. These can be obvious such as weather - which may make a technique that is cost effective in one country not worthwhile in another - or more subtle, such as attitude. The United Kingdom contingent will understand the difficulty that would be encountered when requesting a relaxation of building regulations because the effective 'U' value is 10% (say) lower than the standard value because of the positive effect of infiltration.

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

POSTER S. 11

THE USE OF MODIFIED CONSTANT CONCENTRATION TECHNIQUES TO MEASURE INFILTRATION AND INTERZONE AIR FLOW RATES.

DAVID L BOHAC AND DAVID T HARRJE

Center for Energy and Environmental Studies
The Engineering Quadrangle
Princeton University
Princeton
NJ 08544
USA

SYNOPSIS

The constant concentration tracer gas (CCTG) technique is typically used to measure air infiltration rates in mulitzone 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 techiques 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 and multifamily buildings. The results are compared to those obtained by passive, multiple tracer gas tests.

1.0 INTRODUCTION

The constant concentration tracer gas (CCTG) technique has proven to be useful for real time measurements of infiltration rates in multizone buildings. One of the advantages of the method is that it requires only a single tracer gas (TG) to measure infiltration in a large number of zones of a building. It accomplishes this by injecting the amount of tracer gas into each zone that is required to keep the concentration of the tracer gas constant and at the same level in all of the zones. This allows the infiltration flows into each zone to be measured reguardless of the flows between the zones. Unfortunately, with the typical operation of the CCTG system no information is obtained of the interzone air flow rates.

In many cases the infiltration rates are the only, or most important, flow rate of interest and the CCTG method provides the necessary measurements. There are cases when interzone measurements are also necessary. This is true for studies of nonuniform pollution sources such as the entry of radon into the lower level of buildings and measurement of adequate ventilation rates. For example, a companion paper in this conference[1] presents CCTG measurements in a single family house where infiltration levels in upstair bedrooms are well below present ASHRAE standards[2]. It is hypothesized that the abundance of infiltration air in the downstairs could often provide the necessary "fresh air" if the interaction between the zones is adequate. This paper presents a modified form of the constant concentration technique, called <u>discontinued injection</u>, that measures not only infiltration rates but also air flow rates between the zone where injection is discontinued and the rest of the building.

Our CCTG systems and those developed by other research groups have the ability to operate in ten separate zones. While this is sufficient for most single family houses, it is often inadequate for large, complex structures such as office buildings and multifamily buildings. Two other modifications of the CCTG method have been developed in order to measure air flow rates in these types of buildings. The first, called guarded-zone, "isolates" a zone or set of zones from the rest of the building so that infiltration measurements can be made in these zones. The second, called surrounded sampling, keeps a constant concentration in a zone or set of zones in order to measure infiltration and other incoming air flows into those zones. In addition, the relative amount of air moving from those zones to the surronding zones is also measured.

This paper presents the type of system operation, equations, and analysis needed to perform the three modified CCTG measurements. A set of results are presented from field tests of the guarded-zone and surrounded sampling methods applied to a six-story multifamily building. The results from tests using discontinued injection in an unoccupied single family house during summer-fall and winter conditions are also presented. The uncertainties are discussed and these short term (two hour) results are compared to those from simultaneous long term average measurements using a passive multiple tracer gas system (PFT).

2.0 GUARDED-ZONE

The guarded-zone method is used to measure infiltration flows in a selected area of a building where it is not possible to implement the system in all sections of the building. In this method, all zones adjacent to the test zone (or set of zones) are kept at the same constant concentration as the test zone. Measuring the rate of tracer addition to the "guarded" test zone (g) then yields the rate of the outside air infiltration into the zone. The coupled set of first order differential equations that govern the level of tracer gas in a multizone building is[3]:

$$V_j \frac{dc_j}{dt} = -c_j \cdot \sum_{i=1}^{n} F_{ji} + \sum_{k=1}^{n} c_k \cdot F_{kj} + S_j \qquad (1)$$

where V_j = volume of zone j

F_{ji} = airflow from zone j to i

c_j = tracer gas concentration in zone j

S_j = rate of tracer gas injection into zone j

n = number of zones in building + 1

the n^{th} zone is the outdoors ($c_n = 0$)

If the concentration in a zone is kept constant at a level c_t then equation 1 reduces to:

$$c_t \cdot F_{jT} = \sum_{k=1}^{n} c_k \cdot F_{kj} + S_j \qquad (2)$$

<u>where</u> F_{jT} = total flow out of zone j

For the guarded zone $c_k = c_t$ and equation 2 reduces to:

$$F_{ng} = S_g/c_t \qquad (3)$$

Where F_{ng} is the flow of outside air (zone "n") into the guarded zone.

Thus, the infiltration flow into each guarded zone is approximately the rate of TG injection into the zone divided by the target constant concentration. In practice, the concentration deviates from the target level. An analytical procedure adapted from equation 1 includes the effect of these deviations in the computation of F_{ng}[4].

For the surrounding "unguarded" zones (s), the tracer injection rate can be used to estimate the sum of the infiltration airflow rate plus the rate of air flowing in from zones where there is no injection (assuming that the concentration in those zones, c_p, is negligible):

$$S_s/c_t = F_{ns} + \sum_p (1 - c_p/c_t) F_{ps} \qquad (4)$$

<u>where</u> the p zones are those in which there is no injection.

Our measurements were conducted using the constant concentration tracer gas (CCTG) system[5]. The system uses sulphur hexafloride (SF_6) as a tracer gas with a detectable range of 10 to 300 parts per billion (ppb) and can inject and sample in 10 zones. Recent modifications provide hourly adjustment for detector drift, remote access via telecommunications, and monitoring of an on-site weather station. At present, we record the wind speed, direction, outdoor and indoor temperature each minute, and their average values each hour.

The site for these measurements is a 60-unit, six-story apartment building for senior citizens located in Asbury Park, New Jersey. The floor plan and one elevation of the building are shown in figure 1. The ground floor has offices in one wing and common areas in the other. The apartments are located, six per floor per wing, on the next five floors. The windows are casement type with interior storms, except in the bathrooms where there are no storms. Every apartment has windows on at least two different faces of the building. The apartments on each floor share a hallway, which is connected to a pair of stairwells and an elevator shaft. Both stairwells (for each wing) have outside doors on the ground floor, and one of them also has a door at the top for roof access. In most cases, each apartment can be considered to be a single well-mixed zone. Even with this simplification, the building consists of many interconncected zones where any zone may communicate with as many as six neighbors. In the case studied, there are more than 30 separate zones in each wing with most zones having five adjoining zones.

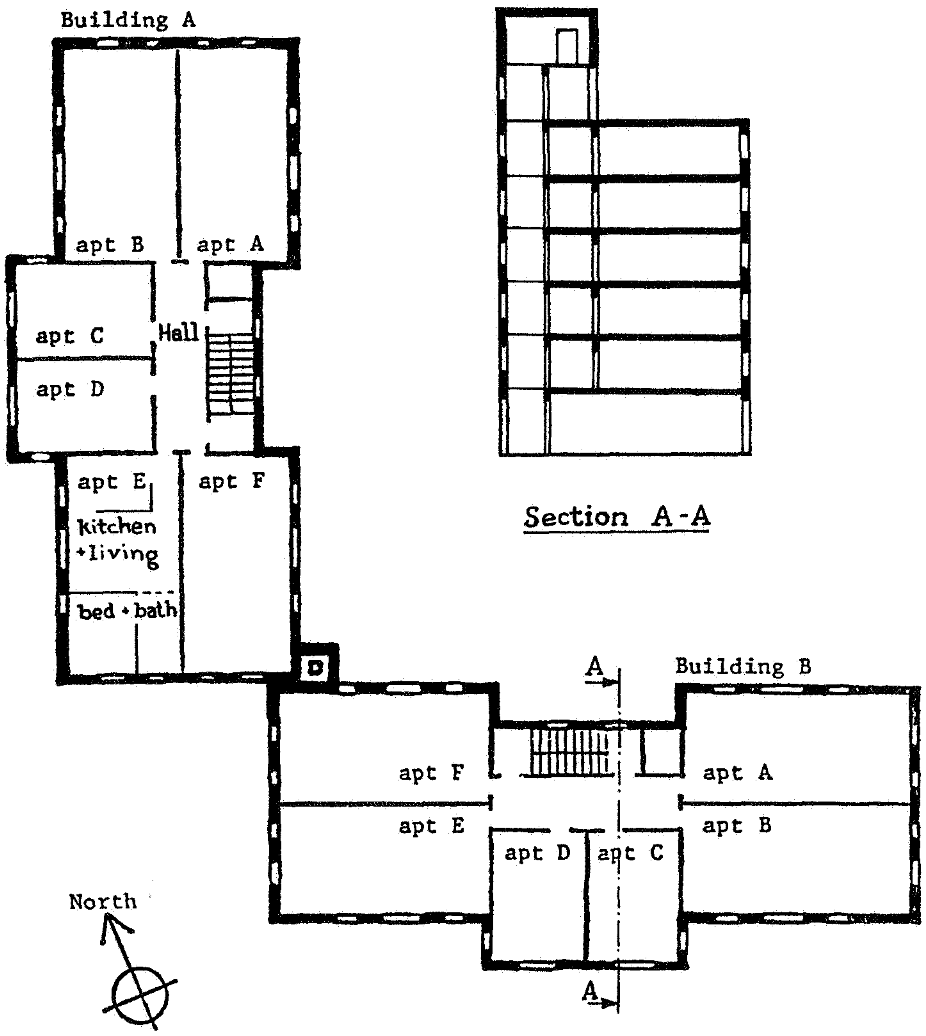


Figure 1. Floor plan and elevation of multifamily test building.

The test apartment for the guarded zone studies was an E unit on the third floor of building A (designated A3E - see figure 1). It is a one-bedroom apartment with a volume of 120 m^3 and was unoccupied during the tests. All of the surrounding apartments, except the adjoining efficiency unit (A3D), were occupied. The test apartment was considered as two separate zones - one consisting of the kitchen and living room (71 m^3) and the other of the bedroom and bathroom (49 m^3). A single TG injection line was placed in each zone with its output placed in the airstream of a fan to help mix the injected gas with room air. An additional mixing fan was placed in each zone and the sample was taken from a blend of two locations in the zone. A single sample line and an injection line were placed in each of the surrounding apartments. In general, the input of the sample line was placed near the center of the zone, and the output of the injection line was placed on a uninsulated steam riser to in the aid dispersement of the gas. A single mixing fan was used in the unoccupied efficiency unit, but none in the occupied zones.

The tracer gas measurements were conducted for about 25 days, using the guarded zone method about half that time. The purpose of the experiment was to estimate infiltration flows in winter with various window openings and to study the ability of the CCTG system to keep the concentration at a target level. The brief duration of the experiment did not allow detailed examination of the dependence of air infiltration on weather conditions or window openings in the rest of the building.

Figure 2 displays the measured airflow of A3D and the two zones of the test apartment and the environmental conditions over a two-day period when the windows of the two apartments were closed. The CCTG method measures airflow rates directly. However, for easier interpretation, the flow rates are divided by the volume of the zones and expressed as air change per hour (ACH). The measured flow for the test apartment is the infiltration flow, while for apartment A3D the measurement includes airflows from its other neighbors as well. Over the two days of tests, the airflows in these zones varied between 0 ACH and 0.35 ACH. These results seem reasonable given the tightness of the apartments indicated by the blower door tests (2.5 to 6.0 air changes per hour at 50 Pa).

The CCTG system records the measured airflow, average concentration, and rms deviation in the concentration from the target for all of the zones on an hourly basis. The average concentration and rms deviation give an indication of how well the concentration was kept near the target. Table 1 displays the average and standard deviation of these three values over one day of data for each of the seven zones. The three unoccupied zones, with mixing fans and closed windows, had average concentrations within 0.1 ppb of the target and rms deviations of about 0.5 ppb or 1.25% of the target. These results are as good or better than those obtained in single-family houses and indicate proper operation of the CCTG system[4]. An error analysis of the CCTG system operating in single-family houses indicates that this level of concentration fluctuation corresponds to an uncertainty of approximately 5% in the estimated airflow rates[4,5]. The concentration deviation for the other apartments is much greater - varying between 6.3 to 18.8 ppb from the target of 40 ppb. The increase in the deviation is most likely due to the absence of mixing fans and the high airflows (i.e. open windows). The high degree of window opening in the occupied apartments of this building is discussed in reference 6.

The guarded zone experiments were also conducted when all the windows in the test and A3D apartments were opened a linear distance of 50mm and then opened wide. Table 2 shows the average flow rates over one day for these window openings. Although the weather conditions for these three sets of data do not allow direct comparisons, the results do indicate the expected order of magnitude of the flow rates for diferent window openings. The data show that opening the casement windows 50mm increases the flow rate by more than an order of magnitude (0.1 ACH to 3 ACH) and opening the windows fully further increases the flow rate by another order of magnitude (39 ACH).

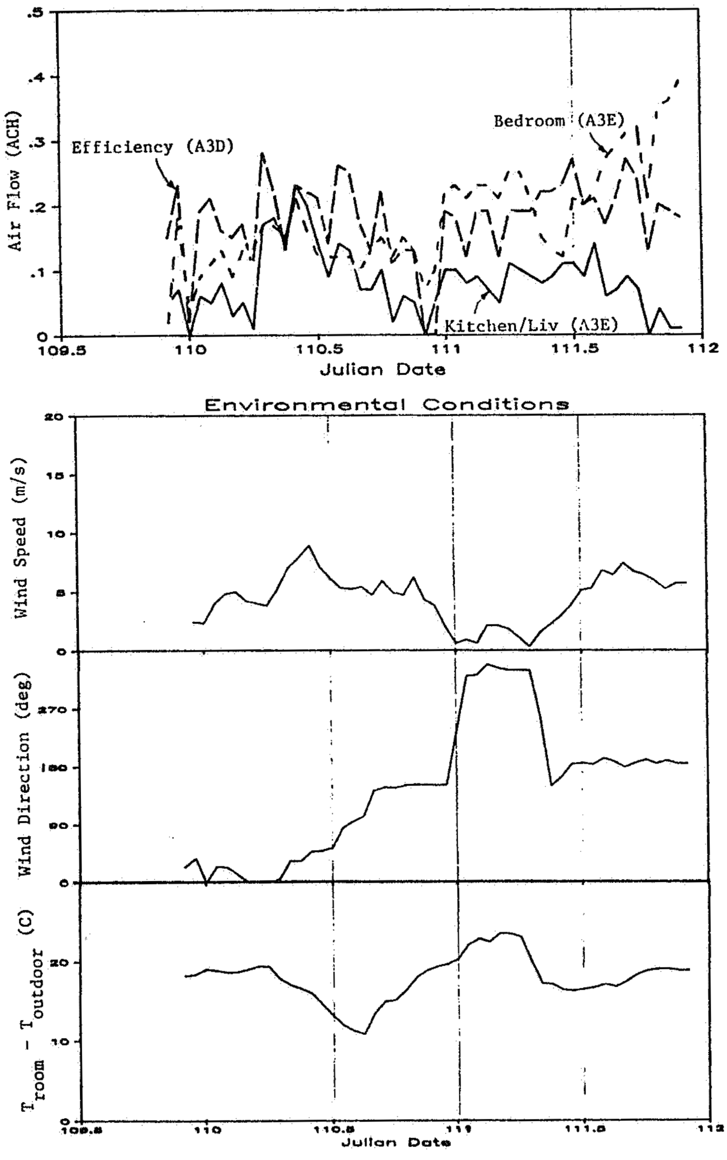


Figure 2. Airflow into an unoccupied efficiency apartment and infiltration into the two zones of the test apartment when windows are closed. Below: environmental conditions.

TABLE 1

Guarded-Zone Constant Concentration Tracer Gas Data: Average of Hourly Values for One Day (Standard Deviation in Parenthesis)

	Unoccupied			Occupied			
	A3E K&L	A3E Bed	A3D	A3F	A2E	A4E	Hall
Air-flow [ACH]	0.09 (0.06)	0.13 (0.03)	0.16 (0.07)	1.6 (1.0)	4.2 (2.8)	2.3 (1.7)	17.2 (7.2)
Avg. Conc. ppb	40.1 (0.3)	40.0 (0.1)	40.1 (0.5)	38.8 (3.4)	38.0 (9.9)	40.2 (7.4)	38.8 (6.8)
RMS Dev Conc ppb	0.5 (0.2)	0.3 (0.1)	0.6 (0.3)	6.3 (5.0)	18.8 (7.8)	11.1 (14.0)	12.0 (6.7)

Day : 110
Tin : 28.0 ±0.7 [°C]
Wind Speed : 5.0 ±1.7 [m/s]
c_t : 40 ppb

A3E and A3D windows closed
Tout : 11.4 ±3.0 [°C]
Direction : 5 ±2 [degrees clockwise from noon]

TABLE 2

Apartment Airflow Rates under Various Window-Opening Conditions: One Day Averages (Standard Deviation in Parenthesis)

Window	Airflow [ACH]			Wind Spd	Dir	Tin	Tout
Position	A3E K&L	A3E Bed	A3D	[m/s]	[deg]	[°C]	[°C]
Closed	0.09 (0.06)	0.13 (0.03)	0.16 (0.07)	5.0 (1.7)	5 (2)	28.0 (0.7)	11.4 (3.0)
All Open 50mm	3.8 (2.0)	3.2 (1.6)	2.5 (0.4)	2.1 (1.1)	338 (83)	24.7 (0.8)	13.4 (1.2)
All Wide Open	32 (26)	66 (47)	14 (2)	4.7 (2.3)	165 (69)	19.7 (0.6)	16.9 (2.0)

3.0 SURROUNDED SAMPLING

This method is used to 'measure incoming air flow rates in a selected set of zones and the relative magnitude of the flow from these zones to the surrounding zones. In this method the tracer concentration is kept constant at c_t in a single zone (x) and is sampled in the surrounding zones (s). By keeping the concentration at c_t, the equation for the TG concentration in zone x is:

$$c_t \cdot F_{xT} = \sum_s c_s \cdot F_{sx} + S_x \qquad (5)$$

By applying the continuity equation (i.e. $F_{xT} = F_{nx} + \sum_s F_{sx}$), this equation is further simplified to:

$$S_x/c_t = F_{nx} + \sum_s (c_t - c_s)F_{sx}/c_t \qquad (6)$$

If the concentration in the surrounding zones is small relative to c_t, then S_x/c_t is approximately equal to the total airflow entering that zone (F_{Tx}). Combined with infiltration airflow rates measured by the guarded CCTG technique under similar weather conditions, we can estimate the magnitude of flow coming from neighboring zones.

In addition, this method gives information about the airflows into the surrounding zones. Assuming that the concentration is steady in an adjacent zone (s), $c_s/c_t = F_{xs}/F_{Ts}$. Although this does not specify an absolute airflow rate, it does indicate where incoming flows are originating and their relative magnitudes.

The experimental setup was similar to that used for the guarded zone method. The TG concentration was kept constant in the two zones of the test apartment (A3E) and its level sampled in the surrounding zones. The concentration was held at a higher level (250 ppb) than for the earlier tests so that lower airflows from the test apartment could be measured. For a c_t of 250 ppb and a lower detection limit of 10 ppb, flows from A3E to an adjacent space that were greater than 4% of the total incoming flow could be measured.

Figure 3 displays the airflow data for the test apartment and the environmental conditions over an 18-hour period. This brief period of data does not allow an in-depth comparison with earlier infiltration data. However, a comparison of these data with that displayed in figure 2 indicates that the infiltration flow is of the same order of magnitude as the total incoming flow. We can conclude that the infiltration flow in the test apartment is a significant portion of the total incoming flow when the windows are closed.

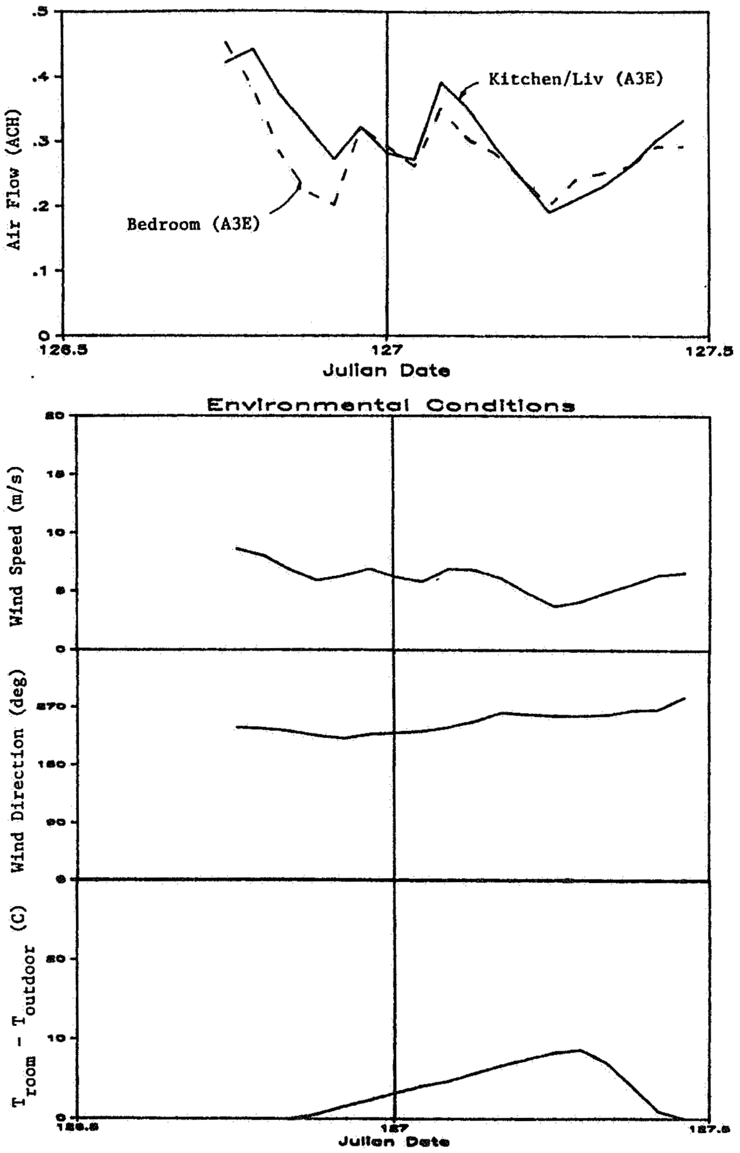


Figure 3. Airflow into the test apartment and environmental conditions during "surrounded sampling".

The average tracer gas concentrations over the test period are (note that for this averaging process the concentration of a sample is considered to be 0 if it is below the detection limit of about 10 ppb):

A3F : 1.2 ppb

A2E : 0.0 ppb

A4E : 0.0 ppb

A3D (eff) : 9.7 ppb

Hall : 22.5 ppb

The results indicate that very little of the flow into apartments A3F, A2E, and A4E came from the test apartment. This could have been a result of either high total incoming flows in those apartments or that only a small amount of the air leaving the test apartment traveled to those apartments. However, if it is assumed that the total air flow rate into these apartments is 3.0 ACH (or 36 m^3/h) the most the flow from the test apartment to these apartment could be is 1.4 m^3/h. This indicates that apartment A3E interacts little with its neighbors.

4.0 DISCONTINUED INJECTION

The discontinued injection technique is used to measure the absolute magnitude of the flows between a single zone and the rest of the zones in the building. The following analysis is performed for a building with the CCTG system operating in all the zones. An analysis of the method applied to a multifamily building is presented in reference 7. A experiment starts with all the zones being kept at a constant concentration - i.e. the typical operation of the constant concentration system. At some point in time, the tracer injection into one of the zones is discontinued. During the following transient period the equation governing the TG concentration in the zone where injection was discontinued (zone d) is given by:

$$V_d \cdot dc_d/dt = -c_d \cdot F_{dT} + c_t \cdot \sum_i F_{id} \qquad (7)$$

Where the zones in which injection is being performed are signified by i. This solution to equation 7 is:

$$c_d(t) = c_t \cdot \frac{F^*_{id}}{F_{dT}} + \left[c_t - c_t \cdot \frac{F^*_{id}}{F_{dT}} \right] \cdot \exp\left[\frac{-F_{dT}}{V_d} \cdot t \right] \qquad (8)$$

where $F^*_{id} = \sum_i F_{id}$, which represents the air flow from the other zones in the building to zone d.

Using equation 8 as a model, a regression technique can be used to solve for F^*_{id} and the total flow leaving zone d (F_{dT}). By applying the continuity equation to zone d, the infiltration in zone d is found to be the difference of F_{dT} and F^*_{id}.

With the concentration constant at the target level in the injection zones, the equation for the TG concentration in each i zone is given by:

$$c_t \cdot F_{jT} = c_d \cdot F_{dj} + c_t \cdot F^*_{ij} + S_j \qquad (9)$$

where zone j is one of the injection zones
F^*_{ij} is the flow from the other i zones

By applying the continuity equation (i.e., $F_{jT} = F_{nj} + F_{dj} + F^{*}_{ij}$), this equation is further simplified:

$$S_j/c_t = F_{nj} + F_{dj}(1 - c_d/c_t) \qquad (10)$$

If it is possible to estimate the infiltration flow in the i zones then equation 10 can be used with the injection and concentration data to estimate the flows from zone d to the i zones:

$$F_{dj} = (S_j/c_t - F_{nj})/(1 - c_d/c_t) \qquad (11)$$

The sum of these flows can be used in the continuity equation of zone d to estimate the exfiltration rate of zone d:

$$F_{dn} = F_{dT} - \sum_j F_{dj} \qquad (12)$$

By summing together the continuity equations for all the i zones the following equation is obtained:

$$\sum_i F_{ni} + \sum_i F_{di} = \sum_i F_{id} + \sum_i F_{in} \qquad (13)$$

Given estimates of the infiltration rates in the i zones, equation 13 can be used to compute the total exfiltration rate ($\sum F_{in}$) from the i zones. Thus, the discontinued injection method provides estimates of the infiltration, exfiltration, and total incoming flows of the discontinued injection zone, the flow to and from that zone to the other zones of the building, and the total exfiltration flow of the other zones.

The test building for this portion of the study is an unoccupied, bi-level, single family house located northwest of Washington D.C.. The house is heated with a heat pump warm air system. There are supply vents in each upstair zone and in the downstair zone. The two return vents are located in the upstairs. Infiltration measurements in this structure have been described in previous AIVC publications, including a companion paper in this conference[1,8]. Figure 4 displays the floor plan of the house and includes the location of the mixing fans and the sample and injection lines. The CCTG system was installed to provide measurements in the downstairs and five separate upstairs zones. The system operated with a sample time of 60 seconds. This resulted in a six minute interval between concentration measurements in a single zone.

The tests were conducted over two separate time periods. The first period began August 21st, 1986 and ended September 9th. The second period began January 14th, 1987 and ended January 22nd. For both periods the system was programmed to stop injection in the downstairs zone every second day starting at 12 midnight and continuing for five hours. At the end of each test the system resumed its normal operation. During a five hour test the system kept the concentration constant in the five upstairs zones and the concentration was measured in the downstairs zone. In addition, a separate data acquisition system recorded the indoor and outdoor temperatures and the wind velocity and direction at each half hour. The results from four different discontinued injection tests from the first period (julian dates 239, 241, 247, and 251) and three from the second period (julian dates 16, 18, and 22) are presented in this section.

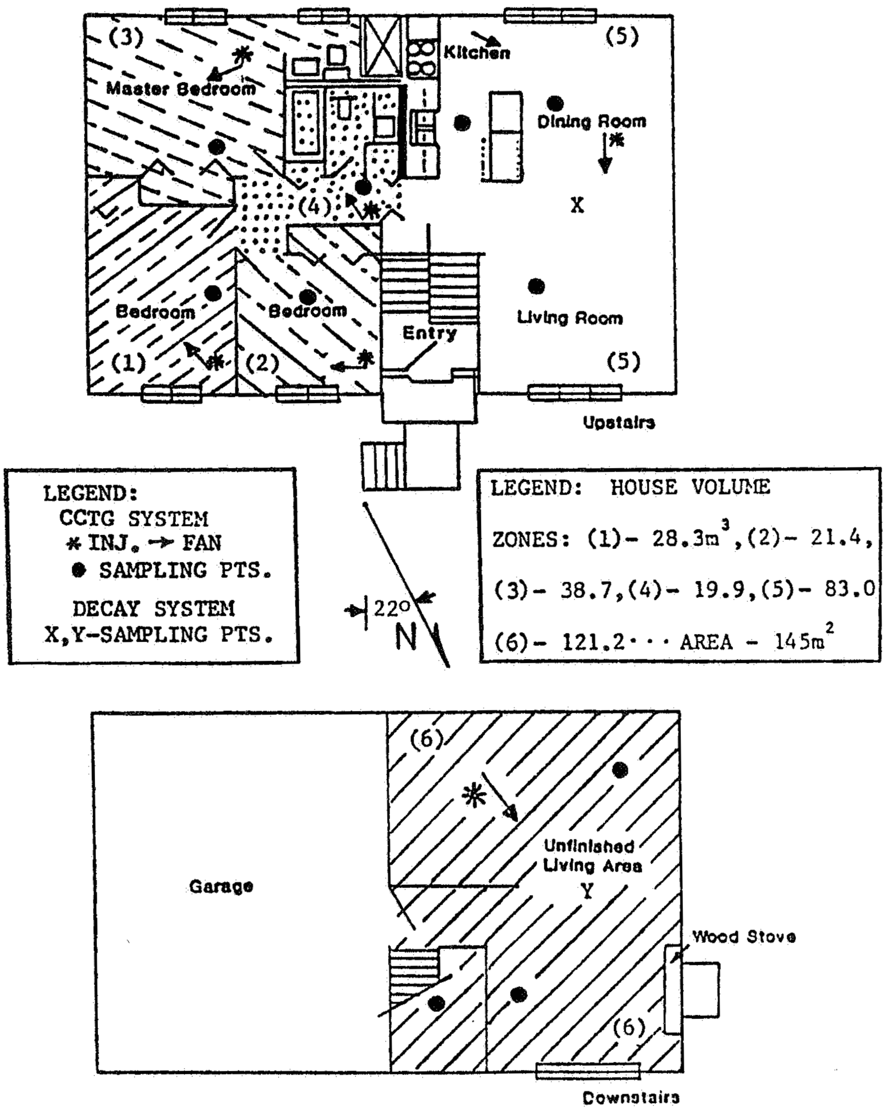


Figure 4. Floor plans of unoccupied test house. The zone volumes and the location of the injection and sampling points, as well as mixing fans are included.

Figures 5 and 6 display the measured concentration in the downstairs and the total normalized injection rate (the SF_6 injection rate divided by the zone volume) in the upstairs for the tests on julian days 18 and 241. For the initial part of the analysis the five upstair zones are grouped together and considered as a single zone. The downstairs concentration and upstairs injection rate respond as expected to the injection being discontinued. The concentration curves from both days show an exponential decrease and the injection rate simultaneously increases. During the test of day 18 the average upstairs concentration was only 3.0% below the target and had a rms deviation about the target of 3.8%. This low deviation from c_t indicates that, even with the downstairs concentration dropping rapidly, the system responds quickly enough to keep the upstairs concentration sufficiently near c_t. When the downstairs injection was started at the end of the test the system typically took one hour to return to stable operation. Thus, the complete test interrupted the normal operation of the CCTG system for six hours. However, as will be shown later, the test period could be reduced to two hours which will reduce the interruption time to three hours.

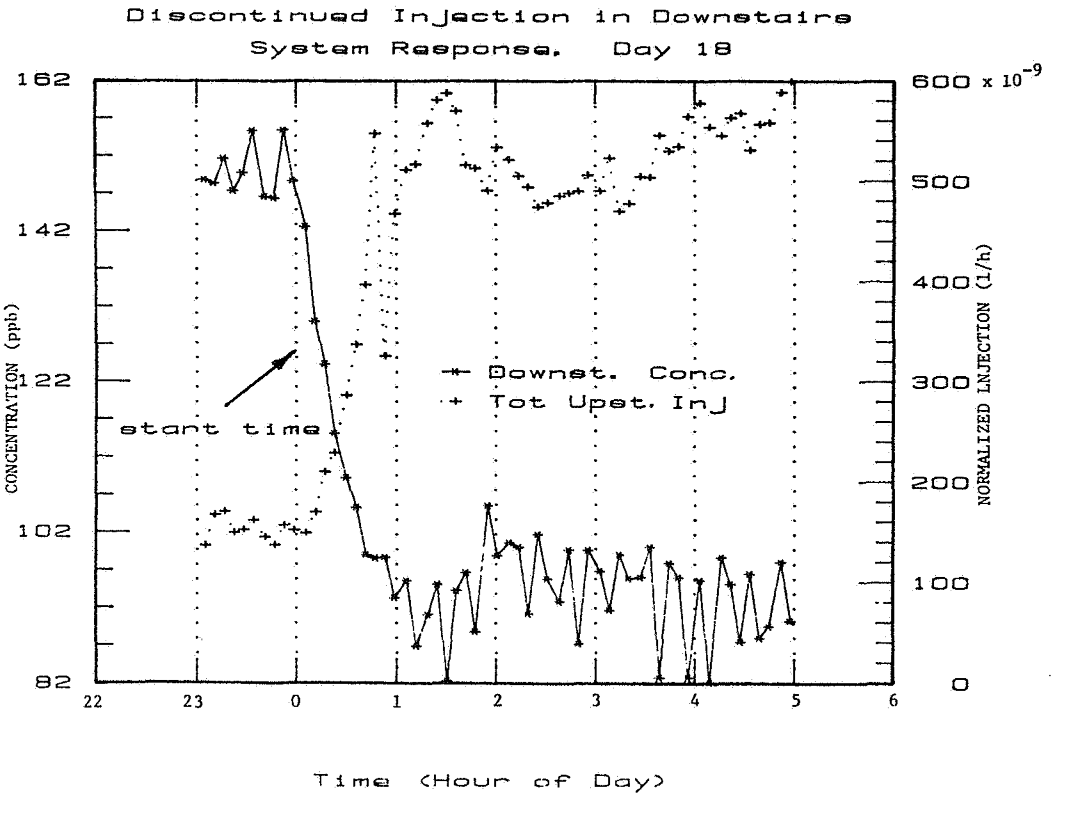


Figure 5. Response of downstairs concentration and upstairs injection rate to discontinued injection downstairs: Day 18.

A rough estimate of some of the flows can be obtained by a quick scan of the data. For example, from equation 8 it is evident that the time constant of the decrease in the downstairs concentration is equal to the total flow entering the downstairs divided by the downstairs volume and the steady-state concentration (c_{ss}) divided by c_t is equal to F^*_{id}/F_{dT}. Figure 5 shows that during the cold winter weather (indoor-outdoor ΔT of 17.6 °C) of day 18 the downstairs reached a c_{ss} of about 95 ppb in approximately one hour. Since c_{ss} is reached in about 3 time constants, the total incoming flow is about three ACH or 360 m^3/h. Also, the ratio of c_{ss} to the target (0.6) indicates that about 60% of the air entering the downstairs came from the upstairs. Finally, the roughly three-fold increase in the upstairs injection rate after injection is discontinued suggests that the air flow from the downstairs to the upstairs is much greater than the upstairs infiltration. In contrast to the winter period, the mild weather data displayed in figure 6 shows a longer decay time and lower c_{ss}. This indicates a lower incoming flow in the downstairs and that less of the incoming flow came from the upstairs. Also, the relatively smaller increase in the upstairs injection rate suggests a smaller flow from the downstairs to the upstairs.

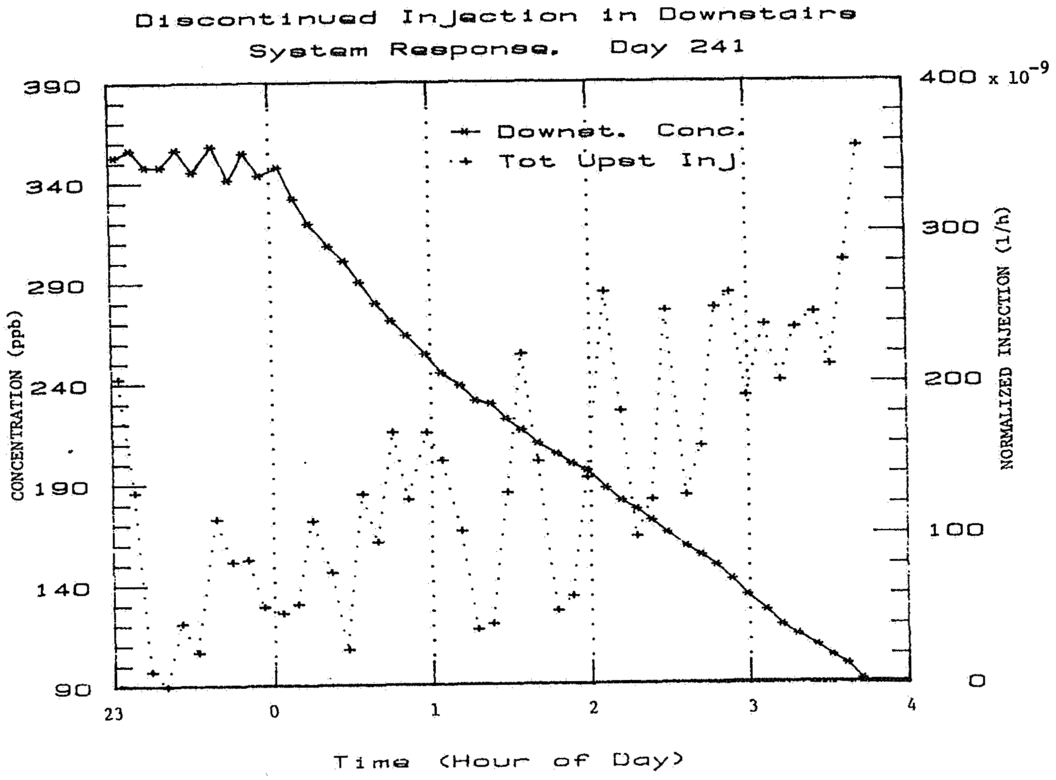


Figure 6. Response of downstairs concentration and upstairs injection rate to discontinued injection downstairs: Day 241.

A rigorous, quantitative analysis of the data can be performed in a number of different ways. The first step of the analysis is to estimate the airflows in equation 8. For this process a choice must be made of which parameter identification method will be used and the length of time over which the analysis is performed. Two different least square regression techniques were studied. The first is a nonlinear method developed by Marquardt[9] that is available in a commercial statistics program. For this method the form of the equation is identified as:

$$c_d = c_t \cdot P_1 + c_t \cdot (1 - P_1) \cdot \exp(-P_2 \cdot (t - t_o)) \qquad (14)$$

<u>where</u> $P_1 = F^*_{id}/F_{dT}$
$P_2 = F_{dT}/V_d$
t_o = the start time of the test

The columns of c_d and t are input to the program to yield the estimates and standard errors of P_1 and P_2. Figures 7 and 8 display the first two hours of concentration data and fitted curve from the regresssion for days 18 and 241. The results show good agreement between the fitted model and the measured concentration with low standard errors for the estimate. As expected from the qualitative analysis performed earlier, the decay is more rapid for day 18 than for day 241 (a time constant of 2.76 compared to 0.58) and the relative value of c_{ss} is higher.

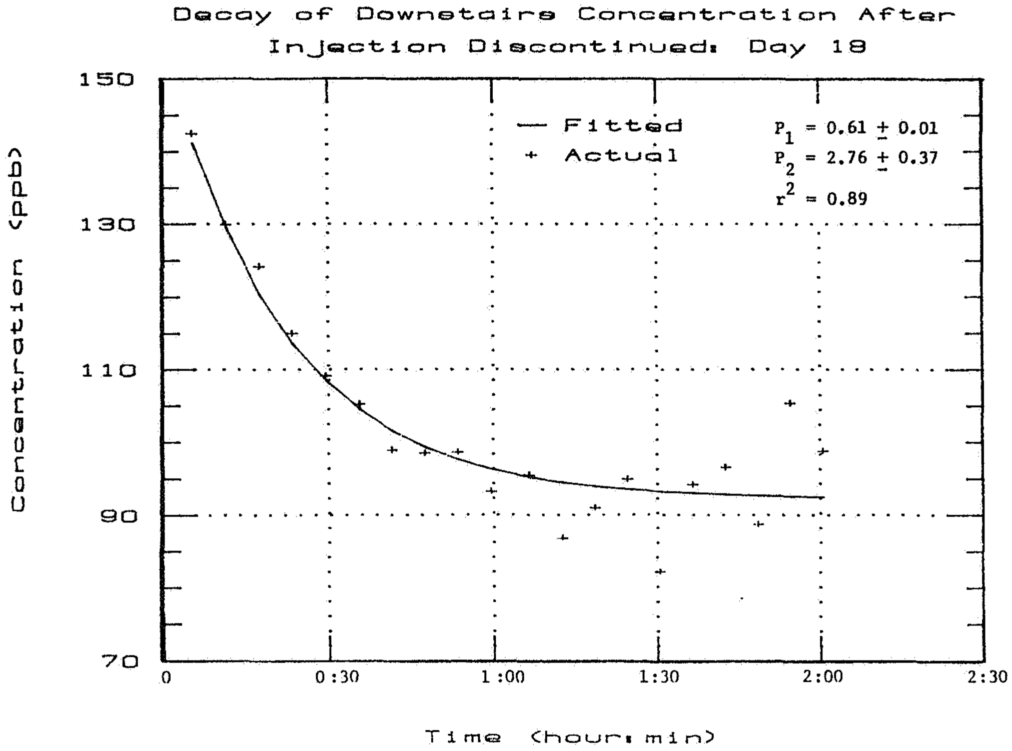


Figure 7. Results of nonlinear regression analysis of the downstairs concentration: Day 18 - two hours.

A second type of regression technique was applied to the concentration data. For this method, c_{ss} is estimated to be the average of the measurements after the concentration appears to be steady. With this value, a log-linear regression of the downstairs concentration minus c_{ss} versus time is performed to yield the time constant of the decay. For the winter data the results from this technique were similar to those from the nonlinear method. However, since the concentration for the summer/fall tests did not reach a steady value by the end of the five hour test, the technique could not be applied to those data sets. This points out one of the drawbacks of this method: a

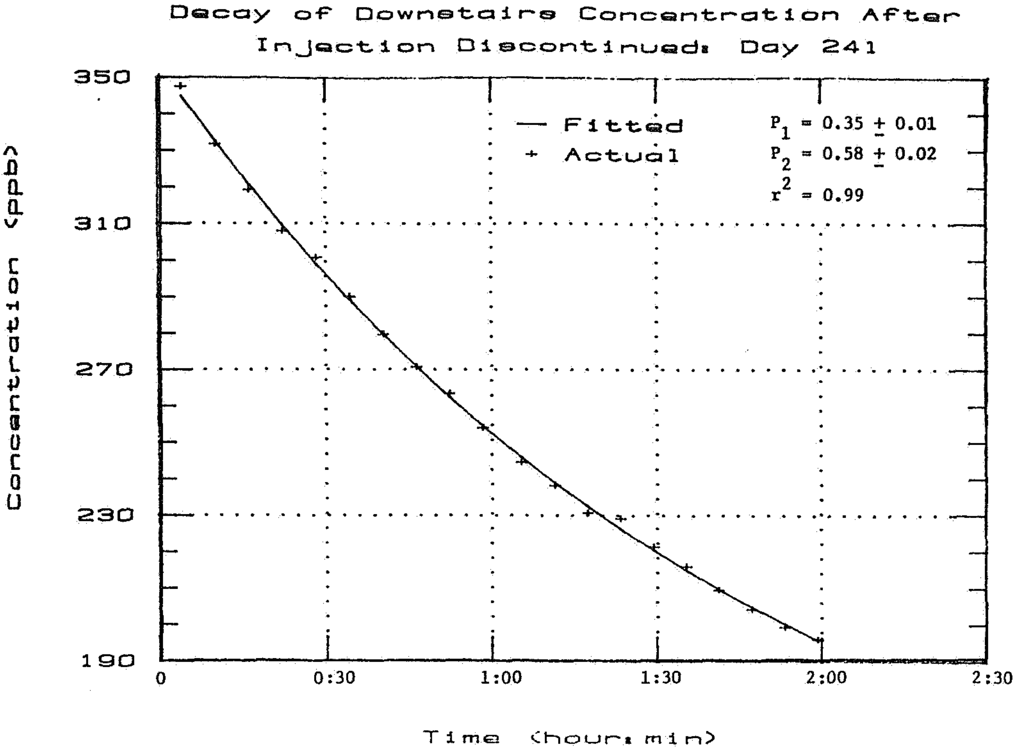


Figure 8. Results of nonlinear regression analysis of the downstairs concentration: Day 241 - two hours.

prohibitively long test period may be required to achieve a steady concentration in the discontinued injection zone. Futhermore, it is not possible to include concentrations in the regression analysis which are lower than c_{ss}. When the steady-state value is approached quickly and there is a moderate amount of scatter, such as occurs on day 18, measurements below c_{ss} are encountered early in the test. If the analysis period is halted when a measurement below c_{ss} is encountered, the analysis period may be too brief. Including only the values above the steady level would result in biased estimates. Because of these drawbacks and the easy implementation of the nonlinear method, the nonlinear method was chosen as the preferred technique.

Another variable in the analysis process is the length of time over which the analysis is performed. In general, there must be enough concentration data for the regression technique to properly determine F_{dT} and F_{nd}. The degree of scatter in the data due to measurement error, nonuniform mixing, and short term fluctuations in the flow rates determines how much data are required to achieve the desired accuracy of the estimates. However, the time period must not be chosen to be so long that some of the assumptions of the model are invalidated. For example, the solution of equation 7 assumes that the flow rates F_{dT} and F^*_{id} are constant. If there is a random fluctuation of these flows then the regression technique will properly estimate their average value but a steady shift in either flow during the analysis period could bias the results. A third consideration is the desired time resolution of the measurements.

The nonlinear regression technique was performed on the data from the seven test days using the first two hours and the entire five hours of data. The estimates and standard errors of the downstairs infiltration and upstairs to downstairs air flows from the two hour analyses are displayed in table 3. The relatively low standard errors (11 to 18% - except for one high percent error that occurred for a low interzone flow) indicate that the 20 values from a two hour period are sufficient to provide good accuracy while maintaining a short enough period to insure approximately stable flows and good resolution. The assumption of steady flows does not always hold for longer periods. Figure 9 displays nearly four hours of the measured concentration and fitted regression curve for day 241 (the measurements went off scale after four hours). Although the fit is good, the regular deviations of the measured values away from the curve indicate that the flows were not constant. As a result, the relative errors of the two parameters are larger than for the two hour analysis and the estimated value of parameter one is physically impossible. In addition, a five hour period was not necessary for the winter periods since the steady concentration was reached during the second hour. Thus, it appears that a two hour analysis period provides good accuracy and adequate time resolution.

TABLE 3

Estimated Air Flow Rates From Discontinued Injection Method
(Uncertainties in parenthesis)

	Weather		Air Flow Rate [m^3/h]					
Day	dT[°C]	V[m/s]	F_{01}	F_{02}	F_{12}	F_{21}	F_{10}	F_{20}
239	4.2	2.4	69	14	5	28	92	-9
			(9)	(4)	(14)	(4)	(18)	(15)
241	13.9	0.4	46	5	31	25	39	12
			(5)	(1)	(12)	(3)	(14)	(12)
247	3.9	1.6	78	14	16	26	88	4
			(14)	(4)	(11)	(5)	(17)	(12)
251	6.0	1.1	92	11	33	4	63	4
			(10)	(3)	(11)	(2)	(15)	(11)
16	10.3	1.5	130	34	179	162	112	52
			(27)	(6)	(36)	(33)	(55)	(49)
18	17.6	1.4	129	40	269	206	65	103
			(23)	(6)	(46)	(37)	(72)	(59)
22	17.1	1.1	170	44	288	257	139	75
			(28)	(6)	(63)	(42)	(90)	(76)

Note: F_{ij} is the flow from zone i to j.
zone 0 is outdoors, 1 is downstairs, 2 is upstairs

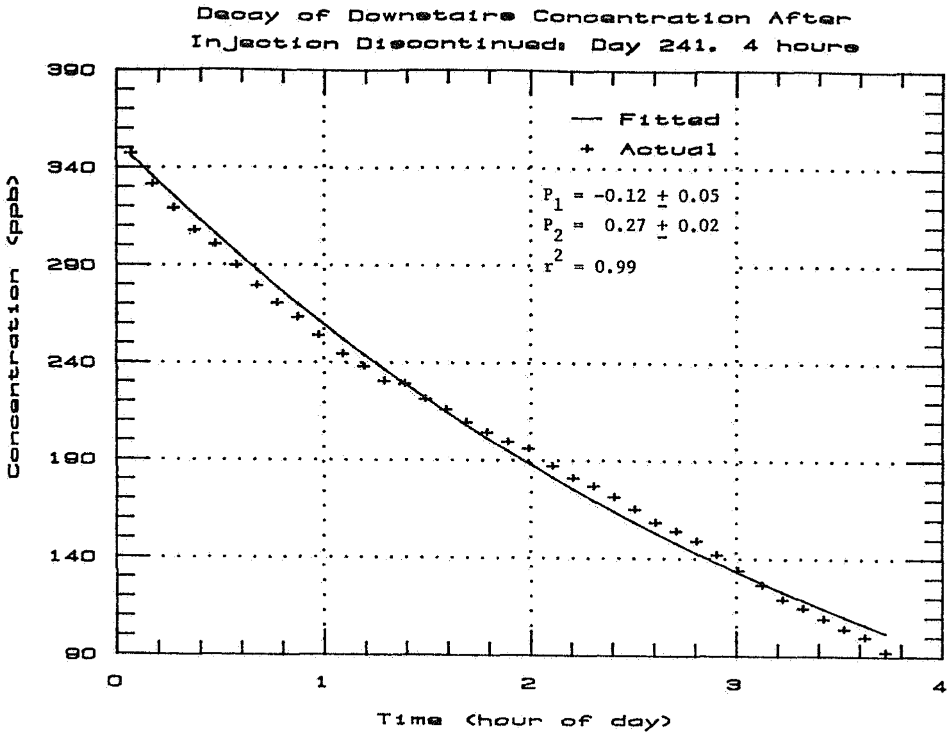


Figure 9. Results of nonlinear regression analysis of the downstairs concentration: Day 241 - four hours.

The solution of the remaining flows begins with using equation 11 to solve for the flows between the discontinued injection zone and the other zones. As stated earlier, the solution of this equation requires an estimate of the infiltration in the other zones. This could be obtained from either the value measured immediately before injection was discontinued, from a separate, simultaneous tracer gas measurement, or from a model of the air flows. A separate measurement would be the most accurate approach but it eliminates the advantages of the single tracer system. An estimate from the previous measurement is the simplest approach but it could be in error if there are significant changes in the weather during the test (the tests are conducted in the early morning to reduce weather variations and occupant effects). The third approach is to use an empirical model relating infiltration to weather variables (and possibly heating system use) that is generated from CCTG measurements in the same building. This method does account for variations in the infiltration due to weather changes, but the amount of data needed for an accurate model is often prohibitive. In most cases, the previous measurement will be preferred since it is readily available and provides reasonable accuracy.

Empirical models of the infiltration rates for the two separate test periods (days 16 to 22 and 235 to 251) were available from a companion study of CCTG measurements in the test house[1]. This model was used for the winter period since the regression fit was relatively good (r^2 = 0.79). However, the fit to the summer-fall data was unsatisfactory (r^2 = 0.36). For the tests during this period the infiltration measurement immediately before the injection was discontinued is used to estimate the upstairs infiltration.

The estimated infiltration rate and average injection rate (S_j) in an injection zone and average concentration in the discontinued injection zone (c_d) are inserted into equation 11 to solve for the average flow from the discontinued injection zone to the injection zones. This relationship is accurate if the flows are relatively constant. The sum of these flows and the total flow leaving the discontinued injection zone are used in equation 12 to compute the zone d exfiltration rate. Equation 13 is then used to compute the total exfiltration flow from the injection zones.

The computational procedure described above was applied to the seven test periods to achieve the air flow rates reported in table 3. The results from days 18 and 241 verify the qualitative analysis discussed earlier. In general, the air flows from the winter tests are much higher than those from the summer-fall (s/f) tests. This is expected since the weather is more severe and the operation of the heating system should increase the mixing between the two zones. For the winter tests the ratios of the average interzone flows divided by the downstairs infiltration were 1.3 to 1.9 while they were much less for the s/f tests: 0.2 to 0.6. This indicates that there will be a greater degree of vertical stratification of indoor pollutants in milder weather. During the winter tests the downstairs to upstairs flows were 1.1 to 1.3 times higher than the upstairs to downstairs flows. This result suggests that the mixing between zones due to the heating system operation overwhelms the expected stack flow from the downstairs to the upstairs. The results also show that, because of the stack effect and the large leakage areas in the downstairs[8], there is consistantly greater infiltration in the downstairs than the upstairs. It is interesting to note that the exfiltration is also greater in the downstairs than the upstairs. This is most likely due to the large downstairs leaks.

A pertubation type error analysis was applied to the air flow equations. Given the uncertainties of the variables in the flow equations, the uncertainty of each air flow rate can be approximated by the Euclidean summation of the uncertainty due to each variable in the flow rate equation[10]. For this error analysis the standard errors from the regression analysis were used to compute the uncertainties of F_{dT} and F^*_{id}. The uncertainty of the downstairs volume measurement was assumed to be 10%. For the winter measurements the uncertainty of the upstairs infiltration was chosen to be the standard error of the estimate for the model - 0.03 ACH. For the summer-fall period it was set equal to 25% of the estimated value. The uncertainty of the concentration measurements and tracer gas injection rate were assumed to be 5 and 10%. These uncertainties were used with the pertubation method to compute the air flow uncertainties shown in parentheses in table 3.

The results of the error analysis show that the flows determined from the regression analysis (F_{01} and F_{21} - where zone 0 is the outdoors, 1 is the downstairs, and 2 is the upstairs) have uncertainties less than 20% of the estimated values. For the winter tests the uncertainties of the flow from the downstairs to the upstairs were also about 20%. However, the relative uncertainties for the small flows of the s/f tests were much higher - 40 to 100%. In general, the exfiltration flows have the greatest relative uncertainty. This occurs because these flows are computed from the difference of other flows. This results in uncertainties for the downstairs exfiltration which vary from 20 to 90%. The uncertainties for the upstairs exfiltration flows are even higher: 60 to 300%. Thus, the discontinued injection method gives an uncertainty of about 20% for the downstairs infiltration, upstairs to downstairs flow, and large downstairs to upstairs flows. However, the uncertainties of the exfiltration flows can be as large as the estimated values.

In addition to the uncertainty analysis, the accuracy of the discontinued approach can be examined by comparing the measurements with those from other techniques. One possiblity is to compare the downstairs infiltration measurement from that obtained by the empirical models. Since the models for both the winter and s/f periods had high correlation coefficients (r^2 = 0.90 and 0.83) and the uncertainty of the measurements are about 20%, it is expected that the difference between the two values should be less than 40%. For the winter and s/f tests the downstairs infiltration measurements differed by 13% and 49% from those predicted from the empirical model. Thus, there is good agreement for the winter conditions but poor agreement for the mild weather conditions. The results from mild weather could be due to an inherent difficulty with measurements under those conditions or simply that there was not enough measurements to make a fair comparison. Further studies are needed to properly explain this result.

The CCTG discontinued injection tests in this house were supplemented with simultaneous passive, multi-tracer measurements. These tests were conducted using the PFT method developed by Brookhaven National Laboratory[11]. The analysis of the capillary adsorption tube samplers and computation of the air flow rates was conducted at Princeton. These measurements, described in more detail in a companion paper in this conference[12], provide average infiltration, exfiltration, and interzone flow rates for the downstairs and upstairs zones. A comparison of the PFT measurements and the average of the discontinued injection tests for the two measurement periods is presented in table 4. This comparison provides some indication of the agreement of the two methods. However, it is important to note that the PFT measurements are average values over the entire operation of the CCTG system. In contrast, the average of the discontinued injection measurements includes only a few flows from two hour periods. The results show good agreement between the two methods for all the infiltration measurements. In addition, there is good agreement between the winter period downstairs to upstairs and s/f period upstairs to downstairs measurements. There are large differences in the other measurements. Further tests are required to determine whether the differences are due to the limited number of measurements using the discontinued method or if there is a consistant difference between the two methods.

TABLE 4

Comparison of Discontinued Injection (DI) and PFT Methods
(Uncertainties in parenthesis)

Test Period		Air Flow Rate [m^3/h] F_{01}	F_{02}	F_{12}	F_{21}	F_{10}	F_{20}
Winter	DI -	143 (26)	39 (6)	245 (48)	208 (37)	105 (72)	77 (61)
	PFT -	109 (23)	39 (41)	273 (88)	72 (23)	-92 (50)	240 (48)
Summer	DI -	71 (10)	11 (3)	21 (12)	21 (4)	71 (16)	3 (13)
/Fall	PFT -	65 (12)	17 (13)	85 (27)	29 (10)	9 (22)	74 (16)

Thus far the analysis has considered the upstairs to be a single zone. However, the tracer gas measurements were conducted in five separate zones of the upstairs. This data can be used in equation 11 to compute the flows from the downstairs into each of these zones. The results of the computations for the seven test periods are reported in table 5. The discrepancy between the total flow and that in table 3 occurs because the infiltration in each upstairs zone is obtained from the previous measurement and not that predicted from the model. The results show that during the s/f tests little, if any, air flows from the downstairs directly to the bedrooms. Instead, it appears that the flow between the downstair and upstairs moves up the large, open staircase and into the kitchen, livingroom, and diningroom area (K,L&D). In contrast, during the winter period the air moves fairly uniformly from the downstairs to the upstairs zones. In fact, if the volume of each zone is considered, the relative amount of flow to each upstairs zone is nearly equal. This indicates that the heating system does an adequate job of mixing the air in the house. Further tests could be performed to evaluate the flows between the upstair zones by discontinuing injection in individual upstair zones.

TABLE 5

Estimated Air Flow Rates From Downstairs
to Individual Upstair Zones

Day	Air Flow Rate [m^3/h] Bed 1	Bed 2	M Bed	Hall	K,L&D	Total
239	-2	-2	-3	1	12	5
241	1	0	4	4	22	31
247	-4	-1	-2	4	19	16
251	2	0	2	4	25	33
16	32	19	39	30	80	200
18	49	37	54	21	114	275
22	41	29	49	51	113	284

The discontinued injection method is extremely useful in indoor air quality studies. As shown in another study of this house, the infiltration flow rate in the bedrooms is much less than that recommended by ASHRAE standards[1]. However, the air entering the downstairs could often provide adequate ventilation of the upstairs if there is good communication between the two areas. These studies indicate that during the winter months when the heating system is operating there is good communication between the downstairs and the bedrooms. In mild weather conditions the communication is poor and the downstairs infiltration can not be counted on to provide ventilation in the bedrooms. With night setback one would also anticipate poor communication just when sleeping occupants would most desire bedroom ventilation.

5.0 CONCLUSIONS

The results show that the modified CCTG techniques are useful extensions to the typical multi-zone infiltration measurements. A series of guarded zone and surrounded sampling tests were conducted to measure infiltration and interzone flows in a 60-unit multifamily building. During the guarded zone tests the system was able to keep the concentration near the target level. The results showed that the infiltration to an apartment with closed windows was typically below 0.35 ACH. Opening the windows a linear distance of 50mm increased the infiltration rates by about a factor of 10 and wide open windows gave another factor of ten increase. The interzone measurements indicated that there is little direct communication between the apartments and that the total incoming flow is of the same order of magnitude as the infiltration flow.

A series of seven discontinued injection tests were successfully performed in a unoccupied single family house. The tests provided measurements of the average downstairs and upstairs infiltration, exfiltration, and interzone flow rates for two hour periods. As expected, the winter flows were much greater than those during mild weather. The operation of the heating system during the winter conditions appeared to provide adequate mixing in the house. In contrast, the upstairs bedrooms had little, if any, communication with the downstairs in mild weather. The results suggest that there may be indoor air quality problems in the upstairs bedrooms during mild weather. The error analysis indicates that the discontinued injection method gives an uncertainty of about 20% for the downstairs infiltration, upstairs to downstairs flow and large downstairs to upstairs flows. However, the uncertainties of the exfiltration flows can be as large as the estimated value. Comparisons of the results with those from empirical models and PFT tests show agreement for some of the flows and poor agreement for others. Further tests are required to properly compare the methods.

REFERENCES

1. HARRJE, D.T., BOHAC, D.L., and FORTMANN, R.C.
"Measurement of Seasonal Air Flow Rates in an Unoccupied Single Family House." Proceedings of the 8th Air Infiltration and Ventilation Centre Conference: Ventilation Technology - Research and Application, Air Infiltration and Ventilation Centre, Great Britian, 1987.

2. ASHRAE
ASHRAE handbook--1985 fundamentals, p. 22.7. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1985.

3. SINDEN, F.W.
"Multi-chamber theory of air infiltration." Building and Environment, Vol. 13.

4. BOHAC, D.L., HARRJE, D.T., and NORFORD, L.K.
"Constant concentration infiltration measurement technique: an analysis of its accuracy and field measurements." Proceedings of the ASHRAE/DOE/BTECC Conference on Thermal Performance of the Exterior Envelopes of Buildings, Clearwater, FL, Dec. 1985.

5. BOHAC, D.L.
"The use of a constant concentration tracer gas system to measure ventilation in buildings." PU/CEES Report No. 205., 1986.

6. HARRJE, D.T. AND KEMPTON, W.M.
"Ventilation, air infiltration and building occupant behavior." Proceedings of the 7th AVIC Conference-Occupant Interaction With Ventilation Systems, Air Infiltration and Ventilation Centre, Great Britian, Document AIVC-PRO-7-86, 1986.

7. BOHAC, D.L., DUTT, G.S., and FEUERMANN, D.
"Approaches to estimating air flows in large multifamily buildings." ASHRAE Transactions, V. 93, Pt. 1, 1986.

8. HARRJE, D.T., BOHAC, D.L., and NAGDA, N.L.
"Air exchange rates based upon individual room and single cell measurements." Proceedings of the 6th AIVC Conference-Ventilation Strategies and Measurement Techniques, Air Infiltration and Ventilation Centre, Great Britian, Document AIVC-PROC-6-85, 1985, pp. 7.1-7.14.

9. MARQUARDT, D.W.
"An algorithm for least squares estimation of nonlinear parameters." Journal of the Society of Industrial and Applied Mathmematics, 2: pp. 431-441, 1963.

10. BECKWITH, T.G., BUCK, N.L., and MARANGONI, R.D.
Mechanical Measurements. Reading, Massuchusetts: Addison-Wesley, 1982.

11. DIETZ, R. N., GOODRICH, R. W., COTE, E. A., and WIESER, R. F. "Detailed description and performance of a passive perfluorocarbon tracer system for building ventilation and air exchange measurement." Measured air leakage of buildings. ASTM STP 904. Philadelphia: American Society for Testing and Materials, 1986.

12. BOHAC, D.L., HARRJE, D.T., and HORNER, G.S. "Field study comparisons of constant concentration and PFT infiltration measurements." Proceedings of the 8th Air Infiltration and Ventilation Centre Conference: Ventilation Technology - Research and Application, Air Infiltration and Ventilation Centre, Great Britian, 1987.

ACKNOWLEDGMENTS

The authors wish to express their gratitude for the funding provided by the New Jersey gas and electric utilities and the New Jersey Department of Energy through the New Jersey Energy Conservation Laboratory at the Center for Energy and Environmental Studies, Princeton University, and by the United States Department of Energy grants DE-FG01-85CE24422 and DE-FG01-86CE23838. We would like to thank the residents of Lumley Homes and the staff of the Asbury Park Housing Authority for their indulgence and cooperation throughout the studies. The authors also wish to thank GEOMET Technologies for the use of the GEOMET research house in the discontinued injection studies.

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

POSTER S.12

A STUDY OF THE DRYING POTENTIAL OF VARIOUS WOOD-FRAME WALL SYSTEMS USED IN ATLANTIC CANADA

Mr. Leo I. McCuaig, P. Eng.
Oboe Engineering Ltd.
404-251 Laurier Avenue West
Ottawa, Ontario
Canada K1P 5J6

Mr. R.D. Stapledon
Project Implementation Division
Canada Mortgage and Housing Corporation
National Office
Ottawa, Ontario
Canada K1A 0P7

1. INTRODUCTION

The concern that a large number of housing units across Canada, and in particular, through Atlantic Canada are exposed to potential damage from wood rot due to moisture trapped within exterior walls caused a joint task force of Canada Mortgage and Housing Corporation and Canadian Home Builders Association representatives to address the "drying of walls" issue. Included in their mandate was a field research project in Atlantic Canada. The project, undertaken by Oboe Engineering Ltd. and ADI Limited. for the Project Implementation Division of CMHC, involved the erection of test huts in Halifax, Nova Scotia; Fredericton, New Brunswick; and St. John's, Newfoundland and the monitoring of the performance of eight different types of wall construction for a one year period.

To assess the drying rates, the wall panels used in this experiment were intentionally designed with saturated lumber. **As such, high values of equilibrium moisture content recorded and presented in this report, must be considered in relation to the design of the experiment, and not a function of the products or materials incorporated in any particular wall assembly.**

The experimental procedure involved monitoring temperature, relative humidity, pressure, structural moisture content, wind speed and direction, and presence of condensation in each wall panel, in each city, each hour, for one year. This report presents an overview of the results, global trends in the drying of walls, and the sensitivity of wall permeance, geographic location, compass heading and presence or absence of furring strips to wall drying.

2. OBJECTIVES OF THE FIELD STUDY

The objectives of the study were:

* To investigate the effect of climatic differences on the drying rate of construction lumber

* To investigate the driving forces that effect wall drying rate

* To assess the differences in drying rates of furred and non-furred walls

3. TEST HUTS AND WALL PANELS

The test huts were one story buildings approximately 11 meters by 6 meters of floor area. The long dimension housed the test wall panels, and were oriented as north and south walls. All test huts were sided with slate blue vinyl siding. The materials used in the construction of each hut were identical from city to city.

The huts were electrically heated with baseboard heaters, and were humidified. The floor plan of a test hut is included as Figure 1.

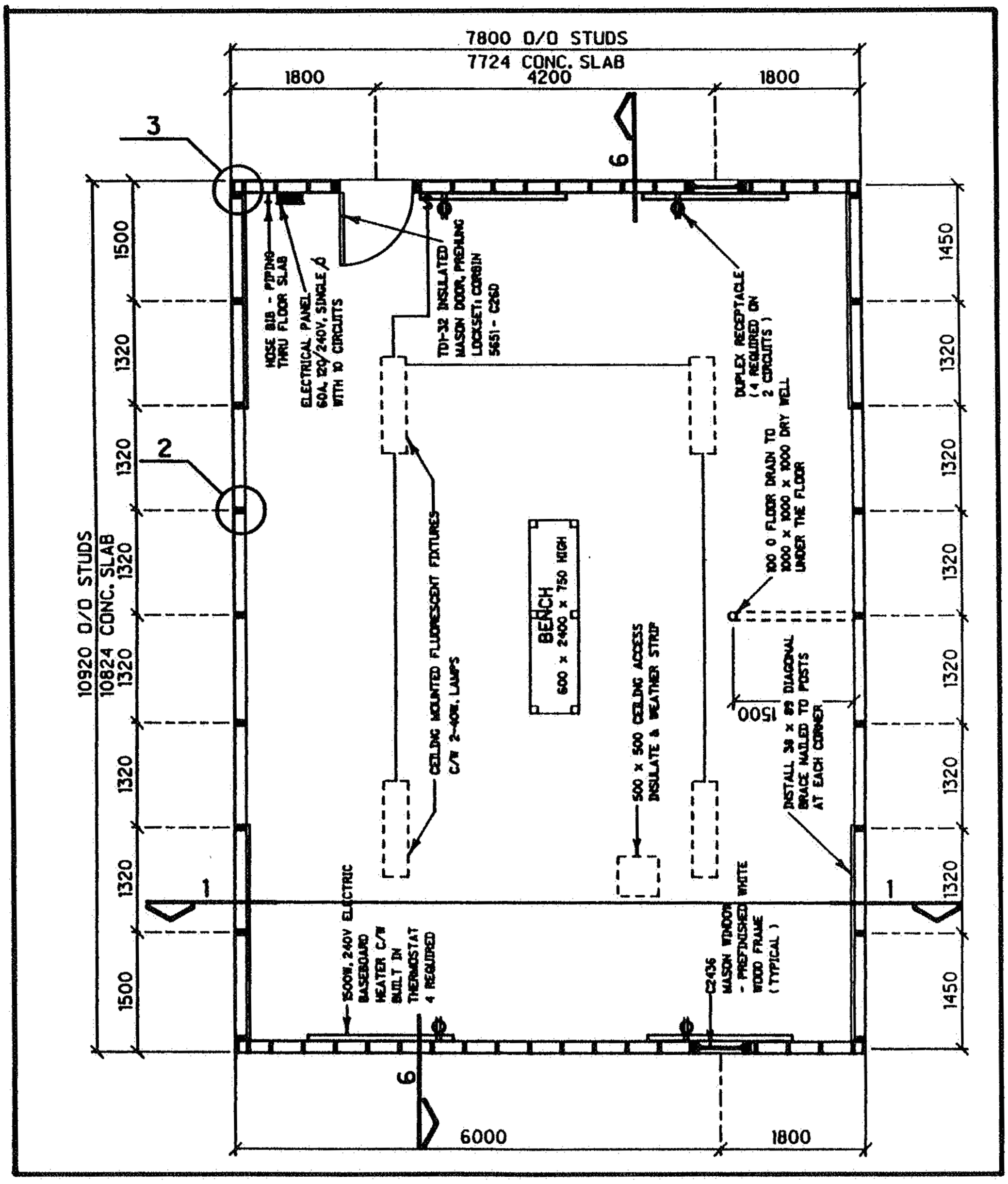


Figure 1: Floor Plan of Test Hut

3.1 Test Hut Construction

The huts were constructed with the cooperation of the University of New Brunswick, the Technical University of Nova Scotia, and the Newfoundland College of Trades and Technology, each of whom supplied on-campus land for the erection of the huts.

3.2 Test Wall Panels

The test wall panels were 2400 mm high by 1200 mm wide, and framed on 400 mm centres. The eight test wall panel set, included as Figures 2 and 3, consisted of a furred and non-furred waferboard sheathed pair, a furred and non-furred rigid fiberglass sheathed pair, a furred and non-furred extruded polystyrene sheathed pair, a cellulose insulated panel, and an expanded polystyrene insulated panel. Throughout this report, the wall panels will be referred to by their respective panel numbers, for simplicity. Note that panel 2 is a furred version of panel 1, that panel 4 is furred version of panel 3, and that panel 6 is a furred version of panel 5. Each panel was instrumented as depicted in Panel 6, Figure 3. Each of the eight panels were installed in the south wall of each test hut, and repeated on the north wall.

The panels were to be constructed using lumber with a moisture content of 26-30%, in comparison to Canadian Building Code requirements of less than 19%. It is of interest to note that the lumber supplied for the construction of the wall panels was from local building supply dealers, from the stockyard. No conditioning was required. All of the lumber was above 26% equilibrium moisture content. These high values are consistent with the results of a framing moisture survey undertaken by the Project Implementation Division of CMHC for the Task Force. In addition, the cellulose panel (Panel 7) was installed as a wet spray, and consequently an additional amount of water was added into that wall cavity.

To minimize the effects of drying towards the edges of each wall, the vapour barrier was wrapped around the edges of each test panel, and sealed against the studs.

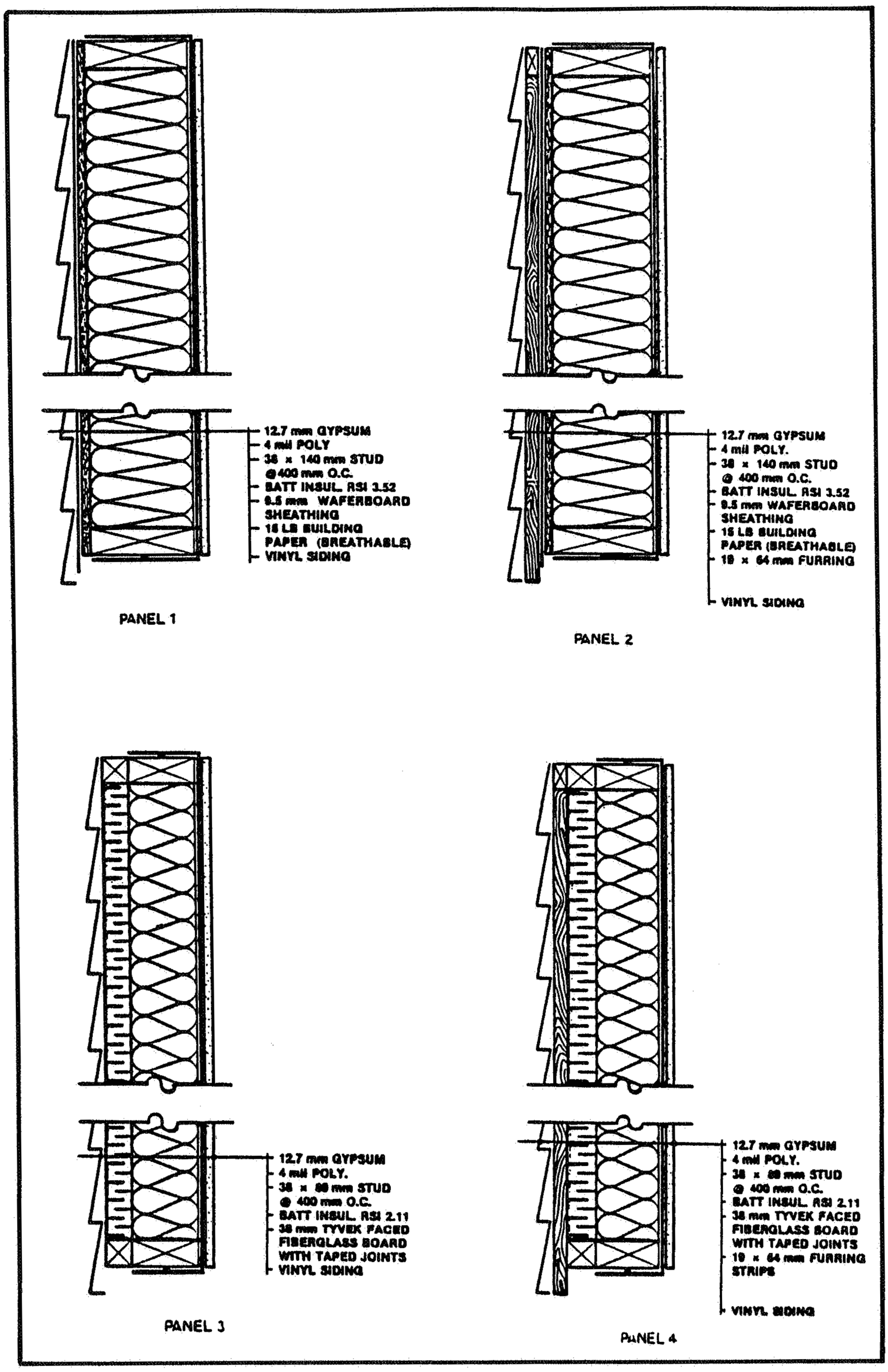


Figure 2: Test Panels 1 to 4

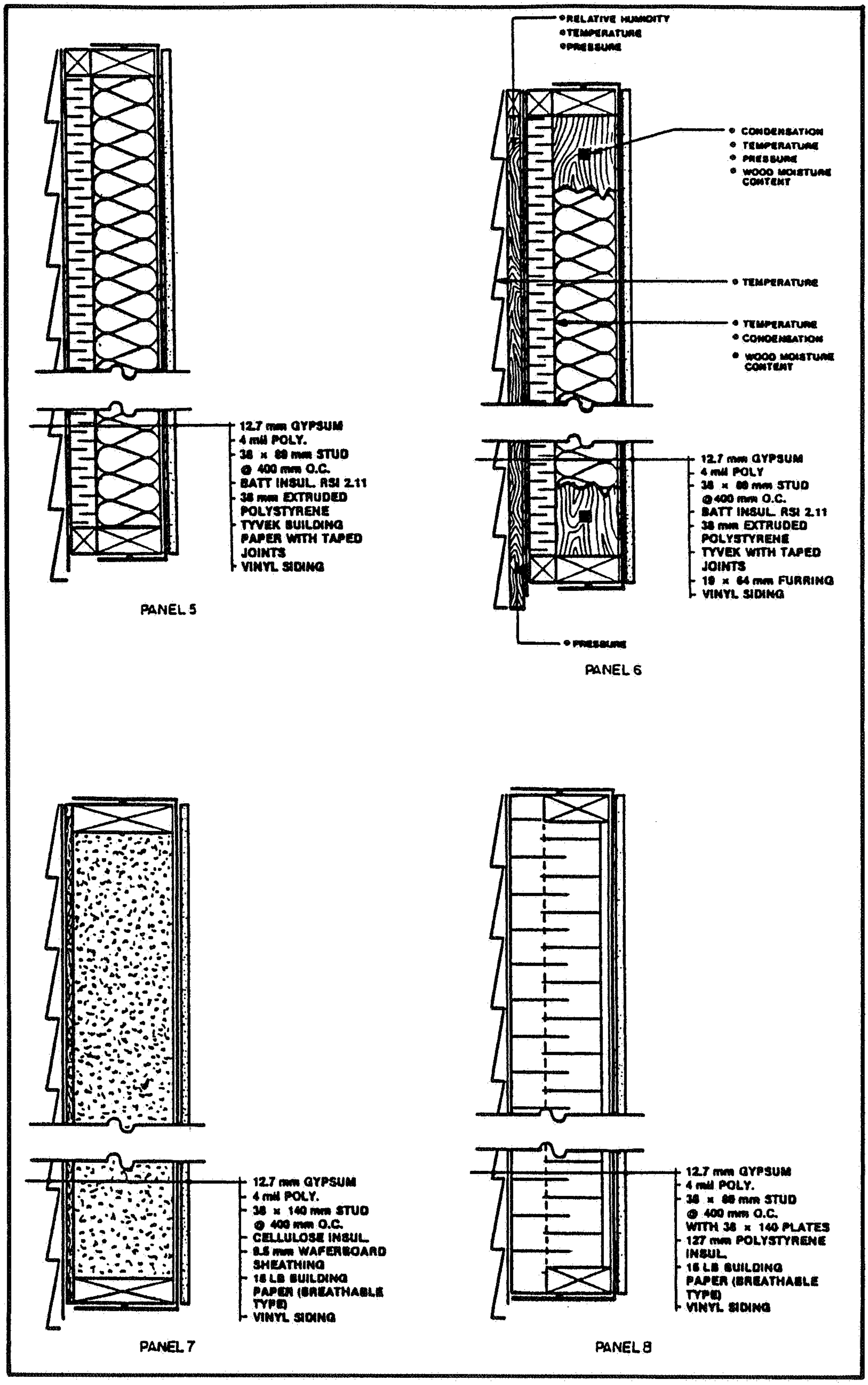


Figure 3: Test Panels 5 to 8

3.3 Test Panel Moisture Transfer and Thermal Properties

The thermal and moisture transfer properties through the insulation of the wall panels are summarized in Figure 4. The thermal resistance is tabulated for the total wall assembly, however, the moisture transfer values include only the sheathing and sheathing paper combinations. It is considered that in the case of this experiment, the moisture flow from the wall cavity will be towards the exterior of the wall and not the interior. This is due in part to the low permeance of the polyethelene vapour barrier, 4 ng/Pa-s-m^2, and its relatively tight installation. As such, each wall's drying capability through the sheathing system is of interest.

Panel	Thermal Resistance (RSI)	Sheathing & Paper Permeance (ng/Pa s m^2)
1. Non-furred, 38x140 studs, batt insulation, wafer board sheathing, 15 lb. building paper, siding.	4.09	43
2. Same as Panel 1, with furring.	4.26	43
3. Non-furred, 38x89 studs, batt insulation, rigid fiberglass sheathing w/Tyvek, siding.	3.77	1723
4. Same as Panel 3, with furring.	3.94	1723
5. Non-furred, 38x89 studs, batt insulation, extruded polystyrene sheathing, Tyvek paper, siding.	3.92	35
6. Same as 5, with furring.	4.09	35
7. Non-furred, 38x140 stud, cellulese insulation, wafer board sheathing, 15 lb. building paper, siding.	3.88	43
8. Non-furred, 28x140 stud expanded polystrene insulation, 15 lb building paper, siding.	3.74	47

Figure 4: Test Wall Thermal and Moisture Transfer Properties

4. OVERVIEW OF THE MONITORING METHODOLOGY

Each panel was instrumented both 150 mm from the top, 150 mm from the bottom of a centre stud of each panel, and at mid height, with the following sensors:

a. Thermocouple
b. Pressure tap
c. Condensation gauge
d. Wood moisture pins

Wood moisture pins were installed in the mid-height position, only in the panels that had wood based sheathings, 1, 2, 7. The instrumentation was placed in the centre 400 mm wide cavity of each wall panel, to minimize any edge effects where the test panels met the building structure.

In addition, the strapped cavities were instrumented for relative humidity (RH) and temperature. At one location on each the north and south walls, the inside surface temperature of the siding was monitored. Exterior relative humidity, temperature, wind speed and direction were measured by sensors located on a three meter high mast extending above the roof peak. Interior relative humidity and temperature were also measured. The interior relative humidity was controlled by the RH sensor connected to a humidifier.

4.1 Data Acquisition System

All sensors were connected to a Sciemetric Instruments Inc. Model 8082 Data Acquisition System which converted their analog signals to digital readings. An Apple IIe microcomputer read these digital values, converted them to the appropriate units (volts, °C, %RH, etc.), and saved them on a data desk. Each sensor was read at twenty minute intervals, and averaged values were saved to disk each hour.

5. RESULTS AND OBSERVATIONS

5.1 Weather Conditions

The ambient temperature, relative humidity, wind speed and direction were recorded three meters above the height of the roof of the test hut, or approximately 7.7 meters above the site grade. The measured values were compared against the averages recorded in the Canadian Climate Normals (Ref. 1 & 2).

On the average, the relative humidity profile was approximately 4%RH higher than the reported long term average values in Fredericton, and 8%RH higher in Halifax and St. John's. In all three locations, the measured temperatures were, on the average, 3° Celcius above the Climatic Normals. The average recorded wind velocity is approximately one-half the values of the Canadian Climatic Normals. However, the Canadian Normals are recorded at 20m mast height, on open terrain (at local airports). As such, the Climatic Normals would be higher than for an urban site.

5.2 Final Structural Moisture Content

Observations from Figure 5:

* In most instances the upper wall positions (2255 mm above grade) dried to a lower value than the lower wall positions (190 mm above finished grade), however the differences are slight.

* South facing walls dried to lower values that the north facing walls.

* The differences in south/north drying is more acute for walls of lower sheathing/sheathing paper permeance (panels 1, 2, 5, 6, permeance 35 - 43) than for walls with highly permeable sheathing combinations (panels 3, 4, permeance 1723).

* The presence or absence of furring strips had little effect on the final structural moisture content.

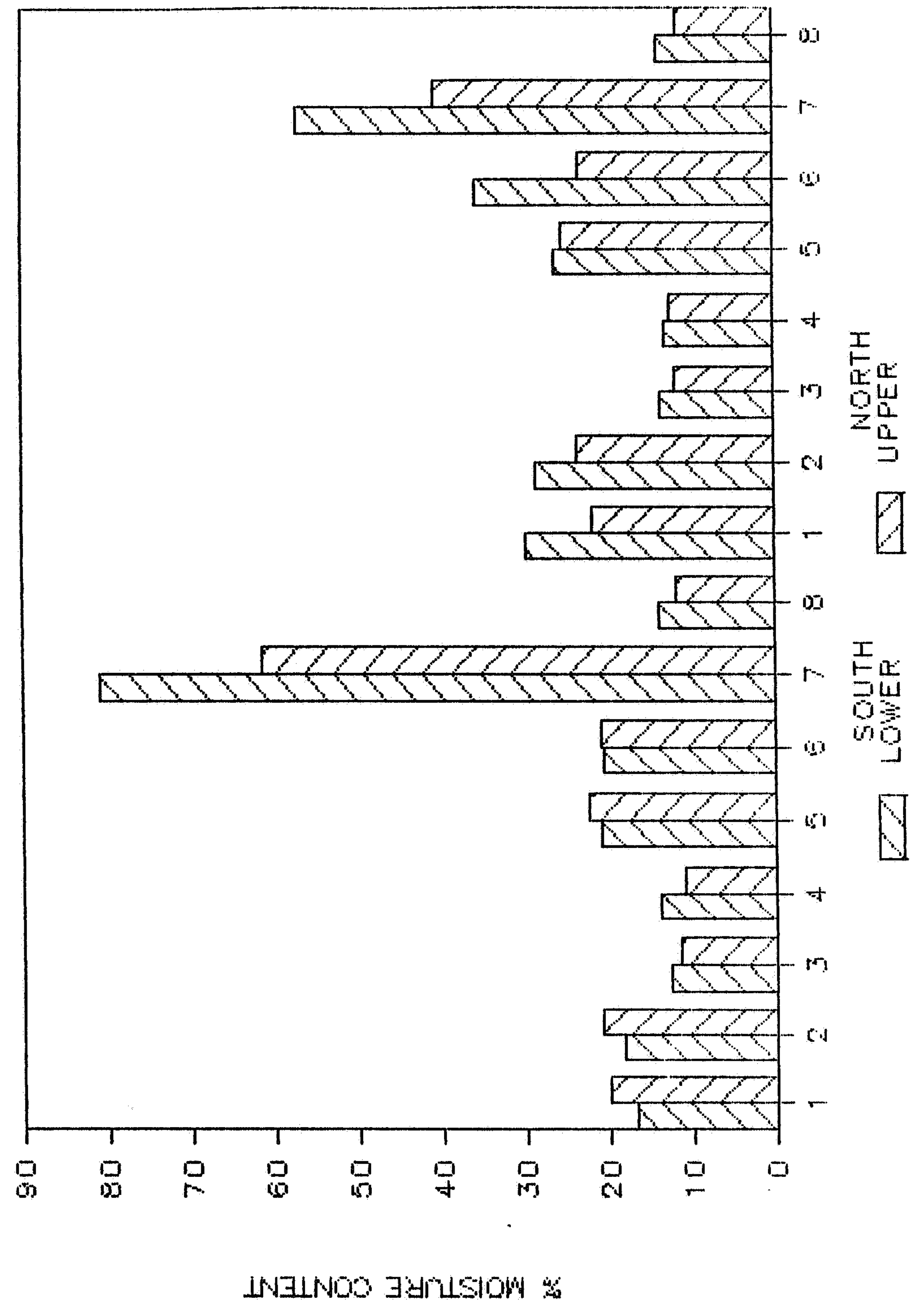


Figure 5: Average of Final Moisture Content Values

- Panel 8, with no sheathing other than felt building paper (permeance 800) performs similar to panels 3 and 4, which have high permeable sheathing combinations (permeance 1723).

5.3 Final Structural Moisture Content, Comparison to Building Code Requirement of Less than 19% MC

Observations from Figure 6:

- On the average, south panels 1, 2, 3, 4 and 8 have dried to the Building Code value.
- South panels 5 and 6 are very close to the Building Code value.
- On the average, north panels 3, 4 and 8 have dried to the Building Code value.
- Moisture conditions that promote decay are present in south panel 7, and north panels 1, 2 ,5, 6, and 7.

		Fredericton		**Halifax**		**St. John's**	
		Lower	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**
South	**1**	14	23	17	17	20	20
	2	16	22	19	23	20	18
	3	11	12	11	11	16	12
	4	15	13	12	10	15	10
	5	16	24	22	25	25	18
	6	26	28	18	20	18	15
	7	65	55	60	62	118	68
	8	14	10	13	12	15	14
North	**1**	28	20	31	25	31	21
	2	23	17	28	29	35	25
	3	11	11	15	13	15	12
	4	12	14	12	12	15	11
	5	33	30	17	23	29	23
	6	35	25	45	25	27	20
	7	45	32	51	45	76	45
	8	13	12	12	12	17	10

Figure 6 Table of Final Structural Moisture Content values, % MC

5.4 Rate of Drying

Observations from Figure 7:

- The south walls lost more water than the north walls. The actual total north wall moisture loss was 90% of the south wall moisture loss.
- In both the north and south walls, non-furred panel 1 dried faster than its furred counterpart, panel 2.
- The presence or absence of furring made very little difference to the drying rate of the high permeance panels, 3 and 4.
- In both the north and south walls, the furred panel 6 dried slightly faster that its non-furred counterpart, panel 5.
- The rate of drying increases as the permeance of the sheathing system increases.

Visual Inspection

5.5

The drywall, vapour barrier, and insulation was removed from the test wall panels in Fredericton on April 14, 1987 and the condition of the structural members noted.

In general, the south facing wall panels were found to be free of mold growth, with the exception of very slight black patches on panel 6. Minor swelling of the waferboard in panel 7 was noted. On the north face, all the waferboard sheathing, panels 1, 2, and 7 experienced swelling, and were visibly wet. In both panels 5 and 6, mold growth (black blotches) were evident on the studs.

The top row of siding was removed, to access the relative humidity sensors, and noted on the south side was total condensation coverage of the inside surface of the siding. The siding was removed at approximately 10:00 AM.

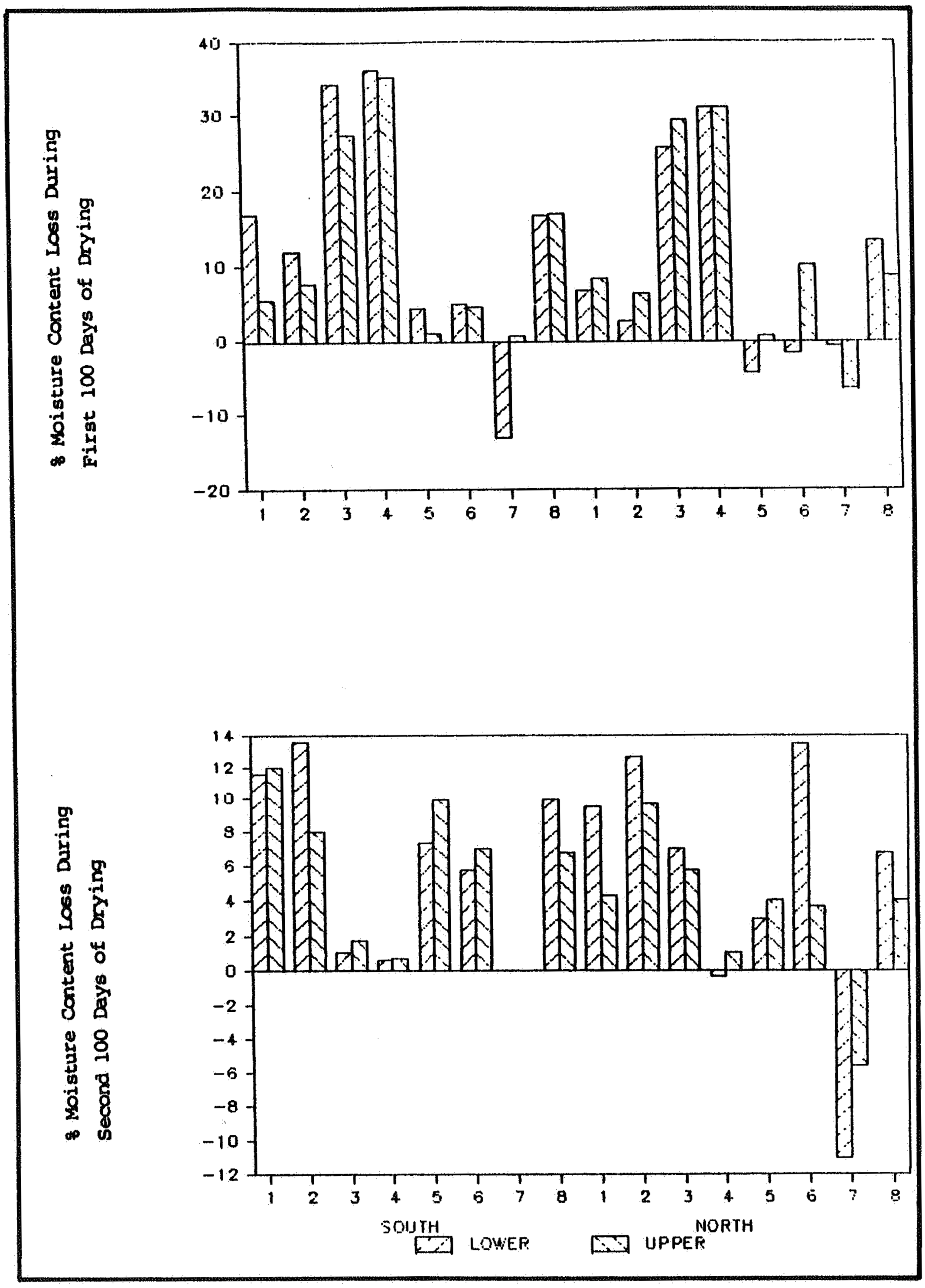


Figure 7: Average Rates of Moisture Loss is Test Studs, All Sites

6. DISCUSSION AND SUMMARY

6.1 Condensation

Conditions that allow condensation to form on the inside surface of the sheathings existed during December to March in all three locations. Conditions that allow condensation to form behind the siding were experienced during winter months, for a short period of time during the very early morning hours. These trends are not limited to the case of saturated walls, but to all wall assemblies, to varying amounts. Condensation can occur in limited instances on the cold side of structural members in a wall assembly in which the structural moisture content is below 19%. In dry assemblies, the low occurence of condensation would not usually present any problems. Indeed, in most of the wall assemblies in this project, the actual calculated occurences of condensation in wall panels of structural moisture content up to 26% was not great.

However, a trend that re-appeared with overwhelming consistancy was early morning condensation behind the siding. These conditions existed in Fredericton from October through April, in Halifax during February, and in St. John's in December and January. This free water was vapourized into the air in the strapped cavity during the daytime, as evidenced by comparing the rise in vapour pressure in the furred cavity, compared to the ambient, during the day. Although sensors were not present behind the siding of the non-furred panels, it is probable that the vapourization of free water was also taking place. However, in the absence of an air gap, the amount of free water vapourized could be less than the amount present, and thus wet conditions would remain.

6.2 Drying Mechanisms

The observations from this experiment suggest correlations of both air leakage and sheathing system permeance to the ability of a wall assembly to dry to the outside.

The north walls were not as consistent as the south walls in either drying rate or final moisture value. The south walls generally dried to acceptable values, while only the high permeance sheathing system panels did so on the north. The combination of low solar gain, and air leakage may reverse the drying trends to form wetting forces. The data from this study suggests this mechanism, but cannot be conclusive.

6.3 Furring Strips

The presence of furring strips had little effect on the structural drying of the test wall panels. However, the presence of the air gap behind the siding may have substantial benefits to the longevity of wood based sidings, and sheathings by providing a receiver for vapourizing water from the siding cavity. Further investigations in this regard are recommended, to validate or disprove this theory.

7. REFERENCES

1. Canadian Climate Normals, 1951-1980, Vol. 5, Wind, Environment Canada, 1982.
2. Canadian Climate Normals, 1951-1980, Vol. 8, Atmospheric Pressure, Temperature and Humidity, Environment Canada, 1982.
3. Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method, CAN/CGSB-14910-M86, Canadian General Standards Board, 1986.
4. Drying of Walls - Atlantic Canada, Instrumentation Report, Oboe Engineering Ltd., 1986.
5. Building Science for a Cold Climate, Hutcheon, N.B. and Handegard, G.O., John Wiley & Sons, 1983.

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

POSTER S.13

FLOWRATE MEASUREMENTS WITH A PRESSURE COMPENSATING DEVICE.

H PHAFF

TNO Division of Technology for Society
P O Box 217
NL-2600 AE Delft
Netherlands

Introduction

In the past years the need has grown for a sensitive flowrate meter with a very low pressure drop. Such a device can be used to measure flowrates of airflows through the grilles of mechanical ventilation systems with low duct pressures. Another application would be the measurement of flowrates through the different rooms of a dwelling during a blower door test.

A prototype was developed based on the very simple principle of a throttled fan. The prototype proved to be accurate and capable of measuring flows on ducts with natural ventilation. Now the device has been redesigned and is produced by an instrument manufacturer.

Some of the specifications

Flowrate 0 to 0.063 m^3/s (230 m^3 per hour or 130 ft^3 per minute)
Flow error < 5% of the reading or +/- 0.0005 m^3/s (2 m^3 per hour or 1 ft^3 per minute)
Supply and Exhaust
Manual pressure compensation resolution < 1 Pa
Fast response << 1 s
Battery operated

Applications

*Duct in- and outlets
 Commissioning, balancing, line diffusors
*Excellent use at low duct pressures
 Passive shafts, natural ventilation
*Direct crackflow measurements
*Distribution of flowrates over internal doors
*Fast determination of the distribution of flowrates during
 blower door or pressurisation tests

Crackflow measurements (Figure 1)

A box is placed over the area in which the cracks are situated. The flowmeter is placed on the opening in the box and will indicate the crackflow. This box does not have to be airtight. Near pressure compensation the unwanted leak flows will be minimal.

Flowrate distribution during pressurisation tests (Figure 2)

Rooms with a low leak flow through the facade can easily be measured by placing a shield of cardboard in the opening of the internal door. The flowmeter is pressed on the opening in the board and will indicate the flow through the facade. Bypass flows through adjacent internal walls will be minimal near pressure compensation. However large internal leak paths will make it impossible to see when compensation is reached.

The flowmeter has a limited range. Large leaks in the facades cannot be measured. In such situations the method of closing the internal door can be used. This method has been developed by P Wouters from Belgium. The pressure will drop in the room with the closed internal door and thus the flow through the facade of that room will decrease. To keep the pressure in the rest of the house constant, one has to reduce the blower door flowrate. This reduction is equal to the reduction of the flowrate through the facade in the room concerned. With the pressure drop in that room the leakage can be calculated. For full determination this has to be done on different pressure levels in the house. Extensions on this procedure can yield results for leakage of internal walls by opening a window during the pressurisation and closing the internal door.

Both methods - the flowmeter and the internal door - are supplementary. If the range of the flowmeter is insufficient the method of the internal door will give a reasonable pressure drop. And if the method of the internal door creates no pressure drop in the room the flow will be small enough for the flowmeter to measure it. However, large bypass leakage paths in the adjacent internal walls can spoil both methods.

Concluding remarks

The Flowmeters have a large applicability in the research field but also in the field of commissioning.
The zero pressure indicator could be somewhat more sensitive in the research field. At high magnetic fields this zero pressure meter will not work as it uses magnets to be forced back in the zero position.
A flexible hood can enlarge the number of grilles the meter will fit on.

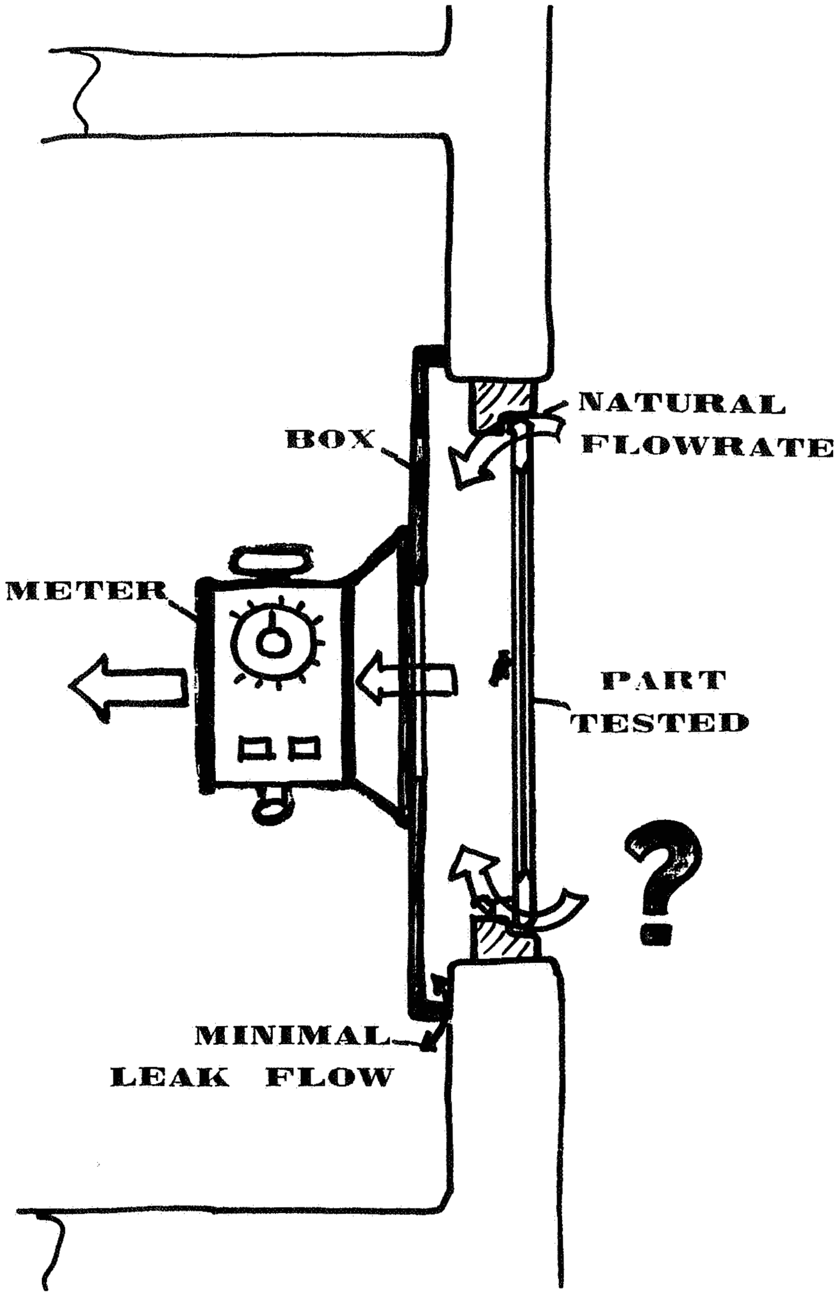


Fig. 1

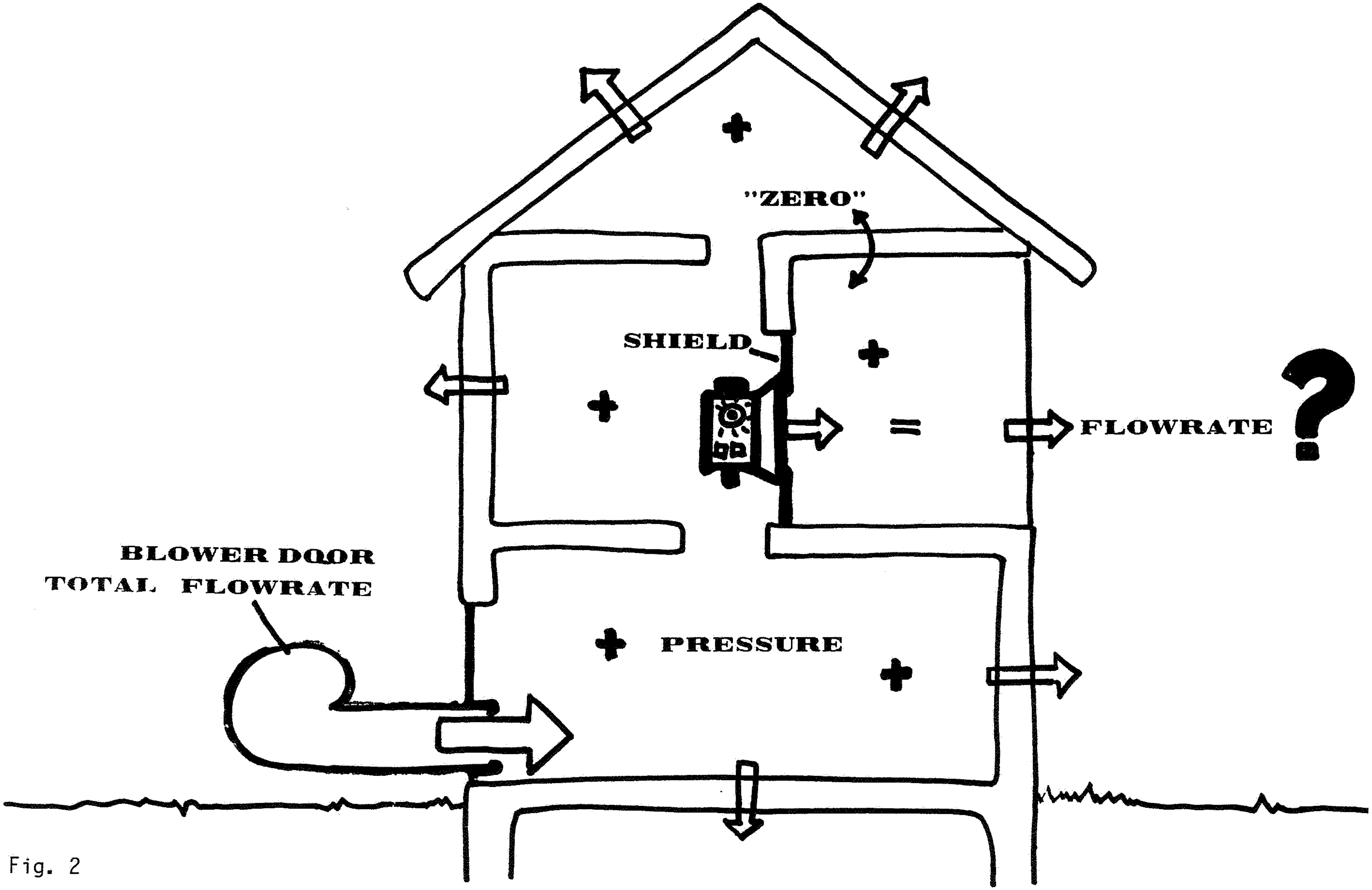


Fig. 2

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

POSTER S .14

THE DEVELOPMENT OF MODELS FOR THE PREDICTION OF INDOOR AIR QUALITY IN BUILDINGS.

RICHARD GROT AND JAMES AXLEY

Indoor Air Quality and Ventilation Group
Center for Building Technology
National Bureau of Standards
Gaithersburg, MD 20899
USA

ABSTRACT

The National Bureau of Standards has undertaken a research effort to develop a general indoor air quality simulation program for buildings. At present there exists three computer programs which can be used to analyze interzonal air movements in multizoned buildings and predict the level of contaminants due to a wide variety of contaminants. This paper will introduce the reader to the scientific and mathematical basis of the models, the preparation of building input data for these programs, and the use of the models for both residential and commercial buildings. Greater detail may be found in reference [1].

1. GENERAL CONSIDERATIONS

Airborne contaminants introduced into a building disperse throughout the building in a complex manner that depends on the nature of air movement in-to (infiltration), out-of (exfiltration), and within the building system, the influence of the heating, ventilating, and air conditioning (HVAC) systems on air movementthe posibility of removal, by filtration, or contribution, by generation, of contaminants, and the possibility of chemical reaction or physical-chemical reaction (e.g., adsorption or absorption) of contaminants with each other or the materials of the buildings construction and furnishings.

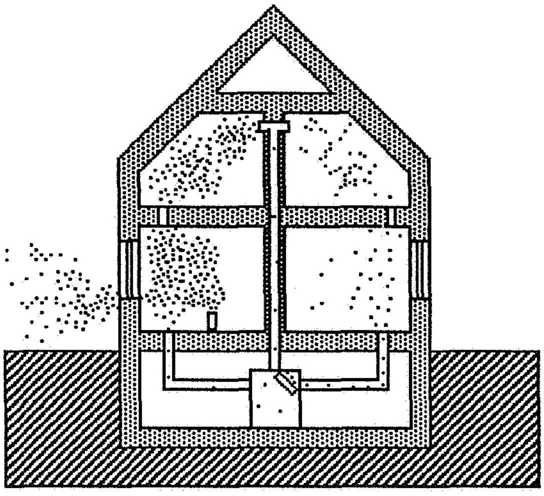


Fig. 1.1 Contaminant Dispersal in a Residence

Our immediate objective, here, is to develop a model of this dispersal process for building systems that comprehensively accounts for all phenomena that affect the actual contaminant dispersal process. We shall, however, attempt, to develop this modeling capability within a more general context so that techniques developed here may be extended to more complex problems of indoor air quality analysis. To this end, in this section, the problem is given a general definition and the basic modeling strategy used to address this problem is outlined.

1.1 Definition of Problem

The building air flow system may be considered to be a three dimensional field within which we seek to completely describe the *state* of infinitesimal air parcels. The *state* of an air parcel will be defined by its temperature, pressure, velocity, and contaminant concentration (for each species of interest) - the ***state variables*** of the indoor air quality modeling problem.

Our immediate task is, then, to determine the spacial and temporal variation of the species concentrations within a building due to thermal, flow, and contaminant *excitation* driven by environmental conditions and the HVAC system and its control, given building characteristics and their control.

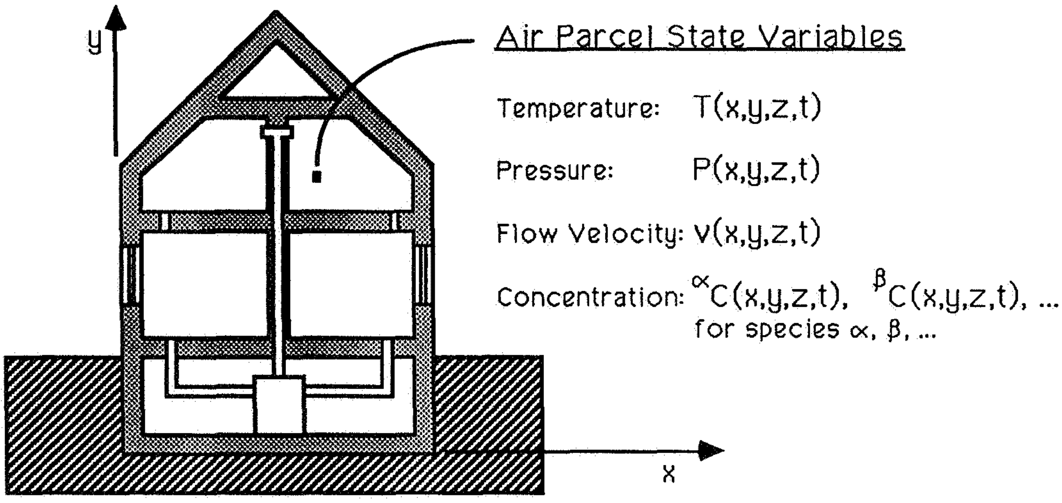


Fig. 1.2 Air Parcel State Variables

That is to say, we seek to determine;

${}^{\alpha}C(x,y,z,t)$; Contaminant " α" Concentration

${}^{\beta}C(x,y,z,t)$; Contaminant "β" Concentration

. . .

where;

C = species mass concentration or mass fraction
[=] mass of species/mass of air
α,β = species type indices
x, y, z = spacial coordinates
t = time

and shall refer to the process of determining the spacial and temporal variation of these species concentrations as ***contaminant dispersal analysis***.

Contaminant dispersal analysis, for a single nonreactive species "α", depends on the air velocity field and its variation with time;

$$ {}^{\alpha}C(x,y,z,t) = {}^{\alpha}C(\, v(x,y,z,t)\,) \;\; \& \;\; \mathrm{B.C.} \quad : \textit{Contam. Dispersal Anal.} \tag{1.1}$$

But, the air velocity field depends on the pressure field which is affected by the temperature field thru bouyancy and, completing the circle, the temperature field is dependent on the velocity field;

$$v(x,y,z,t) = v(\,P(x,y,z,t)\,) \ \& \ \text{B.C.} \quad : \textit{Flow Analysis} \tag{1.2}$$

$$P(x,y,z,t) = P(\,T(x,y,z,t)\,) \ \& \ \text{B.C.} \quad : \textit{Bouyancy Effects} \tag{1.3}$$

$$T(x,y,z,t) = T(\,v(x,y,z,t)\,) \ \& \ \text{B.C.} \quad : \textit{Thermal Analysis} \tag{1.4}$$

where;

B.C. = boundary conditions
v = air flow velocity
P = air pressure
T = air temperature

Thus, in general, contaminant dispersal analysis, for a single nonreactive species, is complicated by a ***coupled nonlinear flow-thermal analysis*** problem. Therefore, a comprehensive indoor air quality model will eventually have to address the related flow and thermal problems.

For cases of reactive contaminants, contaminant dispersal analysis, itself, will become a coupled (and, generally, nonlinear) analysis problem as individual species' concentrations will depend on other species' concentrations in addition to the air velocity field;

$${}^{\alpha}C(x,y,z,t) = {}^{\alpha}C(v, {}^{\alpha}C, {}^{\beta}C, \ldots) \quad : \textit{Species } \alpha \textit{ Dispersal Analysis} \tag{1.5a}$$

$${}^{\beta}C(x,y,z,t) = {}^{\beta}C(v, {}^{\alpha}C, {}^{\beta}C, \ldots) \quad : \textit{Species } \beta \textit{ Dispersal Analysis} \tag{1.5b}$$

$$\ldots$$

In this paper we shall focus on single, nonreactive species dispersal analysis and the associated problem of flow analysis, for a completely defined thermal field and its variation. The approach taken, however, has been formulated to be compatible with thermal analysis modeling techniques developed earlier [2]. Presently, we are addressing the reactive, multiple species dispersahalysis problem and see no difficulting with extending the approach to this more complex situation.

1.2 Modeling Approaches

We shall attempt to solve the general field problems posed above by attempting to determine the state of air at discrete points in the building air flow system. It will be shown that this ***spacial discretization*** allows the formulation of systems of ordinary differential equations that describe the temporal variation of the state fields. Two basic approaches may be considered, one based upon the microscopic equations of motion (i.e., continuity, motion, and energy equations for fluids) and the other based upon a "well-mixed" zone simplification of macroscopic mass, momentum, and energy balances for flow systems.

In the microscopic modeling approach one of several techniques of the generalized finite element method, which includes the finite difference method, could be used to transform the systems of governing partial differential equations into systems of ordinary differential equations that then can be solved using a variety of numerical methods. The macroscopic modeling approach leads directly to similar systems of ordinary differential equations.

In both approaches the building air flow system is modeled as an assemblage of discrete flow ***elements*** connected at discrete system ***nodes***. Systems of ordinary differential equations governing the behavior of elements are then formed and assembled to generate systems of ordinary differential equations that describe the behavior of the system as a whole. These systems of equations may then be solved, given system excitation and boundary conditions, to complete the analysis.

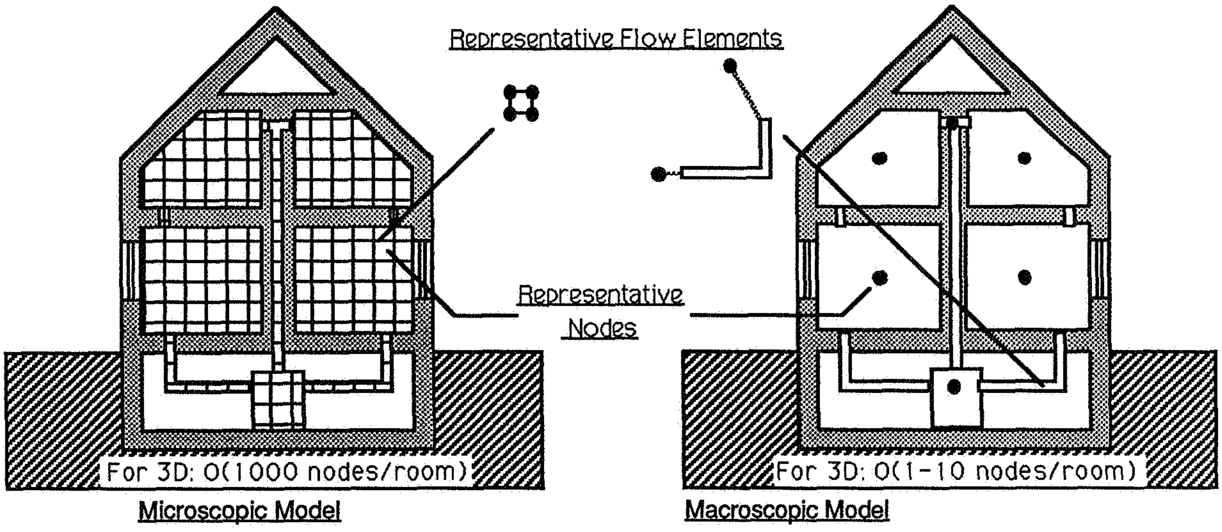


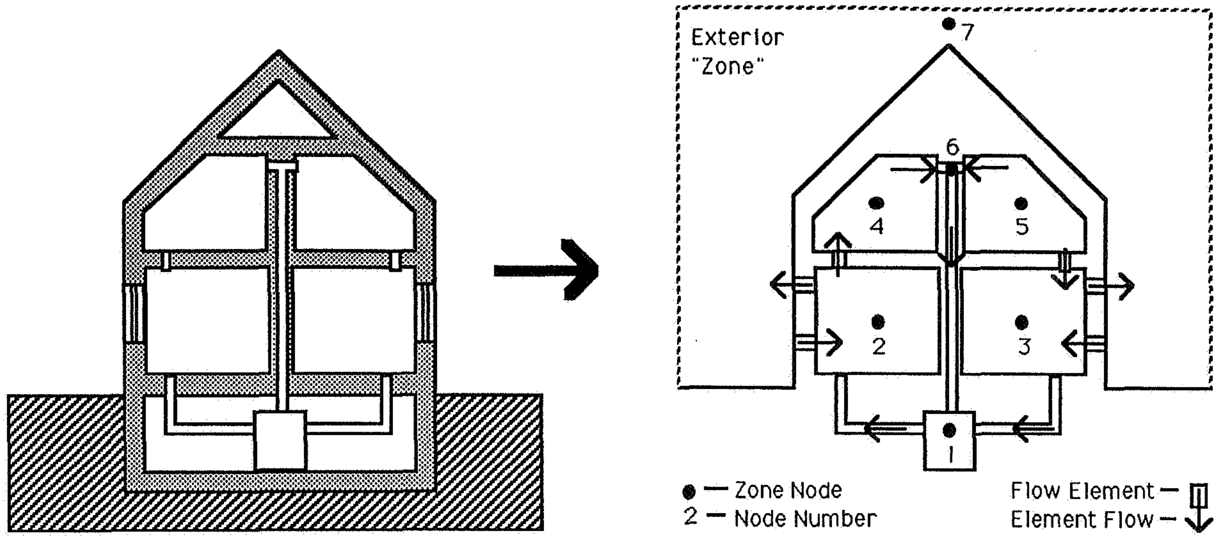
Fig. 1.3 Basic Spacial Discretization Apporaches

Virtually all computational procedures, except those used to form the element equations, would be practically identical for both approaches. From a practical point of view, however, microscopic modeling will involve on the order of 1000 nodes per room while the macroscopic model will involve on the order of only 10 nodes/room to realize acceptably accurate results. Consequently, the microscopic modeling approach can lead to extremely large systems of equations that therefore limit its use, at this time, to research inquiry. The macroscopic approach, resulting in systems of equations that are on the order of two magnitudes smaller than the microscopic approach, is a reasonable candidate for practical analysis, although it can not provide the detail of the microscopic approach.

Within this report we shall limit consideration to the macroscopic approach, although the specific techniques employed to implement this approach have been formulated to be compatible with the microscopic approach and it is expected that one may, in the future, be able to use both approaches in analysis to gain the benefits of detail in specific areas of the building system and yet account for full-system interaction.

1.3 The Well-Mixed Macroscopic Model

Here, the building air flow system shall be modeled as an assemblage of *flow elements* connected to discrete *system nodes* corresponding to well-mixed air *zones*.



Actual Building

Air-Flow System Idealization

Fig. 1.4 Well-Mixed Macroscopic Model

Limiting our attention to the contaminant dispersal and flow analysis problems we associate with each system node the discrete variables or ***degrees of freedom*** (DOFs) of pressure, air mass generation (typically zero), species concentration, species mass generation, and temperature;

$$\{P\} = \{P_1, P_2, P_3, \dots\} \qquad : \textit{Pressure DOFs} \qquad (1.6)$$

$$\{W\} = \{W_1, W_2, W_3, \dots\} \qquad : \textit{Air Mass Generation DOFs} \qquad (1.7)$$

$$\{{}^{\alpha}C\} = \{{}^{\alpha}C_1, {}^{\alpha}C_2, {}^{\alpha}C_3, \dots\} \qquad : \textit{Species } \alpha \textit{ Conc. DOFs} \qquad (1.8)$$

$$\{{}^{\alpha}G\} = \{{}^{\alpha}G_1, {}^{\alpha}G_2, {}^{\alpha}G_3, \dots\} \qquad : \textit{Species } \alpha \textit{ Gen. DOFs} \qquad (1.9)$$

$$\{T\} = \{T_1, T_2, T_3, \dots\} \qquad : \textit{Temp. DOFs} \qquad (1.10)$$

as well as the key system characteristic of nodal volumetric mass, V_1, V_2, V_3, ... The pressure, concentration, and temperature DOFs will approximate the corresponding values of the state field variables at the spacial locations of the system nodes.

With each element "e" in the system assemblage we note the *element connectivity* - the system nodes that the element connects - and identify an element air mass flow rate, w^e. The element mass flow rates will be related to the nodal state variables through specific properties associated with each particular element to form *element equations.*

In the formulation of both the contaminant dispersal model, presented in Section 2, and the flow model, presented in Section 3, we will *assemble* the governing element equations to form equations governing the behavior of the building system as a whole - the *system equations* - by demanding conservation of mass flow at each system node.

2. Contaminant Dispersal Analysis

In this section contaminant dispersal element equations are formulated. Demanding continuity of mass flow at each system node these element equations are then assembled to form contaminant dispersal equations governing the behavior of the full building system. Finally, methods for solution of the system equations are outlined.

2.1 Element Equations

Two nodes and a total mass flow rate, w^e, will be associated with each flow element, where flow from node i to j is defined to be positive. An element species concentration, ${}^{\alpha}C_k^e$, and an element species mass flow rate, ${}^{\alpha}w_k^e$, will be associated with each element node, k=i, j. The element species mass flow rate is defined so that flow from each node into the element is positive.

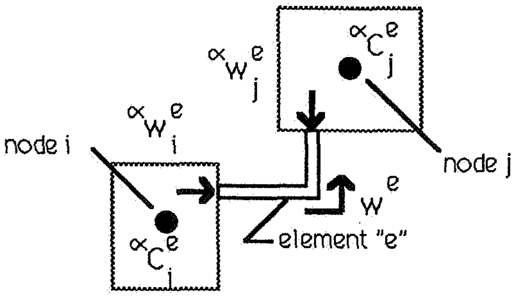


Fig. 2.1 Contaminant Dispersal Element DOFs

It follows from fundamental considerations that these element variables are related directly to the element total mass flow rate as;

$$\{{}^{\alpha}\mathbf{w}^e\} = w^e\begin{bmatrix} 1 & 0 \\ -1 & 0 \end{bmatrix}\{{}^{\alpha}\mathbf{C}^e\} \qquad ;\text{for } w^e \geq 0 \qquad (2.1a)$$

$$\{{}^{\alpha}\mathbf{w}^e\} = w^e\begin{bmatrix} 0 & -1 \\ 0 & 1 \end{bmatrix}\{{}^{\alpha}\mathbf{C}^e\} \qquad ;\text{for } w^e \leq 0 \qquad (2.1b)$$

or

$$\boxed{\{{}^{\alpha}\mathbf{w}^e\} = [\mathbf{f}^e]\{{}^{\alpha}\mathbf{C}^e\}} \qquad (2.1c)$$

where;

$\{{}^{\alpha}\mathbf{w}^e\} = \{{}^{\alpha}w_i^e, {}^{\alpha}w_j^e\}^T$; element species mass flow rate vector

$\{{}^{\alpha}\mathbf{C}^e\} = \{{}^{\alpha}C_i^e, {}^{\alpha}C_j^e\}^T$; element species concentration vector

$[\mathbf{f}^e]$ = element total mass flow rate matrix

$$= w^e\begin{bmatrix} 1 & 0 \\ -1 & 0 \end{bmatrix} \qquad ;\text{for } w^e \geq 0 \qquad (2.1d)$$

$$= w^e\begin{bmatrix} 0 & -1 \\ 0 & 1 \end{bmatrix} \qquad ;\text{for } w^e \leq 0 \qquad (2.1e)$$

If the element acts as a filter and removes a fraction, η , of the contaminant passing thru the filter then the element flow rate matrix becomes;

$$[f^e] = \text{element total mass flow rate matrix}$$

$$= w^e\begin{bmatrix} 1 & 0 \\ (\eta-1) & 0 \end{bmatrix} \quad ;\text{for } w^e \geq 0 \tag{2.1f}$$

$$= w^e\begin{bmatrix} 0 & (\eta-1) \\ 0 & 1 \end{bmatrix} \quad ;\text{for } w^e \leq 0 \tag{2.1g}$$

The fraction, η , is commonly known as the "filter efficiency" and may have values in the range of 0.0 to 1.0.

2.2 System Equations

System equations that relate the system concentration DOFs, $\{{}^{\alpha}C\}$, to the system generation DOFs,$\{{}^{\alpha}G\}$, may be assembled from the element equations by first transforming the element equations to the system DOFs and then demanding conservation of species mass flow at each system node.

There exists a one-to-one correspondance between each element's concentration DOFs, $\{{}^{\alpha}C^e\}$, and the system concentration DOFs, $\{{}^{\alpha}C\}$, that may be defined by a simple *Boolean* transformation;

$$\{{}^{\alpha}C^e\} = [{}^{\alpha}B^e]\{{}^{\alpha}C\} \tag{2.2}$$

where;

$[{}^{\alpha}B^e]$ is an m x n Boolean transformation matrix consisting of zeros and ones; m = the number of element nodes (here, m=2); n = the number of system nodes

For example, an element with nodes i & j (or 1 & 2) connected to system nodes 5 & 9, respectively, of a 12-node system would have ones in the 1st row, 5th column and the 2nd row, 9th column and all other elements of the 2 x 12 Boolean transformation matrix would be set equal to zero.

In a similar manner, we may define a "system-sized vector" to represent the net species mass flow rate from the system node into an element "e", $\{{}^{\alpha}W^e\}$, and relate it to the corresponding element species mass flow rate using the same transformation matrix, as;

$$\{{}^{\alpha}W^e\} = [{}^{\alpha}B^e]^T\{{}^{\alpha}w^e\} \tag{2.3}$$

For an arbitrary system node n, with connected elements "a", "b", ... as indicated below in Fig. 2.2, we then demand conservation of species mass as;

$$\left\{ \sum_{\substack{\text{connected}\\ \text{elements}}} (\text{elem. species mass flow}) + \begin{pmatrix} \text{rate of change} \\ \text{of} \\ \text{species mass} \end{pmatrix} = \begin{pmatrix} \text{generation} \\ \text{of} \\ \text{species mass} \end{pmatrix} \right\}_{\text{system node n}} \tag{2.4}$$

or,

$$ {}^{\alpha}W_n^a + {}^{\alpha}W_n^b + \ldots + V_n \frac{d\,{}^{\alpha}C_n}{dt} = {}^{\alpha}G_n \qquad (2.5) $$

or, for the system as a whole;

$$ \sum_{e=a,b,\ldots} \{{}^{\alpha}W^e\} + [V]\left\{\frac{d\,{}^{\alpha}C}{dt}\right\} = \{{}^{\alpha}G\} \qquad (2.6) $$

where;

$[V]$ = diag(V_1, V_2, ...) ; the *system volumetric mass matrix*
V_i = the volumetric mass of node i

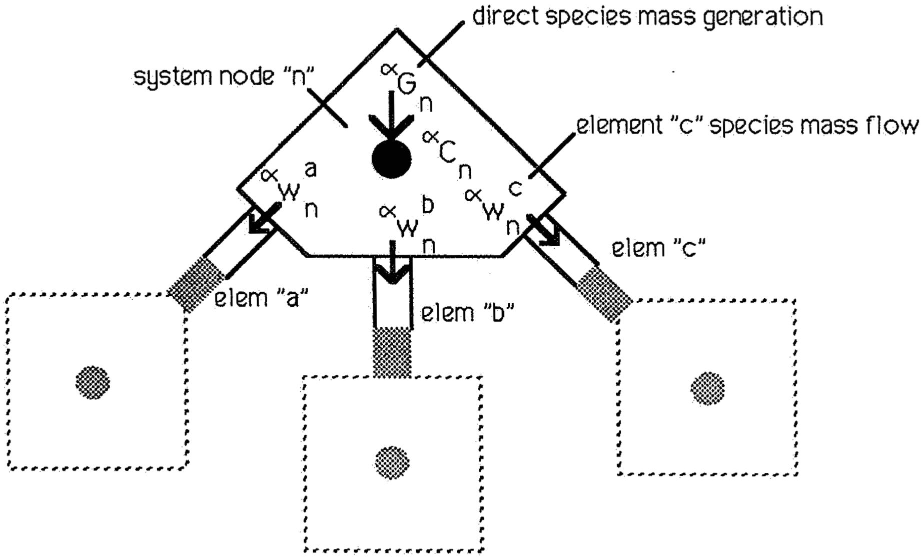


Fig. 2.2 Conservation of Species α Mass Flow at System Node n

Substituting relations (2.2) and (2.3) we obtain the final result;

$$ \boxed{[F]\{{}^{\alpha}C\} + [V]\left\{\frac{d\,{}^{\alpha}C}{dt}\right\} = \{{}^{\alpha}G\}} \qquad (2.7a) $$

where;

$$ [F] = \sum_{e=a,b,\ldots} [{}^{\alpha}B^e]^T[f^e][{}^{\alpha}B^e] \qquad (2.7b) $$

= the *system mass flow matrix*

$\equiv \mathcal{A}[f^e]$; the direct assembly sum of element flow matrices

Equation (2.7a) defines the contaminant dispersal behavior of the system as a whole and is said to be *assembled* from the element equations through the relation given by equation (2.7b). The assembly process, as formally represented in equation (2.7b), has found widespread application in the simulation of systems governed by conservation principles and is, therefore, often represented by the so-called assembly operator A as indicated above. It should be noted that while the formal representation of the assembly process is important from a theoretical point of view it is generally far more efficient, computationally, to assemble the element equations directly, without explicitly transforming them (see, for example, the "LM Algorithm" in [3]).

2.3 Boundary Conditions and Solution of System Equations

Concentration or generation rate, but not both, may be specified at system nodes. Concentration or generation conditions in the discrete model are equivalent to boundary conditions in the corresponding continuum model and will, therefore, be refered to as such. Formally then, we may distinguish between those DOFs for which concentration will be specified, $\{^{\alpha}C_C\}$, and those for which generation rate will be specified, $\{^{\alpha}C_g\}$, and partition the system of equations accordingly;

$$\begin{bmatrix} F_{cc} & F_{cg} \\ F_{gc} & F_{gg} \end{bmatrix} \begin{Bmatrix} {}^{\alpha}C_c \\ {}^{\alpha}C_g \end{Bmatrix} + \begin{bmatrix} V_{cc} & 0 \\ 0 & V_{gg} \end{bmatrix} \begin{Bmatrix} \dfrac{d^{\alpha}C_c}{dt} \\ \dfrac{d^{\alpha}C_g}{dt} \end{Bmatrix} = \begin{Bmatrix} {}^{\alpha}G_c \\ {}^{\alpha}G_g \end{Bmatrix} \qquad (2.8)$$

Using the second equation and simplifying we obtain;

$$[F_{gg}]\{{}^{\alpha}C_g\} + [V_{gg}]\left\{\frac{d^{\alpha}C_g}{dt}\right\} = \{{}^{\alpha}G_g\} - [F_{gc}]\{{}^{\alpha}C_c\} \qquad (2.9a)$$

or

$$\boxed{[\hat{F}]\{{}^{\alpha}\hat{C}\} + [\hat{V}]\left\{\frac{d^{\alpha}\hat{C}}{dt}\right\} = \{{}^{\alpha}\hat{E}\}} \qquad (2.9b)$$

where;

$[\hat{F}] \equiv [F_{gg}]$; the generation driven mass flow matrix

$\{{}^{\alpha}\hat{C}\} \equiv \{{}^{\alpha}C_g\}$; the generation driven nodal concentration vector

$\{{}^{\alpha}\hat{E}\} \equiv \{{}^{\alpha}G_g\} - [F_{gc}]\{{}^{\alpha}C_c\}$; the system *excitation* (2.9c)

It should be noted that the response of the system is driven by the system *excitation* involving both specified contaminant mass generation rates and contaminant concentrations which may, in general, vary with time.

Equation (2.9b) most directly defines the contaminant dispersal behavior of the system. The formation and solution of equation (2.9b) will be considered the central task of contaminant dispersal analysis. Three classes of solution are important;

a) steady state solution for conditions of steady flow and excitation,
b) dynamic solution for arbitrary system excitation and flow variation, and

c) the associated eigen solution, defined only for conditions of steady flow, that provides the steady-flow system time constants.

It may be shown that the generation driven mass flow matrix is a nonsingular matrix of a special form, a nonsingular "M-matrix" [1], and as a result computationally efficient numerical methods based on LU decomposition of the generation driven mass flow matrix may be used to solve both the steady state and dynamic problems. The eigen solution is computationally more difficult.

3. Air Flow Analysis

In this section air flow element equations are formulated that relate mass flow rate through flow elements to pressure differences across the elements, the assembly of these element equations to form equations governing the flow behavior of the building air flow system is discussed, and methods of solving these equations are outlined. The formulation of the air flow equations presented herein is based, in large part, on the work of Walton [4], an example presented by Carnahan et. al. [5], and Chapter 33 of the ASHRAE Handbook 1985 Fundamentals [6].

3.1 Pressure Variation within Zones

For the well-mixed macroscopic model, fluid density within any zone i, ρ_i, will be assumed constant and thus the variation of static pressure within a zone, $p_i(z)$, will be given by;

$$p_i(z) = P_i + \frac{g}{g_c}\rho_i(z_i - z) \tag{3.1}$$

where;

z_i = the elevation of node i relative to an arbitrary datum

z = elevation relative to an arbitrary datum

g = the acceleration due to gravity

g_c = dimensional constant (1.0 (kg m)/(N s^2))

Static pressures (i.e., under still conditions) acting on exterior surfaces may be approximated as;

$$p(z) = P_a - \frac{g}{g_c}\rho_a z \qquad \text{; on exterior surfaces, calm conditions} \tag{3.2}$$

where P_a and ρ_a are the atmospheric pressure and air density at the level of the outdoor datum.

To account for pressures due to wind effects the pressure on any exterior surface may be approximated using published wind pressure coefficients [6] as;

$$p(z) = P_a + C_p\frac{\rho_a U_H^2}{2} \qquad \text{; on exterior surfaces, windy conditions} \tag{3.3}$$

where C_p is a dimensionless pressure coefficient associated with the position on the exterior surface and the characteristics of the wind and U_H is the wind speed at the roof level of the building.

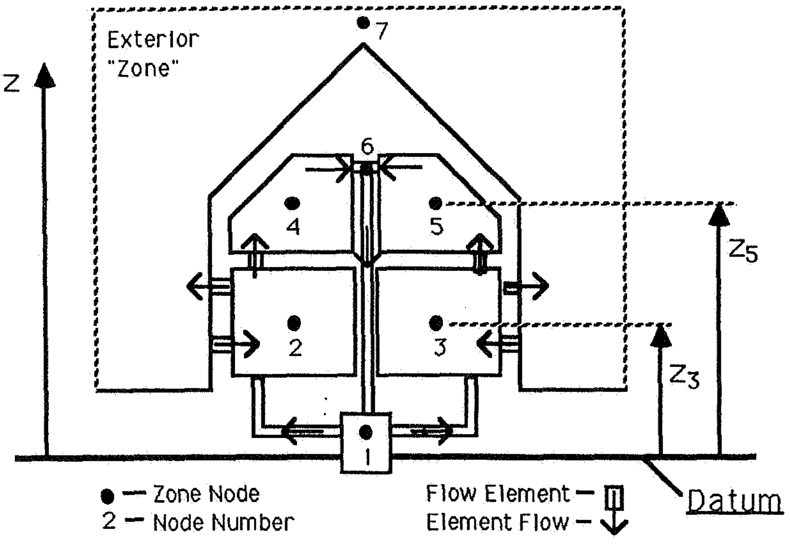


Fig. 3.1 Elevations Defined Relative to a Datum

3.2 Element Equations

Two classes of flow elements have been developed; *flow resistance elements* and *fan/pump elements.* The theoretical basis of the flow resistance element will be outlined here; the reader is referred to [1] for the development of the fan/pump element.

The flow resistance element is a very general element that may be used to model a large variety of flow paths that provide passive resistance to flow (e.g., conduits, ducts, ductwork assemblies, small orifices such as cracks, etc.); the fan/pump element may be used to model HVAC fans given the performance characteristics of a specific fan. These two classes of elements should allow modeling of a large variety of complex and complete building airflow systems.

Resistance to flow will be modeled by flow elements having a single entry and exit (e.g., simple ducts, openings between zones, orifices, etc.). Flow components with multiple entries, exits, or both may be modeled by assemblages of these simpler elements.

Flow resistance elements shall be two-node elements. With each node we associate element pressure, P_i^e , temperature, T_i^e, and flow rate, w_i^e, DOFs (i.e., for flow from the node into the element).

Fluid flow within each flow resistance element is assumed to be incompressible, isothermal, and governed by the Bernoulli equation as applied to duct design [6];

$$(P_1 + \frac{\rho V_1^2}{2g_c}) - (P_2 + \frac{\rho V_2^2}{2g_c}) + \frac{g}{g_c}\rho(z_1^e - z_2^e) = \sum \Delta p_o \qquad (3.4)$$

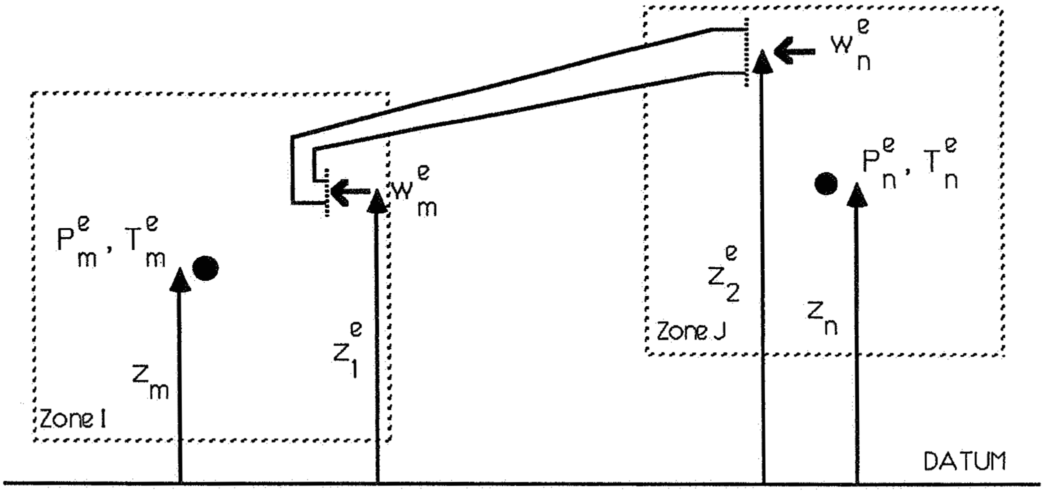


Fig. 3.2 Flow Resistance Element DOFs

Where, for the purposes of developing the general element equations, the more conventional flow variables, indicated below, have been used;

P_1, P_2 = entry and exit pressures, respectively
V_1, V_2 = entry and exit mean velocities, respectively
g_c = dimensional constant, 1.0 (kg-m)/(N-sec^2)
g = the acceleration of gravity (e.g., 0.980665 m/sec^2)
ρ = density of fluid flowing through the element
z_1, z_2 = elevations of entry and exits, respectively
w^e = mass flow rate through the element
$\Sigma \Delta p_o$ = the sum of all frictional and dynamic losses in the elements

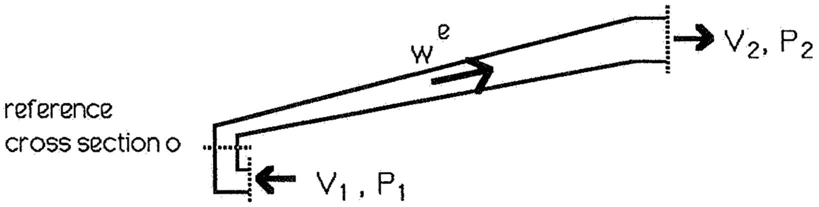


Fig. 3.3 Conventional Flow Variables

The losses, $\Sigma \Delta p_o$, are commonly related to the velocity pressure, $\rho V_o^2 / 2g_c$, of the fluid flow at reference crossections "o", for conduits, fittings, or orfices, as;

$$\Delta p_o = C_o \frac{\rho V_o^2}{2g_c} \tag{3.5}$$

where; C_o = loss coefficient

Thus the loss sum takes the form;

$$\sum \Delta p_o = \left(\frac{1}{2g_c}\right)\left(C_o \rho V_o^2 + C_p \rho V_p^2 + C_q \rho V_q^2 + \dots\right) \tag{3.6}$$

Recognizing the mass flow rate, w^e, at each of these sections must be equal;

$$w^e = \rho V_1 A_1 = \dots = \rho V_o A_o = \rho V_p A_p = \rho V_q A_q = \dots = \rho V_2 A_2 \tag{3.7}$$

equation (3.6) may be rewritten in terms of mass flow rate as;

$$\sum \Delta p_o = (1/2g_c\rho)(C_o/A_o^2 + C_p/A_p^2 + C_q/A_q^2 + \dots)(w^e)^2 \tag{3.8}$$

and equation (3.4) then simplifies to;

$$(P_1 - P_2) + \frac{g\rho}{g_c}(z_1^e - z_2^e) = C^e(w^e)^2 \tag{3.9}$$

where;

$$C^e = (1/2g_c\rho)(-1/A_1^2 + \dots C_o/A_o^2 + C_p/A_p^2 + C_q/A_q^2 \dots + 1/A_2^2) \tag{3.10}$$

Equation (3.9) may now be rewritten in terms of the element pressure DOFs, using equation (3.1), as;

$$(P_m^e - P_n^e) + \frac{g}{g_c}(\rho_m(z_m - z_1^e) + \rho(z_1^e - z_2^e) + \rho_n(z_2^e - z_n)) = C^e(w^e)^2 \tag{3.11}$$

It may be seen from equation (3.11) that mass flow through element e is driven by the absolute pressure differences between zones ($P_m^e - P_n^e$) modified by bouyancy effects created by density differences that are, in turn, due to zone temperature differences.

Introducing a new variable, B^e, for the bouyancy induced pressure component;

$$B^e = \frac{g}{g_c}(\rho_m(z_m - z_1^e) + \rho(z_1^e - z_2^e) + \rho_n(z_2^e - z_n)) \tag{3.12}$$

equation (3.11) may be rewritten as;

$$|w^e| = (C^e)^{-1/2}(|P_m^e - P_n^e + B^e|)^{1/2} \tag{3.13a}$$

or

$$w^e = a^e(P^e_m - P^e_n) + a^eB^e \tag{3.13b}$$

$$\text{where; } a^e = (C^e|P^e_m - P^e_n + B^e|)^{-1/2} \tag{3.13c}$$

where the second form, equations (3.13b) and (3.13c), will provide the correct sign for w^e.

Variation of Flow With Zone Pressure

It is useful, at this point, to develop analytical expressions for the variation of mass flow with zone pressure. This expressions will be seen to be useful for solving the nonlinear flow system equations using schemes based upon the classical Newton-Raphson iteration method. Therefore, from equations (3.13b) and (3.13c) we obtain;

$$\frac{\partial w^e}{\partial P^e_m} = -\frac{1}{2}(C^e)^{-3/2}\frac{\partial C^e}{\partial P^e_m}(|P^e_m - P^e_n + B^e|)^{1/2} + \frac{1}{2}(C^e)^{-1/2}(|P^e_m - P^e_n + B^e|)^{-1/2} \tag{3.14a}$$

$$\frac{\partial w^e}{\partial P^e_n} = -\frac{1}{2}(C^e)^{-3/2}\frac{\partial C^e}{\partial P^e_n}(|P^e_m - P^e_n + B^e|)^{1/2} - \frac{1}{2}(C^e)^{-1/2}(|P^e_m - P^e_n + B^e|)^{-1/2} \tag{3.14b}$$

and from equation (3.10) we obtain;

$$\frac{\partial C^e}{\partial P^e_m} = (1/2g_c\rho)(A_o^{-2}\frac{\partial C_o}{\partial P^e_m} + A_p^{-2}\frac{\partial C_p}{\partial P^e_m} + A_q^{-2}\frac{\partial C_q}{\partial P^e_m} + \ldots) \tag{3.15a}$$

$$\frac{\partial C^e}{\partial P^e_n} = (1/2g_c\rho)(A_o^{-2}\frac{\partial C_o}{\partial P^e_n} + A_p^{-2}\frac{\partial C_p}{\partial P^e_n} + A_q^{-2}\frac{\partial C_q}{\partial P^e_n} + \ldots) \tag{3.15b}$$

that is, the variation of C^e with pressure is simply a weighted sum of the variation of individual pressure loss coefficients contributing to the total pressure loss along the element. Analytical expressions for these partial derivatives of the pressure loss coeficients are not easily formulated, but by considering limiting cases of flow we can gain some insight.

In general, the loss coefficients depend, in a rather complex and poorly understood way, upon the nature of flow, as indicated by the Reynolds number, Re, and detailed characteristics of the flow geometry (e.g., roughness, constrictions, etc.). For many situations, however, the loss coefficients are practically constant for the limiting case of fully turbulent flow (i.e., Re > 10^6), at one extreme, and proportional to 1/Re for laminar flow (i.e., Re < 2 x 10^3) at the other;

C_o ≈ constant for fully developed turbulent flow (3.16)
$C_o \approx C^*_o/Re = C^*_o\,\mu/\rho D_o V_o$ for fully developed laminar flow (3.17)

where; C^*_o = constant

In fully developed turbulent flow, with each of the pressure loss coefficients constant, the partial derivatives of equations (3.15) become zero and consequently the first term of equations (3.14) becomes zero and, using equations (3.13), may be simplified to;

$$\frac{\partial w^e}{\partial P^e_m} = \frac{1}{2} a^e \quad \text{; for fully turbulent flow} \qquad (3.18a)$$

$$\frac{\partial w^e}{\partial P^e_n} = -\frac{1}{2} a^e \quad \text{; for fully turbulent flow} \qquad (3.18b)$$

Limiting consideration to flow resistance elements of constant cross-section, we may formulate a modified expression for laminar flow in an element, in a manner similar to that used to formulate equations (3.13). We obtain;

$$w^e \approx a^e_L (P^e_m - P^e_n) + a^e_L B^e \qquad (3.19a)$$

$$\text{where; } a^e_L = (2g_c\rho/\mu)\left(\frac{C^*_o}{D_o A_o} + \frac{C^*_p}{D_p A_p} + \frac{C^*_q}{D_q A_q} + \dots\right) \qquad (3.19b)$$

for which the evaluation of the variation of flow with pressure is straightforward;

$$\frac{\partial w^e}{\partial P^e_m} = a^e_L \quad \text{; laminar flow, constant cross section} \qquad (3.20a)$$

$$\frac{\partial w^e}{\partial P^e_n} = -a^e_L \quad \text{; laminar flow, constant cross section} \qquad (3.20b)$$

It is instructive to compare the fully turbulent flow equation, equation (3.13) with C^e constant, with this particular case (i.e., constant cross section) fully laminar flow equation as shown in figure 3.4 below.

It is seen that a^e, the tangent slope of the fully turbulent curve, becomes unbounded as flow approaches zero-flow conditions while a^e_L does not.

If the variations of the pressure loss coefficients, C_o, C_p, C_q, ..., with flow are well defined (i.e., for conduits: if the friction factor relations are reliable) then the flow defined by equations (3.13) should asymtoptically approach these two curves at the upper and lower limits of flow. (Note: this is not to say that these two curves provide an upper or lower bound to flow magnitude, in fact, they do not.

Our purpose, here, is not to use these limiting-case flow relations in place of the more general relation of equations (3.13), but rather to use these limiting cases to provide an estimate of the variation of element flow with zone pressure to be used in nonlinear solution algorithms.

Specifically, we shall only employ equations (3.19) and (3.20) for very low flow conditions, when the more general expression for flow, equation (3.13b), and the approximation for the variation of flow with pressure, equations (3.18), will tend to become unbounded.

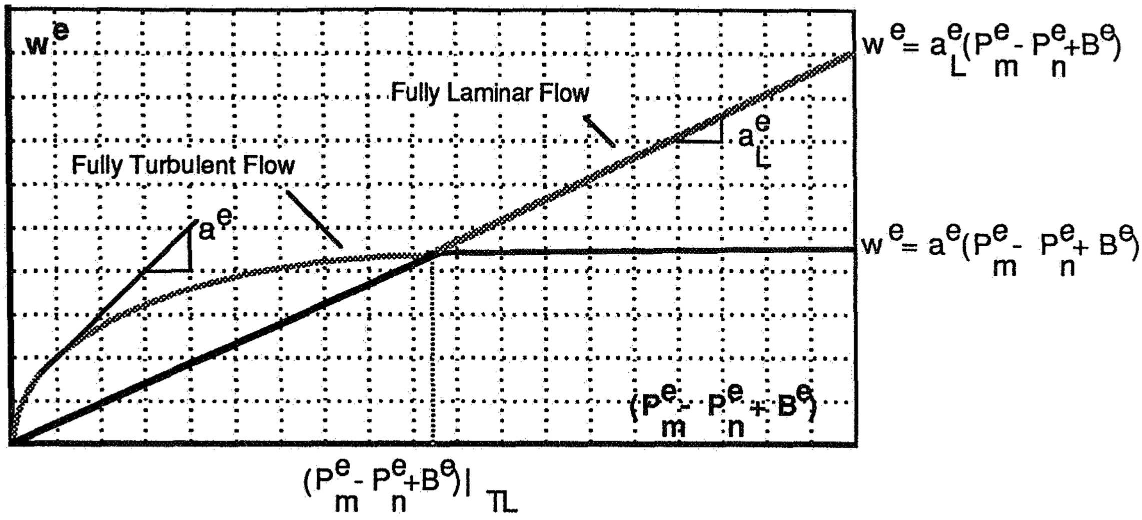


Fig. 3.4 Limiting Case Flow Relations- Elements of Constant Cross-Section

Matrix Formulation of the Element Flow Equations

The element equations may be recast into matrix form, using the element DOFs defined above, by first noting;

$$w^e = w^e_m = -w^e_n \tag{3.21}$$

thus;

$$\boxed{\{w^e_{net}\} = [a^e]\{P^e\} + \{w^e_B\}} \tag{3.22a}$$

where;

$$\{w^e_{net}\} = \{w^e_m , w^e_n\}^T \tag{3.22b}$$

= the element net mass flow rate vector

$$\{P^e\} = \{P^e_m , P^e_n\}^T \tag{3.22c}$$

= the element pressure vector

$$[a^e] = a^e \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \quad \text{; for all but very low flow conditions} \qquad (3.22d)$$

$$= a_L^e \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \quad \text{; for very low flow conditions} \qquad (3.22e)$$

= matrix of pressure-flow coefficients

$$\{w_B^e\} = a^e B^e \{\,1 \;\; -1\,\}^T \quad \text{; for all but very low flow conditions} \qquad (3.22f)$$

$$= a_L^e B^e \{\,1 \;\; -1\,\}^T \quad \text{; for very low flow conditions} \qquad (3.22g)$$

= bouyancy-induced mass flow rate vector

and;

$$\frac{\partial\{w_{net}^e\}}{\partial\{P^e\}} = \frac{a^e}{2} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \quad \text{; for all but very low flow conditions} \qquad (3.23a)$$

$$= a_L^e \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \quad \text{; for very low flow conditions} \qquad (3.23b)$$

The element pressure-flow coefficients a^e and a_L^e are defined in such a way that they are always positive, therefore, the matrix of pressure-flow coefficients will be positive semi-definite.

Some complicating details deserve special note;

a) the direction of flow will be determined by the sign of $(P_m^e - P_n^e + B^e)$; if positive, the flow will be from m to n,

b) the density ρ, of the fluid flowing through the element, will depend on the direction of flow;

$\rho = \rho_m$; for flow from m to n

$\rho = \rho_n$; for flow from n to m

c) the flow coefficient, C^e, will also depend on the direction of flow due to the dependency of ρ on direction and the dependency of the pressure loss coefficients C_0 that also, in general, depend on the direction of flow,

d) the pressure-flow coefficient matrix $[a^e]$ will also be flow-direction dependent due to the flow-direction dependency of C^e and B^e,

e) equation (3.22a) is highly nonlinear due to the flow-direction dependencies, noted above, the dependency of the pressure-flow coefficient matrix $[a^e]$ and the bouyancy-induced mass flow rate vector $\{w_B^e\}$ on the pressure, and the dependency of density on fluid temperatures which are, in turn, dependent on the rate of flow.

3.3 System Equations and Their Solution

Element equations similar to those presented above may be developed for a fan/pump element [1]. Flow resistance and fan/pump element equations, for a given flow system idealization, may then be assembled by demanding the conservation of mass at each system node to form system flow equations;

$$\boxed{\{W\} = [A]\{P\} + \{W_B\} + \{W_O\}} \qquad (3.24a)$$

where;

$[A] \equiv \mathsf{A}[a^e]$; the assembly of element matrices (3.24b)

$\{W_B\} \equiv \mathsf{A}\{w_B^e\}$; the assembly of element bouyancy vectors (3.24c)

$\{W_O\} \equiv \mathsf{A}\{w_O^e\}$; the assembly of fan free–delivery flow vectors (3.24d)

The derivation of equation (3.24a) is similar to that used in the derivation of the contaminant dispersal equations (2.7a) and, again, solution will require the specification of at least one pressure boundary condition - a single zone's pressure will suffice.

Equation (3.24a) defines the flow analysis problem. It is assembled from nonlinear element equations and, therefore, is nonlinear. Two classic nonlinear solution strategies and their variations;

a) Method of Successive Substitutions or Fixed-Point Iteration
  - Direct
  - Jacobi Iteration
  - Zeid's Modified Jacobi Iteration
  - Gauss-Seidel Iteration
  - Successive Overrelaxation Method

b) Newton-Raphson Method
  - Classic Newton-Raphson Method
  - Modified Newton-Raphson Method

as well as incremental formulations of these methods, provide reasonable candidates for solving this system of nonlinear flow equations.

4. CONTAM86

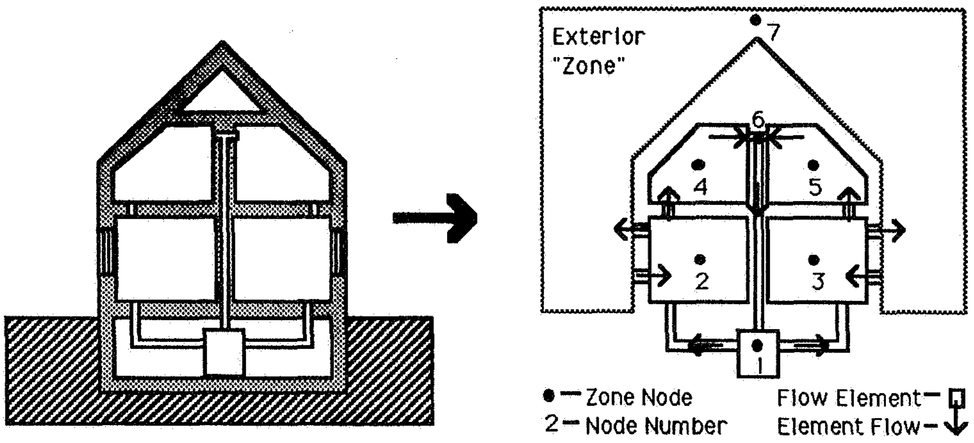
CONTAM86 is the first program in a series of programs being developed to implement the NBS indoor air quality model; it is an implementation of the nonreactive contaminant dispersal theory presented above and is written in ANSI Standard FORTRAN77 with IBM PC™ and Apple Macintosh™ version available. Other programs currently under development include AIRMOV, a partial implementation of the flow analysis theory presented above, CONTAM87 a FORTRAN 77 extension of CONTAM86 that allows consideration of reactive contaminant dispersal, and CONTAMEZ a C language adaptation of the CONTAM family designed to be particularly user friendly.

With CONTAM86 the analyst may consider steady state analysis, system time constant analysis for conditions of steady flow, and dynamic analyses for arbitrary conditions of unsteady flow and unsteady system excitation. Nonreactive contaminant dispersal systems of arbitrary complexity may be modeled with system size limited only by available memory.

CONTAM86 is a command processor; it responds to commands in the order that they are presented and processes data associated with each command. Commands may be presented to the program interactively, using keyboard and monitor, orthrough the use of command/data input files; that is to say, it offers two modes of operation - interactive and batch modes.

For most practical problems of contaminant dispersal analysis the batch mode of operation will be preferred. For these problems, analysis involves three basic steps;

<u>Step 1</u>: Idealization of the Building System and Excitation



Actual Building

Air-Flow System Idealization

Fig. 4.1 Idealization of the Building System and Excitation

Idealization of the building flow system involves;

a) discretization of the system as an assemblage of appropriate flow elements connected at system nodes,
b) identification of boundary conditions, and
c) numbering of system nodes optimally (i.e., to minimize the bandwidth - node number difference - of system equations).

The excitation (i.e., specified contaminant concentrations and generation rates) may be modeled to be steady or defined in terms of arbitrary time histories. For the latter case initial conditions of nodal contaminant concentration will have to also be specified.

Step 2: Preparation of Command/Data Input File

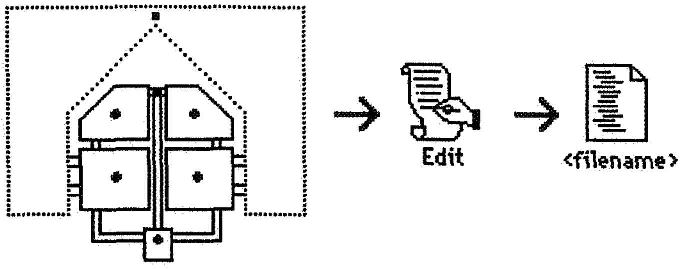


Fig. 4.2 Preparation of Input Command/Data File

In the batch mode, the program reads ASCII text files of commands and associated data, collected together in distinct data groups, that define the building flow idealization and excitation. The command/data input file may be prepared with any available ASCII text editing program and given a file name, <filename>, specified by the user. The <filename> must, however, consist of 8 or less alphanumeric characters and can not include an extension (i.e., characters separated from the filename by a period, ".").

Step 3: Execution of CONTAM86

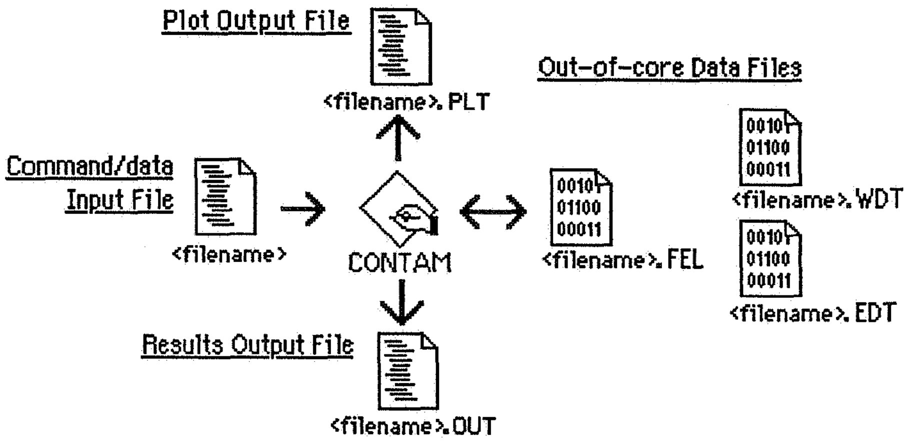
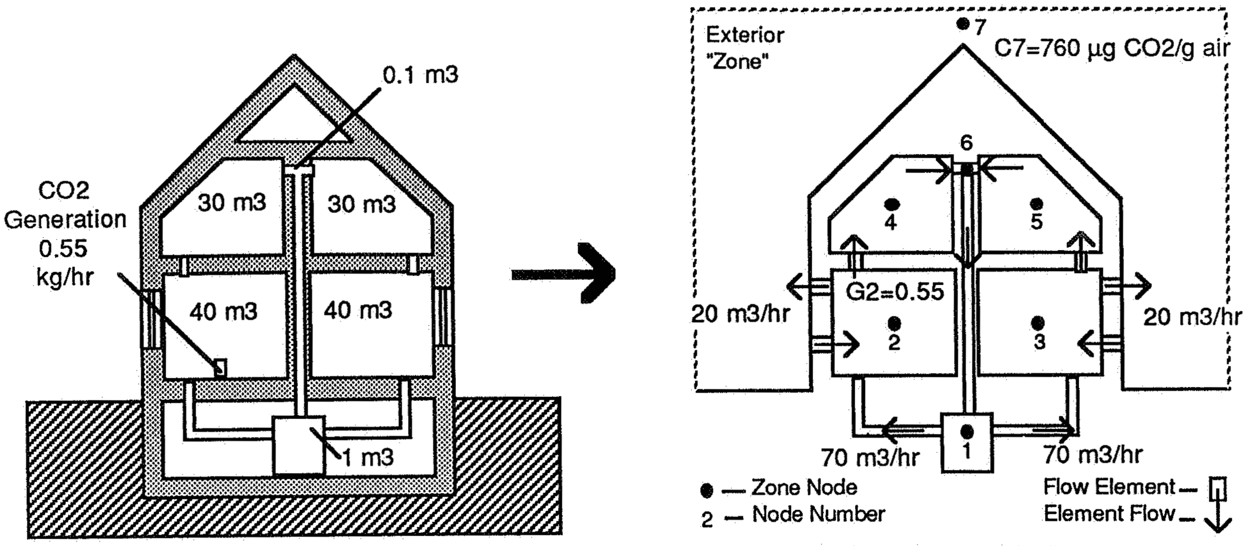


Fig. 4.3 Execution of CONTAM86

CONTAM86 is then executed. Initially CONTAM86 will be in the interactive mode. To enter the batch mode the command "SUBMIT F=<filename>" may be used to "submit" the command/data input file to the program. The program will then proceed to form element and system arrays and compute the solution to the posed problem. CONTAM86 reads the ASCII command/data input file and creates an ASCII (i.e., printable) output file <filename>.OUT. The results of an analysis, <filename>.OUT, may be conveniently reviewed using an ASCII editor and, from the editor, portions or all of the results may be printed out. Key response results are also written to the ASCII file <filename>.PLT in a format that may easily be transferred to some spreadsheet and plotting programs (i.e., data values within each line are separated by the tab character) for plotting or subsequent processing.

Introductory Example

Consider the two-story residence with basement shown, in section, below. In this residence interior air is circulated by a forced-air furnace and exterior air infiltrates the house through leaks around the two first floor windows. The flow system may be idealized using flow elements to model the ductwork, room-to-room, and infiltration flow paths as shown below.

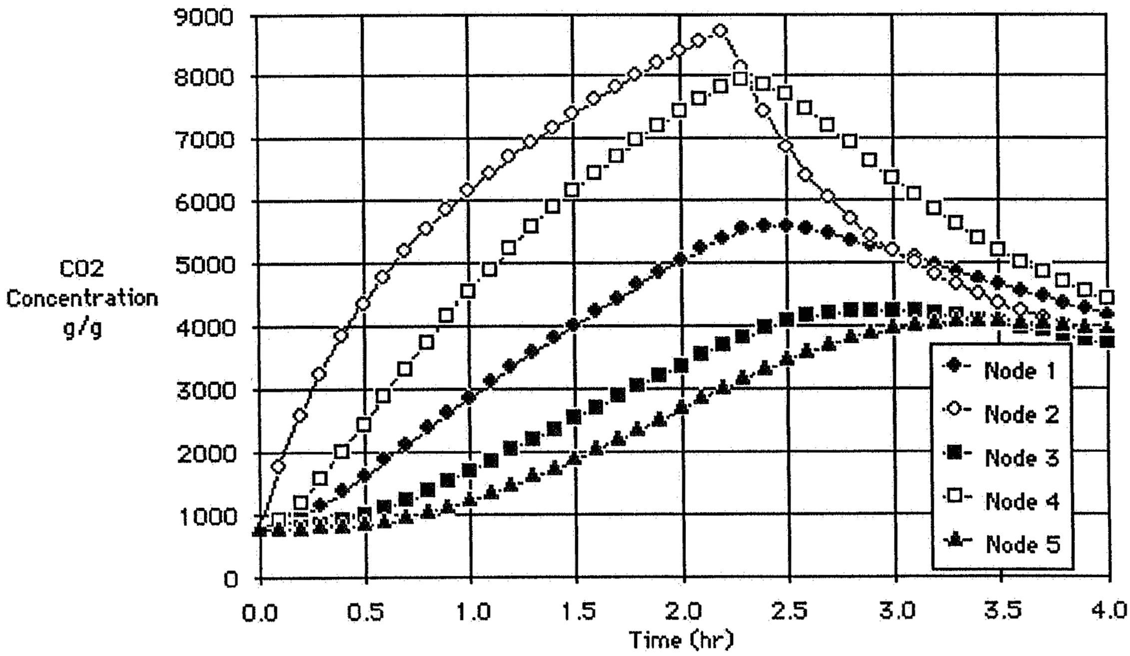


Actual Building

Air-Flow System Idealization

Fig 4.4 Hypothetical Residential Example

For this example, CO_2 generated in one room of a two story four room residence is dispersed throughout the building by the hot-air system and diluted by outside air infiltration at the rate of 0.5 ACH in the two lower rooms. The CO_2 is generated by a portable kerosene heater operated for 133 minutes and then turned off. The results of the analysis are plotted below illustrating the detailed dynamic variation of pollutant concentration in the building air flow system.



The CONTAM command/data input file used for this study is listed below.

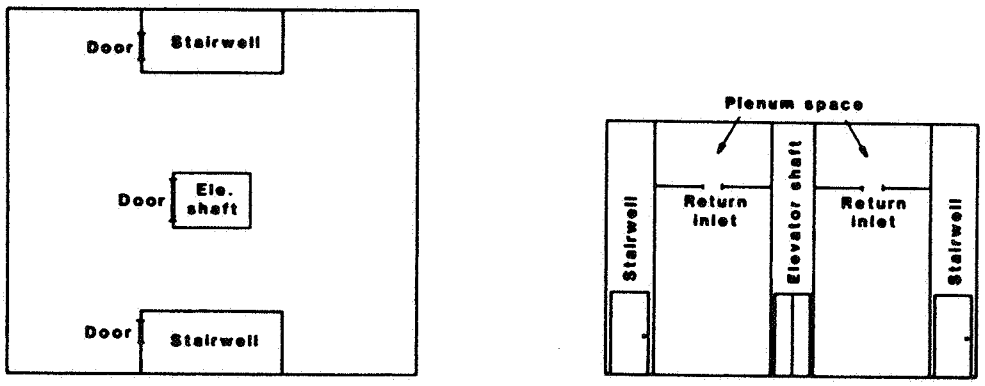
```
FLOWSYS N=7       : Six-Zone (7-node) Example
7 BC=C            : Exterior "Zone" (Node 7) Will Have Conc. Specified
END
FLOWELEM
1 I=1,2           : Flow Element 1
2 I=1,3           : Flow Element 2
3 I=7,2           : Flow Element 3
4 I=2,7           : Flow Element 4
5 I=7,3           : Flow Element 5
6 I=3,7           : Flow Element 6
7 I=2,4           : Flow Element 7
8 I=3,5           : Flow Element 8
9 I=4,6           : Flow Element 9
10 I=5,6          : Flow Element 10
11 I=6,1          : Flow Element 11
END
FLOWDAT           : Element Mass Flow Rates [=] kgm/hr
TIME=0
1,2  W=70*1.2     : 0.50 Building ACH each
3,6  W=20*1.2     : 0.25 Room ACH each
7,10 W=70*1.2     : 0.50 Building ACH each
11 W=140*1.2      : 1.00 Building ACH
:
TIME=5
1,2  W=70*1.2     : 0.50 Building ACH each
3,6  W=20*1.2     : 0.25 Room ACH each
7,10 W=70*1.2     : 0.50 Building ACH each
11 W=140*1.2      : 1.00 Building ACH
END
EXCITDAT          : Excitation
TIME=0
2 CG=0.549        : Node 2: Generation Rate [=] kg/hr
7 CG=0.000760     : Node 7: Exterior CO2 Concentration [=] kg CO2/kg
:
TIME=133/60       : Kerosene Heater Turned Off at 133 minutes
2 CG=0.0          : Node 2: Generation Rate [=] kg/hr
7 CG=0.000760     : Node 7: Exterior CO2 Concentration [=] kg CO2/kg
:
TIME=5
2 CG=0.0          : Node 2: Generation Rate [=] kg/hr
3 CG=0.000760     : Node 3: Exterior CO2 Concentration [=] kg CO2/kg
:
END
DYNAMIC
T=0,4,0.5               : Initial Time, Final Time, Time Increment
1    V=1.2*1.0          : Node 1: Volumetric Mass [=] kg
2,3  V=1.2*40.0         : Nodes 2 & 3: Volumetric Mass [=] kg
4,5  V=1.2*30.0         : Nodes 4 & 5: Volumetric Mass [=] kg
6    V=1.2*0.1          : Node 6: Volumetric Mass [=] kg
7 V=1.2*1.0E+09         : Node 7: Exterior Volumetric Mass [=] kg
:
1,7 IC=0.000760         : Initial Concentration [=] kg CO2/kg
END
RETURN
```

5. AIRMOV

The solution of the simultaneous mass balance equations is presently accomplished by the computer program AIRMOV. This program was originally a series of subroutines in the Thermal Analysis Research Program (TARP) developed by George Walton of the National Bureau of Standards [4]. There are two versions of the program which are presently distributed: AIRMOV4 and AIRMOV10. AIRMOV4 is a Fortran-77 version which can be compiled and run on an IBM-PC™ compatible computer using the IBM Professional Fortran compiler. AIRMOV10 is a Pascal version which has been compiled using TURBO-Pascal on the IBM-PC. AIRMOV4 can handle up to 1000 openings and up to 50 zones. AIRMOV10 uses the dynamic memory allocation procedures available in Pascal and has no practical limitation as to the number of zones or openings. AIRMOV10 has also taken advantage of the more sophisticated data structure possible in a structured language such as Pascal to implement a series of linked lists for storing the zone and opening data. A laminar flow model is also used for pressure differences across an opening of less than 0.1 Pa. This not only more closely approximates the physical flow through an opening, but also greatly improves the convergence of the numerical solution of the nonlinear equations for the conditions of small induced pressures (low wind or small temperature differences) or large openings (such as open doorways or open windows).

Input Data

The input file for AIRMOV must be called AIRMOV.DTA. A sample for a model of a two story office building is included. This office building is modeled as 6 zones. Each floor has two zones: an occupied zone and the ceiling plenum. The other two zones are the two stairwells which are treated as one zone and the elevator shaft.



OVERHEAD VIEW OF TYPICAL FLOOR **SIDE VIEW OF TYPICAL FLOOR**

Fig. 5.1 Schematic of Pittsfield Building

The first line of the input file contains the building title. The second line contains program control parameters (the maximum number of iterations, a list parameter which controls output (usually set to 1) and the number of contaminants).

The next group of lines provide information on each zone. Each line corresponds to a zone and includes the following;

Zone reference height in meters
Zone temperature in Celsius
Zone volume in m^3
Initial concentrations of the contaminants in kg/kg of air

When you are finished describing all zone data, include a terminator line with a negative value for the reference height.

The next group of lines provide information on each flow opening. These make use of a zone numbering scheme based on the order of the zone data lines, i.e. zone 1 is the first zone listed and so on. Zone 0 corresponds to the outside. Each line in this group corresponds to an opening and contains the following;

Near side zone number
Far side zone number (may be 0 for outside)
Opening Area in m^2

Flow exponent n
Flow coefficient C
Opening orientation in degrees from north*
Opening middle height (where stack pressure is felt)
Top Height of wall containing opening (where wind pressure is calculated) *
* used only for exterior openings

This group of input is terminated by a line with a near side zone number of zero or less.

The next group of lines proved zone information for the run. There must be one line for each zone. Each line contains the zone temperature in Celsius, a forced airflow rate in the zone in kg/s (negative flow rates indicate an exhaust) and contaminant generation and absorption rates in kg/s for each contaminant.

The last group of lines are the ambient conditions and there can be as many as desired. Each line contains a time in seconds for which the conditions are valid, the ambient temperature in Celsius, the barometric pressure in Pa, the wind speed in m/s, the wind direction and the ambient contaminant concentrations[1]. If one is not calculating contaminant concentrations, the time step value may be set to 1. This will give only the air flows for each weather condition. The last line of the input file should have a time step of zero or less.

Included is a sample output for the first weather conditions for this description of the office building.

Sample Input File (AIRMOV.DTA)

```
PITTSFIELD: 2 ISOLATED ZONES, 3 EQUAL OPENINGS PER FACE
20 1 0
7.9 22. 2923. 0. 0. 0. 0.
7.9 22. 2894. 0. 0. 0. 0.
7.9 22. 335. 0. 0. 0. 0.
7.9 22. 30. 0. 0. 0. 0.
7.9 22. 974. 0. 0. 0. 0.
7.9 22. 965. 0. 0. 0. 0.
-1.0 20. 60. 0. 0. 0. 0.
1 0 0.0167 .65 1.0 0. 0.0  7.9
1 0 0.0167 .65 1.0 0. 1.95 7.9
5 0 0.0100 .65 1.0 0. 3.5 7.9
1 0 0.0167 .65 1.0 90. 0.0  7.9
1 0 0.0167 .65 1.0 90. 1.95 7.9
5 0 0.0100 .65 1.0 90. 3.5 7.9
1 0 0.0167 .65 1.0 180. 0.0  7.9
1 0 0.0167 .65 1.0 180. 1.95 7.9
5 0 0.0100 .65 1.0 180. 3.5 7.9
1 0 0.0167 .65 1.0 270. 0.0  7.9
1 0 0.0167 .65 1.0 270. 1.95 7.9
5 0 0.0100 .65 1.0 270. 3.5 7.9
2 0 0.0167 .65 1.0 0. 4.0 7.9
2 0 0.0167 .65 1.0 0. 5.95 7.9
6 0 0.0100 .65 1.0 0. 7.5 7.9
2 0 0.0167 .65 1.0 90. 4.0 7.9
2 0 0.0167 .65 1.0 90. 5.95 7.9
6 0 0.0100 .65 1.0 90. 7.5 7.9
```

---

[1] AIRMOV contaminant dispersal analysis is an early implementation; the CONTAM series of programs offer more advanced modeling capabilities

```
2 0 0.0167 .65 1.0 180. 4.0 7.9
2 0 0.0167 .65 1.0 180. 5.95 7.9
6 0 0.0100 .65 1.0 180. 7.5 7.9
2 0 0.0167 .65 1.0 270. 4.0 7.9
2 0 0.0167 .65 1.0 270. 5.95 7.9
6 0 0.0100 .65 1.0 270. 7.5 7.9
3 1 0.0600 .65 1.0 0. 1.1 7.9
3 1 0.0068 .65 1.0 0. 2.0 7.9
3 2 0.0300 .65 1.0 0. 5.1 7.9
3 2 0.0064 .65 1.0 0. 6.0 7.9
4 1 0.0330 .65 1.0 0. 1.1 7.9
4 1 0.0130 .65 1.0 0. 2.0 7.9
4 2 0.0330 .65 1.0 0. 5.1 7.9
4 2 0.0120 .65 1.0 0. 6.0 7.9
3 5 0.0020 .65 1.0 0. 3.5 7.9
3 6 0.0019 .65 1.0 0. 7.5 7.9
4 5 0.0039 .65 1.0 0. 3.5 7.9
4 6 0.0037 .65 1.0 0. 7.5 7.9
5 1 1.9300 .65 .65 0. 3.0 7.9
6 2 1.8880 .65 .65 0. 7.0 7.9
5 2 0.0504 .65 .65 0. 4.0 7.9
0 1 1.0 .5 .6 0. 0. 0.
22. 0.0 0. 0.
22. 0.0 0. 0.
22. 0. 0. 0.
22. 0. 0. 0.
22. -0.0 0. 0.
22. -0.0 0. 0.
3600 17.0 101325. 0. 0. 0. 0. 0. 0
3600 12.0 101325. 0. 0. 0. 0. 0. 0.

   . . .

3600 -8.0 101325. 10. 0. 0. 0. 0. 0.
0 0. 101325. 5. 0. 0. 0. 0. 0. 0.
```

Sample Output for AIRMOV (first weather conditions)

```
NBS INTERZONAL AIR MOVEMENT & CONTAMINANT DISPERSAL PROGRAM
Project Title: PITTSFIELD: 2 ISOLATED ZONES, 3 EQUAL OPENINGS PER FACE
    Maximum Number of Iterations:     20
            Print Output Control:      1
         Number of Contaminants:       0

        N        ZZ       TZ      VOL
NZON:    1      7.90    22.00 2923.00
NZON:    2      7.90    22.00 2894.00
NZON:    3      7.90    22.00  335.00
NZON:    4      7.90    22.00   30.00
NZON:    5      7.90    22.00  974.00
NZON:    6      7.90    22.00  965.00

 Number of Zones =      6

 Building Volume =       8121  M^3
```

```
Begin next time step
  HBTSTP      TA       PB       WS       WD
    3600   17.00   101325     0.00        0

      Opening Flows & Pressure Differences
 Opening     N   M        Flow                    DP
Flow:    1   1   0        0.0171 kg/sec           0.52 Pascals
Flow:    2   1   0        0.0068 kg/sec           0.13 Pascals
Flow:    3   5   0       -0.0050 kg/sec          -0.18 Pascals
Flow:    4   1   0        0.0171 kg/sec           0.52 Pascals
Flow:    5   1   0        0.0068 kg/sec           0.13 Pascals
Flow:    6   5   0       -0.0050 kg/sec          -0.18 Pascals
Flow:    7   1   0        0.0171 kg/sec           0.52 Pascals
Flow:    8   1   0        0.0068 kg/sec           0.13 Pascals
Flow:    9   5   0       -0.0050 kg/sec          -0.18 Pascals
Flow:   10   1   0        0.0171 kg/sec           0.52 Pascals
Flow:   11   1   0        0.0068 kg/sec           0.13 Pascals
Flow:   12   5   0       -0.0050 kg/sec          -0.18 Pascals
Flow:   13   2   0        0.0048 kg/sec           0.08 Pascals
Flow:   14   2   0       -0.0123 kg/sec          -0.32 Pascals
Flow:   15   6   0       -0.0114 kg/sec          -0.62 Pascals
Flow:   16   2   0        0.0048 kg/sec           0.08 Pascals
Flow:   17   2   0       -0.0123 kg/sec          -0.32 Pascals
Flow:   18   6   0       -0.0114 kg/sec          -0.62 Pascals
Flow:   19   2   0        0.0048 kg/sec           0.08 Pascals
Flow:   20   2   0       -0.0123 kg/sec          -0.32 Pascals
Flow:   21   6   0       -0.0114 kg/sec          -0.62 Pascals
Flow:   22   2   0        0.0048 kg/sec           0.08 Pascals
Flow:   23   2   0       -0.0123 kg/sec          -0.32 Pascals
Flow:   24   6   0       -0.0114 kg/sec          -0.62 Pascals
Flow:   25   3   1        0.0214 kg/sec           0.10 Pascals
Flow:   26   3   1        0.0024 kg/sec           0.10 Pascals
Flow:   27   3   2       -0.0192 kg/sec          -0.26 Pascals
Flow:   28   3   2       -0.0041 kg/sec          -0.26 Pascals
Flow:   29   4   1        0.0166 kg/sec           0.18 Pascals
Flow:   30   4   1        0.0066 kg/sec           0.18 Pascals
Flow:   31   4   2       -0.0170 kg/sec          -0.18 Pascals
Flow:   32   4   2       -0.0062 kg/sec          -0.18 Pascals
Flow:   33   3   5        0.0007 kg/sec           0.10 Pascals
Flow:   34   3   6       -0.0012 kg/sec          -0.26 Pascals
Flow:   35   4   5        0.0019 kg/sec           0.17 Pascals
Flow:   36   4   6       -0.0020 kg/sec          -0.19 Pascals
Flow:   37   5   1        0.0485 kg/sec           0.01 Pascals
Flow:   38   6   2        0.0423 kg/sec           0.01 Pascals
Flow:   39   5   2       -0.0258 kg/sec          -0.35 Pascals

Infiltration Rate:  0.04 /hr    Exfiltration Rate:  0.04 /hr
 No more time step data
```

REFERENCES

[1] Axley, J.W., Indoor Air Quality Modeling: Phase II Report, (presently under review for publication by the National Bureau of Standards, Building Environment Division, Center for Building

Technology)

[2] Axley, J.W., DTAM1: A Discrete Thermal Analysis Method for Building Energy Simulation: Part I Linear Thermal Systems with DTAM1 Users' Manual, (presently under review for publication by the National Bureau of Standards, Building Environment Division, Center for Building Technology)

[3] Bathe, K.J., Finite Element Procedures in Engineering Analysis, Second Edition, John Wiley & Sons, New York, 1982

[4] Walton, G., Thermal Analysis Research Program Reference Manual, NBSIR 83-2655, U.S. Dept. of Com., National Bureau of Standards, Gaithersburg, MD, March 83

[5] Carnahan, B., Luther, H.A., Wilkes, J.O., Applied Numerical Methods, John Wiley & Sons, 1969

[6] ASHRAE, ASHRAE Handbook: 1985 Fundamentals , ASHRAE, Atlanta, GA, 1985

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

POSTER S.15

A PROTOTYPE EXPERT SYSTEM FOR DIAGNOSING MOISTURE PROBLEMS IN HOUSES

ANDREW K. PERSILY

Indoor Air Quality and Ventilation Group
Building Environment Division
Center for Building Technology
National Bureau of Standards
Gaithersburg, Maryland 20899

This paper was presented at the BTECC Symposium on Air Infiltration, Ventilation, and Moisture Transfer in Ft. Worth, Texas (December 1986) and appears in the proceedings of the symposium.

A PROTOTYPE EXPERT SYSTEM FOR DIAGNOSING MOISTURE PROBLEMS IN HOUSES

A knowledge based expert system is under development to assist in the identification and diagnosis of air leakage problems in residential buildings. The expert system is intended for use by home energy auditors who are familiar with house construction and building performance issues, but do not have the expertise necessary to deal effectively with the wide variety of circumstances encountered in houses. The system development is beginning with a prototype to diagnose moisture-related problems. This prototype is the first step in the development of the more comprehensive expert system that will deal with air leakage problems associated with indoor air quality, thermal comfort, and heat loss and gain.

In this paper the moisture-diagnosis prototype is described and discussed. This prototype system requires the user to describe the symptoms of the existing moisture problems and provide information on house characteristics. Based on additional information on the symptoms and the house, this interactive program produces a list of probable causes and recommendations for remedial action. In addition to describing the current prototype system, this paper also discusses the results of an evaluation of the system based on its use by human experts in the field of residential building moisture. This evaluation, along with insights obtained through the efforts of the system's developers, has led to several proposed improvements of the prototype.

1. INTRODUCTION

Over recent years numerous houses have been audited to determine appropriate energy conserving retrofits and to identify the causes of problems related to thermal comfort, excessive energy use, moisture, and air quality. These audits have ranged from uninstrumented visual inspections lasting about one hour to more extensive procedures that employ instrumentation to examine the building envelope and equipment in detail. The simpler type of audit necessarily considers only general attributes of the house without recognizing the complexity of building thermal characteristics, including the importance of unexpected air leakage sites and other thermal anamolies. Such audits generally involve surveys of insulation levels, condition of windows and doors, mechanical equipment type and other building features, but neglect many other important factors such as leaks in attic floors, convective loops within the insulation system, basement air leakage and other obscure air leakage sites. Based on various simplified guidelines these audits produce suggestions regarding retrofit actions, but the audits are generally not designed to diagnose the causes of many air leakage problems and the suggestions do not involve many important air leaks.

More extensive audit procedures, sometimes refered to as "house doctoring" (Diamond et al 1982, Energy Resources Center 1983, Harrje et al 1979 and 1980), provide a much more detailed evaluation of the house and its thermal performance. House doctoring is not a standardized procedure, and different individuals and organizations have developed their own approaches. In order to locate heat loss and air leakage sites, house doctors employ fan pressurization, infrared thermography and other techniques (ASTM 1986, Harrje et al 1979 and 1980, Socolow 1978). The use of these procedures enables one to locate unexpected air leakage sites and other thermal defects in the building envelope that are otherwise difficult or impossible to detect. These unanticipated defects often constitute a more significant portion of the energy loss of a home than the more mundane defects considered by "pencil-and-paper" audits. With regard to air leakage sites, obvious leaks, such as those associated with windows and doors, generally account for only a small percentage of the total leakage of a house (ASHRAE 1985). Most of the leaks are due to a variety of other less obvious, and often very elusive, sources.

House doctors have inspected thousands of houses in North America and have obtained a great deal of experience regarding the location and significance of air leakage sites, as well as other thermal defects in houses. In some cases, extremely experienced house doctors can anticipate construction defects and other leakage problems without the use of instrumentation, from knowledge of a house's age, construction style, geographic location, and other features. In addition to identifying thermal defects in the building envelope, expert house doctors have experience with, and a general understanding of, other air leakage issues such as thermal comfort, moisture, and indoor air quality. The experience of these expert house doctors and other building performance experts constitutes a valuable resource for solving air leakage problems in homes.

It would be extremely beneficial if the knowledge of these experts could be used to improve the effectiveness of energy audits by nonexperts. Expert systems constitute a computer software approach employing the techniques of artificial intelligence to real-world problems (Forsyth 1984, Hayes-Roth et al 1984) that could potentially provide this knowledge regarding air leakage problems to nonexpert auditors. Expert systems are particularly applicable to the problem of identifying and diagnosing air leakage problems in residential buildings because these systems are appropriate to domains characterized by uncertain data and incomplete information. A traditional, computational approach to analyzing infiltration would calculate the quantities of interest by applying computational algorithms to a numerical model of a house. While there is sufficient physical understanding to determine infiltration rates, airflow rates into and out of specific locations, and interior contaminant concentrations, moisture levels and temperatures in this manner, the calculation of these quantities is prevented by the inability to determine all of the required inputs. One must know the location and leakage characteristics of every opening in the building envelope and in the interior partitions. In addition, wind pressure coefficients must be known over the building envelope as a function of wind direction. The determination of indoor contaminant and moisture levels also requires values of interior source strengths and outdoor concentrations as a function of time. Such detailed knowledge about a specific building is generally unobtainable without intensive instrumentation and study. Even if all of this information were available, it is not clear whether a detailed computational approach is appropriate to deal with the types of problems that are encountered in the field. Alternatively, an expert system can deal with the more realistic situation in which there is incomplete knowledge of a home's detailed infiltration characteristics, but valuable nonquantitative information is available. The ability of expert systems to deal with qualitative information makes them appropriate to the problems associated with air leakage and to use the knowledge of expert house doctors.

This paper begins with a description of a proposed expert system intended to deal with air leakage problems. This expert system has been described in general terms in a previous report (Persily 1986), and is intended to identify and diagnose air leakage problems related to heat loss and gain, thermal comfort, moisture, and indoor air quality. The current effort toward the development of this system involves a prototype concerned primarily with the diagnosis of moisture problems in homes, and a description and discussion of this prototype constitutes the bulk of this paper. The prototype is serving to explore conceptual approaches to the general problem of diagnosing and identifying air leakage problems to assist in developing the proposed system, as well as to develop a useful tool for the domain of moisture problem diagnosis.

2. GLOBAL SYSTEM FRAMEWORK

The term global expert system refers to the proposed expert system intended to deal with air leakage problems related to heat transfer, air quality, moisture, and thermal comfort. The development of this global system itself has not yet begun, but a conceptual framework does exist and this section describes the current conception.

The basic goal of the global system is to use the knowledge of house doctors, and other experts in the area of air leakage problems, in order to improve the effectiveness of procedures employed by less experienced auditors. The proposed expert system is intended to be used by on-site auditors who are familiar with home construction and building energy conservation, but are not experts in the field. The expert system will deal with three basic situations or questions regarding air leakage: diagnosis, identification, and retrofit planning. The diagnosis mode is intended to determine the causes of existing air leakage problems. In this situation, the house has a problem such as drafts, a cold room, lingering odors, or moisture damage. The system will determine why these symptoms are occurring and suggest corrective action. The second problem type concerns the identification of air leakage problems that are presently unknown to the occupant and auditor, but that may be potentially serious in the future. These problems might involve the potential for moisture damage, excessive heat loss, or poor indoor air quality. The final situation that the expert system will address is retrofit planning. Given that the homeowner is contemplating air leakage and/or other retrofits to the building, the system determines the most appropriate and effective retrofits and anticipates potentially adverse side effects of the proposed retrofits. The expert system is intended to explore these three questions for existing homes, but the potential exists for expanding the system to include the anticipation of air leakage problems in new buildings at the design stage.

2.1 Content of the Knowledge Base

The types of air leakage problems that the expert system will deal with concern heat loss and gain, thermal comfort, moisture, and indoor air quality, and several examples are listed in table 1. These are general problem types, as opposed to their specific causes and the symptoms that reveal their presence. For example, the cause of a cold interior surface of an outside wall may be air leaking into the wall system at a second-story overhang and flowing within the wall. The symptoms of this problem may include occupant discomfort, and perhaps condensation or mildew on that wall. To further explain the content of the knowledge base, this example is considered in relation to the three situations discussed above. In the diagnosis mode, the symptoms of the cold room will be entered, along with other house information such as the existence of an overhang, and the expert system will suggest a leak into the wall as a potential cause. The system may specify additional inspections to the auditor in order to support the diagnosis, as well as provide appropriate techniques for repairing the leak. In the identification mode the expert system will consider the fact that the house has a second floor overhang, and based on experience regarding this house style and its construction, will suggest the possibility that such a leak exists. Again, appropriate verification and repair techniques will be provided. Finally, if the user is planning to retrofit the house, including the installation of wall insulation, the expert system will identify this leakage site as an important envelope tightening retrofit and as a means of making the proposed insulation more effective.

In addition to the types of problems listed in table 1, the knowledge base of the expert system will contain other information. Table 2 presents an outline of the content of the knowledge base. There are two basic types of information that will be included in the knowledge base, factual and heuristic. The factual information consists of descriptive information regarding houses, their construction, air leakage problems, and symptoms associated with such air leakage problems. All of this factual information serves as the components for developing a useful characterization of a house within the expert system.

The second type of expert knowledge to be included in the knowledge base, referred to as heuristic, is divided into problem specific and strategic. Heuristics are generally acquired from experts and are used in solving the problems in the expert system's domain. The heuristic knowledge consists of relationships between building characteristics and air leakage problems and other building characteristics, problems, and retrofit procedures, as noted in table 2. The strategic heuristics refer to more general rules that embody the problem solving approaches of the system.

2.2 Structure of Knowledge Base

The global expert system is envisioned as an interactive program in which information provided by the auditor will be used to create an "image" of the house under consideration. This image will be a combination of characteristics, varying in degree of detail and quantification, and will include information provided by the auditor and default values supplied by the expert system. Based on the application of the rules discussed above, and additional information supplied by the user, the house image will be progressively refined and made more useful.

A session will begin with the auditor providing preliminary information on the home. Initial inputs will include which of the three situations discussed above, diagnosis, identification and retrofit planning, are relevant. In addition, information regarding the home's physical description, age, mechanical equipment, and other features may be added at this stage. The system will interact with the user/auditor as this information is being input, for instance requesting additional explanation of the inputs. At the conclusion of this initial session, the system will produce a tentative list of conclusions (i.e. problems, causes, and/or retrofits), plus a list of requests to the auditor for further information. These requests may involve physical inspections ("Go to the kitchen and determine whether the exhaust fan actually exhausts to the outside or simply recirculates"), or discussion with the building occupants ("Ask the homeowner if they experienced eye irritation before obtaining the new furniture"). The auditor will obtain the additional information and the interaction with the system will continue, entering the new information as appropriate. The system will then produce a new list of conclusions that is more detailed and building specific, and possibly additional requests for information. The appropriate number of iterations and length of a session will be explored in developing the system. The system may also suggest more involved study of the building, such as pollutant concentration measurements with passive monitors or pressurization measurements of whole building airtightness, followed by another session with the system at a later date.

As mentioned above, the information provided by the user will be used by the system to create an image of the house. This image will not be a detailed, physical model of the house for use in a calculation of infiltration, involving exact descriptions of every leakage site, the building geometry, pollutant source strengths, and outdoor pollutant concentrations. Instead it will be a descriptive characterization of the building including both quantitative information (e.g. floor area, number of occupants, year of construction) and qualitative information (e.g. existence of a basement, geographic location, construction style). The rules contained in the expert system knowledge base will be used to convert the initial set of attributes of the home to a more specific and useful set of attributes. As the system employs these rules, and as additional information is provided by the user, the working image of the house will provide useful information to the user.

At this point it is not clear what solution strategies and software approaches will be most appropriate for this expert system. The development of the moisture-diagnosis prototype will assist in making these important decisions.

2.3 Knowledge Base Resources

Several different sources have been identified for use in developing the knowledge base for the expert system. These sources include both written documents and human experts, as outlined in table 3. The written documents include both audit and retrofit manuals that have been developed for specific retrofit programs or as general guides for retrofit planning (Diamond et al 1982, Energy Resources Center 1983, Knight 1981, Marbek 1984, Marshall and Argue 1981). These documents provide both general and specific information for locating and repairing air leakage sites in houses. They will be useful for identifying specific air leakage sites in existing buildings and determining appropriate retrofit measures for their repair. Reports on specific retrofit demonstration projects and discussions of specific energy auditing techniques will be useful in identifying air leakage sites and in suggesting appropriate measures for their repair. There are also many guides to energy-efficient house construction which supply specific information for building houses with high levels of thermal integrity (Elmroth and Levin 1983, Erye and Jennings

1983, Nisson and Dutt 1985). Many descriptions of construction details are included to enable construction of building envelopes which are extremely well-insulated and airtight. It may be assumed that these details have been redesigned with so much attention because they have been the source of problems in past construction. Therefore these energy-efficient construction guides may be sources of air leakage sites in existing buildings and, in some cases, of retrofit measures for their repair. There are also house construction guides that describe the techniques used for building more typical U.S. homes, as well as architectural guides that provide general classifications of houses and useful terminology for the expert system.

There are a variety of human experts available for developing the knowledge base of the expert system, as listed in table 3. House doctors and other expert auditors are sources of both the factual information and heuristics. These auditors have a great deal of experience in inspecting and retrofitting houses. They know of many air leakage sites, their causes and effects, and appropriate retrofit measures for their repair. They also have observed many relationships between housing style and construction, and the existence of specific air leakage sites, which will be used in developing the problem solving heuristics listed in table 2. The approaches that they use in conducting their audits will be used in developing the strategic heuristics. Energy-efficient housing designers and builders are sources of general knowledge on how to build houses properly, thereby avoiding the problems that are the domain of this system. Another source of human expertise are home inspectors that are used by prospective purchasers of houses to determine the condition of the house in question. These inspectors are familiar with many aspects of construction and the types of defects that occur in houses. Their experience, and the approaches they use to inspect houses, may also be useful in developing the knowledge base of the expert system.

3.0 MOISTURE-DIAGNOSIS PROTOTYPE SYSTEM

In developing an expert system, it is generally suggested that one produce a prototype system that deals with a limited aspect of one's problem domain. This process assists in choosing an appropriate software approach for the problem area of concern and in providing the system developer with experience that is useful in planning beyond the prototype system. Based on this recommended starting point, a prototype system is being developed in anticipation of producing the air leakage expert system discussed above. This prototype is restricted to the diagnosis of moisture related problems in houses and is called AIRDEX. The development of AIRDEX has employed several useful documents on moisture problems in buildings that contain discussions of general issues as well as case studies (Bales and Trechsel 1984, Eakes 1982, NCAT 1983, NRCC 1984, Woods and

Lovatt 1986). The development of this prototype has been an evolutionary process with modifications being made continuously. The description of AIRDEX that follows therefore presents only its basic structure with several examples of its detailed content. Roughly one-half of a person-year has been expended in the development of AIRDEX.

Rather than putting a great deal of effort at this early stage into software development that might turn out to be inappropriate to this problem domain, AIRDEX is being written in a commercially available, microcomputer-based expert system shell. Such a shell allows one to enter the rules constituting one´s knowledge base and quickly get a working system on line. The shell being employed is a goal-driven, backward-chaining system in which the expert system developer enters a goal or goals and a series of "if-then" rules, in the form of a text file. This file is then "compiled" with the shell. When the expert system is run, the shell attempts to prove as true or false those rules that contain the system goals as their "then" statements or consequents. The shell does this by examining the "if" portions, or antecedents, of these same rules, and attempting to prove as true or false the rules that have these goal antecedents as their consequents. The shell backtracks in this manner until it requires antecedents that are not concluded by any rules. The expert system user is then prompted to provide information regarding these antecedents in an appropriate form such as numeric quantities, true or false responses to assertions, or selections among lists of responses. In addition to proving or disproving the final goal, much important information is contained in the intermediate conclusions that are proven or disproven in the attempt to prove the final goal.

The expert system shell used for AIRDEX allows one to associate a confidence level, from 0 to 100, with user inputs or with the conclusions of rules. Several different rules may have the same conclusion but different confidence levels, depending on the strength of the supporting facts. The use of confidence levels allows one to distinguish between lines of reasoning with different degrees of certainty.

In AIRDEX the final goal is to determine the so-called "Problem" that is causing the "Symptom" of the moisture problem(s). There may be more than one such Problem that is proven to be true, and a sample list of Problems includes:

1. Interior relative humidity too high from excessive moisture sources
2. Interior relative humidity too high from insuffícent ventilation
3. Cold exterior envelope surfaces
4. Excessive airflow from living space to attic
5. Insufficient attic ventilation
6. Wind-driven moisture penetration into walls

7. Excessive basement moisture
8. Plumbing or roof leak

Several different rules will conclude that the Problem is one of the above, but they are all of the basic form:

IF Symptom is __________
AND The house characteristics are known
AND The Moisture Problem is __________
THEN The Problem is __________

Examination of the form of the above rule indicates how the system runs. The goal of the system is to prove or disprove rules with a consequent of the form "Problem is __________." Proving the validity of these consequents requires three separate antecedents to be true. These antecedents concern "Symptoms", house characteristics and "Moisture Problems," and they are investigated in the order listed. The system first tries to prove as true that the "Symptom" of the moisture related problem is that one given in the rule being investigated. In practice this means the system has the user specify what the symptom(s) is (are). There are many possible Symptoms that the user can choose from and they include:

1. Window condensation

2. Wall mold

3. Basement moisture (puddles, efflorescence,...)

4. Attic misture (mold, ice, wet insulation,...)

5. Exterior siding damage

6. Wet surfaces (walls, floors, ceilings)

The system therefore begins by asking the user to choose from among these general symptom types, and more than one symptom can be selected if appropriate.

After the Symptoms are selected, the next antecendent in the rule is "The house characteristics are known." This statement is the conclusion of a series of rules that has the system request from the user some basic information regarding the house. This information includes the number of occupants, floor area, year of construction, whether the house airtightness has been measured, and whether there is a basement, attic or crawl space. Once this information has been gathered, the system .pa concludes as true that "The house characteristics are known," and the system proceeds to the next antecedent in the rule.

Finally, conclusion of a "Problem" being true requires the conclusion of a so-called "Moisture Problem." These Moisture Problems are really just more specific descriptions of the problems causing the house´s existing moisture symptoms. In the most current version of the AIRDEX prototype, these Moisture Problems include:

1. Excessive moisture sources
2. Insufficient ventilation
3. Uninsulated walls
4. Poorly insulated walls
5. Thermal bridges
6. Cold rooms
7. Basement wall water leakage
8. Exposed crawl space
9. Poor rainwater runoff
10. Poor foundation drainage
11. Bath exhaust fan exhausting into attic
12. Air leakage at attic floor
13. Undersized attic vents

Many of these Moisture Problems are similar to the final Problems, and this occurs in order to maintain a parallel among the many paths to the final Problems. Proving of the Moisture Problems as true or false constitutes the substance of the AIRDEX system. The investigation of each Moisture Problem requires more specific information on the particular symptom(s) that is(are) occuring and house characteristics.

In the current version of AIRDEX, the Moisture Problems of excessive moisture sources and insufficient ventilation are investigated in the most detail, while some of the Moisture Problems do not yet serve as the conclusions of any rules within the system. The means of determining whether "excessive moisture sources" and "insufficient ventilation" are Moisture Problems is described below. Regarding the determination of whether the Moisture Problem is excessive moisture sources, AIRDEX considers several sources of moisture and associates a weighting factor with each. For example, the weighting factor associated with a clothes dryer venting into the basement or living space is equal to ten times the number of occupants. Unvented space heaters are weighted at two times the number of hours operated per week. The other sources include whole house and local humidifiers, plants, firewood stored indoors, indoor pools, hot tubs and saunas, basement water leakage, crawl space moisture, and the fact that the house was recently constructed. The user is asked to identify which sources exist within the house and to provide any additional information required to determine the weighting factor associated with each source. After the weighting factor of each source is established, all of the individual weighting factors are added together. An arbitrary cutoff between the existence of an excessive source problem and the lack of such a problem is a total weighting factor of one hundred. A total of greater than two hundred is labelled as a serious problem, and a total between fifty and one hundred is labelled as marginal. The values of these weighting factors and these cutoffs are based on the judgement of the system's developers. These weighting factors are used in order to avoid physical units for fear that they may then be associated with a higher degree of physical significance than appropriate. One problem with these weighting factors is that if the background information (e.g. hours per week of unvented heater use) is not available, the corresponding weight can not be determined. In addition, this scheme has the shortcoming of judging the sources' excessiveness without any reference to house volume or airtightness.

The existence of the Moisture Problem of insufficient ventilation is based on a comparison of the house's estimated ventilation rate and the desired ventilation rate based on ventilation requirements. The estimated ventilation rate is derived from the house airtightness as determined by a whole house pressurization test. The pressurization test result in units of air changes per hour at 50 Pa is simply divided by twenty to obtain a crude estimate of the current ventilation rate. The desired ventilation rate is set equal to the larger of two calculated ventilation rates, one based on the number of rooms and the other based on the number of occupants. The room-based ventilation rate is simply the number of rooms multiplied by 5 l/s and divided by the house volume to obtain air changes per hour. The people-based ventilation rate is equal to the number of occupants multiplied by 2.5 l/s and divided by the house volume. The current and the desired ventilation rates are then compared to determine if the house has sufficient ventilation. If the current ventilation rate is less than or equal to 80% of the desired rate, then insufficient ventilation is a problem. If the current rate is between 80% and 95% of the desired rate, then insufficient ventilation is only a possible problem. If the current rate is within 5% of the desired rate, the house's ventilation is probably adequate. Current ventilation rates that are between 5% and 20% above the desired level are more likely to be sufficient, and current rates more than 20% above the desired level are definitely adequate. This determination of the sufficiency of ventilation is simplistic and can not be used if the house has not been pressure tested. It does not consider other methods of determining the actual ventilation rate such as actual measurement or more physical prediction methods, nor does it employ any default values. Finally, the sufficiency of the ventilation rate is not based at all on the moisture generation rate within the house.

4.0 SYSTEM EVALUATION AND CURRENT EFFORTS

There are two important reasons for beginning the development of an expert system with a prototype such as AIRDEX. First, having a working system enables experts in the problem domain to evaluate the system by running it on sample problems and examining its responses. Also, since the knowledge base is explicitly visible in the system rules, these experts can examine its content and the system's organization. The second benefit of developing a prototype is that through the process of forming the knowledge base rules the system's developers obtain insights that can result in improvements to the system. The development of AIRDEX and its examination by several experts in residential moisture has been a valuable process and has led to several proposed improvements. In addition, further examination of the relevant literature by the system's developers has revealed other improvements that can be made in the system.

The evaluation of AIRDEX involved several experts in residential moisture issues who applied sample problems to the system, examined the rules contained in the system listing, and discussed moisture problem diagnosis issues with the system developers. The results of the moisture experts' evaluation, as well as the system's developers insights, concern three basic areas: the predominant moisture problems that occur in houses, the quantification of moisture source strengths, and the information that is often contained in the symptoms of the problems.

4.1 Predominant Moisture Problems

While there is less hard data than anecdotal experience, the predominant cause of living space moisture problems appears to be excessive sources of moisture. If this is indeed true, then the system should first investigate the existence of unusually strong sources, rather than beginning with equal expectations that the problem is due to excessive sources, insufficient ventilation, or cold surfaces. Similarly, the predominant causes of attic moisture problems are airflow into the attic from the living space, inadequate attic ventilation, and reduced attic temperatures due to recent insulation work. Thus, in attempting to diagnose the cause of attic moisture problems, one can assume these factors probably exist and concentrate on details of airflow paths in the attic floor, attic venting and recent attic insulation work. The other predominant moisture problems appear to be wind-driven rain penetration of the building envelope, leaky pipes and roofs, and poor rainwater runoff and foundation drainage. The fact that these common causative factors exist suggests that the system concentrate on these issues first, rather than using the open-ended approach of the current version. The approach that has been taken in developing AIRDEX is to employ a thorough investigation of the characteristics of the house, occupants and symptoms and draw conclusions based on this information. Continuing to develop AIRDEX in this manner would ultimately result in a very large system, and in a time-consuming and seemingly undirected interaction with the user. The ability to begin with reasonable expectations of the causes of residential moisture problems will be used to make future versions of AIRDEX more direct in its investigations.

4.2 Quantification of Moisture Source Strengths

The discussions with residential moisture experts and examinations of the literature have also led to questions regarding the appropriate manner of quantifying source strengths. As discussed above, the current version of AIRDEX employs a nonphysical weighting scheme to determine if the various moisture sources in the house constitute an excessive moisture generation rate. The experts who evaluated AIRDEX suggested a more physical and detailed approach to quantifying source strengths and to determining the existence of an excessive source problem. The suggested approach includes using physical units for moisture source strengths, and considering the house volume and ventilation rate in determining whether the source is excessive.

While the moisture generation rates associated with some of the sources are difficult to know, many of them can be quantified in physical terms (liters per day, l/d) and associated with factors related to the occupants and the structure. In addition, some generation rates can be determined with greater or lesser certainty depending on which factors are used to determine their values. The degree of certainty in the determination of a particular source strength can be reflected within the system by the value of an associated confidence level. For example, the moisture generation rate associated with a clothes dryer that is vented indoors is related to the number of loads per week and can be converted to l/d based on an assumption as to the number of liters of water associated with a load of laundry. Alternatively, one can estimate the generation rate associated with a clothes dryer with less certainty by basing it on the number of occupants and assuming a value for the number of loads per occupant. Similarly, the moisture generation rate associated with houseplants is most directly related to the amount of water used, followed by the frequency of watering, and finally the number of plants. The relation between generation rates and these various factors will not always be well-established, but a more physical and quantitative approach to their determination will be employed in future versions of AIRDEX.

The recommendation of a more physical approach to source strengths goes along with a more quantitative consideration of the ventilation rate in determining the indoor level of relative humidity, and the reason the humidity may be too high. Current versions of AIRDEX consider the question of adequate ventilation with reference to ventilation standards only, and then only associate a ventilation rate with a house if the structure has been pressure tested. Future versions will always use a numerical value for the ventilation rate in combination with the moisture source strength to determine an interior relative humidity level. The ventilation rate will be associated with varying degrees of certainty depending on the source of its value. If the ventilation rate is based on tracer gas measurements it will be associated with a high degree of certainty. Lesser degrees of certainty will be associated with ventilation rates based on pressurization test results in combination with models, estimates based on house features such as age and condition, and default values. Such a physical approach to determining interior relative humidity is superior to the current arbitrary weighting scheme that neglects the ventilation rate and the house volume.

Based on the expert evaluations and further study of the literature, future versions of AIRDEX will employ an alternative to the numerical determination of the existence of excessive source strengths discussed above. This alternative will investigate the existence of exceptional moisture sources before employing the above numerical approach. Some residential moisture experts believe that unless the house is very tight, typical moisture sources will not lead to excessive interior relative humidity. These typical sources include respiration, bathing, plants, cooking and dishwashing, clothes drying (even if vented to the interior), and indoor firewood storage. This viewpoint maintains that there must be unusual sources such as unnecessarily high levels of intentional humidification, high moisture content in building materials in a newly constructed buildings, a new building that was closed-in during a rainy period, the existence of an indoor pool or attached greenhouse, or a very large number of occupants. If these extreme sources can be determined to exist with a high degree of certainty, it may be unnecessary to go through the detailed evaluation of less important sources and ventilation rate. A less certain determination of the existence of such extreme sources will increase the need to employ the detailed evaluation discussed above.

4.3 Information from Symptoms

The last item that was learned from the interaction with the moisture experts is the ability to use information on the symptoms to learn about the cause and severity of the moisture problem. A good example of this use of symptoms is the case of window condensation and information on its timing, extent and duration. If window condensation occurs all winter long it is a sign of continuously excessive indoor relative humidity and a severe problem. On the other hand, sporadic occurences of window condensation may provide information on the source of the moisture. For example, if window condensation is associated with cooking, bathing or unvented heater use, one probably knows the source of the excessive moisture and therefore has a good indication on how to remedy the situation. The duration of sporadic occurences reveals information about the severity of the problem. If condensation occurs during showers or cooking and then dries up quickly, then there probably is not much of a problem. But if the moisture remains for many hours, then the source needs to be controlled. Similarly, the location of the condensation provides information on the severity of the problem. If the windows in all rooms exhibit condensation, then the problem is more severe than if the condensation occurs only in the bathroom or kitchen. There are other cases where information regarding the symptoms provide information on the problem´s cause and severity, and these can be used to quickly get to the important causes rather than question the user about a great many house characteristics, many of which will be irrelevent to the situation.

Many of the above conclusions based on the experts´ evaluation, the developer´s moisture research, and efforts in developing AIRDEX, suggest the incorporation of these heuristics into the system. The current version of this prototype system was organized with the approach of investigating almost everything, i.e. looking in detail into many characteristics of the symptoms, house and occupants. The current all-inclusive approach, if pursued, would have resulted in a large system that would ask the user for a great deal of information. It now appears that it would be better to direct the system´s investigation towards those specific, dominant situations that were discussed above. These include starting the diagnostic investigation by expecting the common causes of moisture problems, and in the case of excessive generation rates looking for unusual moisture sources first. In addition, key questions regarding certain symptoms should be used to get important information quickly. Such streamlined investigative procedures are exactly the type of useful input that can be provided by domain experts to make expert systems work more quickly and effectively. Future versions of AIRDEX will be modified to employ these "short-cuts."

5.0 SUMMARY

In this paper we have presented a general description of an expert system proposed to deal with air leakage problems in houses. This system is intended to deal with the diagnosis and identification of such problems, as well as assist in the planning of energy conserving retrofits as they relate to air leakage. This effort has begun with the development of a prototype system, referred to as AIRDEX, that deals with the limited domain of the diagnosis of moisture problems in houses. Early evaluations of AIRDEX by residential moisture experts, as well as observations made by the system´s developers in the process of formulating and working with the system, have revealed the need to modify AIRDEX so that it employs more of what is known about the nature of moisture problems in houses. The basic effect of these intended changes will be to alter AIRDEX's current direction of attempting to cover all possiblities with equal emphasis and to instead have it begin by pursuing its investigations along the lines suggested by common moisture problems and by existing knowledge concerning these problems.

6.0 ACKNOWLEDGMENTS

The author wishes to acknowledge the assistence of Gautam Dutt, Kenneth Gadsby and David Harrje of Princeton University in particpating in the evaluation of AIRDEX.

7.0 REFERENCES

ASHRAE, Handbook of Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1985.

ASTM, "Standard Practice for Air Leakage Site Detection in Building Envelopes," Draft of Proposed Standard, Amercian Society for Testing and Materials, 1986.

Bales, E., Trechsel, H., eds., Moisture Control in Buildings, Building Thermal Envelope Coordinating Coucil, 1985.

Diamond, R.C., Dickinson, J.B., Lipschutz, R.D., O'Regan, R., Shohl, B., The House Doctor's Manual, PUB-3017, Energy Performance of Buildings Group, Lawrence Berkeley Labortory, 1982.

Eakes, J., Insulation Aftermath, Ontario Marketing Productions Limited, Toronto, 1982.

Elmroth, A., Levin, P., Air Infiltration Control in Housing. A Guide to International Practice, D2:1983, Swedish Council of Building Research, Stockholm, 1983.

Energy Resources Center, How to House Doctor, University of Illinois at Chicago, 1983.

Erye, D., Jennings, D., Air-Vapour Barriers, Energy, Mines and Resources Canada, Ottawa, 1983.

Forsyth, R., ed., Expert Systems. Principles and Case Studies, Chapman and Hall, Ltd., London, 1984.

Harrje. D.T., Dutt, G.S., Beyea, J., "Locating and Eliminating Obscure but Major Energy Losses in Residential Buildings," ASHRAE Transactions, Vol.85, Part 2, 1979.

Harrje, D.T., Dutt, G.S., Gadsby, K.J., "Isolating the Building Thermal Envelope," proceedings of Thermosense III, Society of Photo-Optical Instrumentation Engineers, Minneapolis, 1980.

Hayes-Roth, F., Waterman, D.A., Lenat, D.B., eds., Building Expert Systems, Addison-Wesley Publishing Co., Inc., Wesley, MA, 1983.

Knight, P.A., The Energy Resources Center Illustrated Guide to Home Retrofitting for Energy Savings, McGraw Hill, New York, 1981.

Marbek Resource Consultants, Air Sealing Homes for Energy Conservation, Second Draft, Energy, Mines and Resources Canada, 1984.

Marshall, B., Argue, R., The Super-Insulated Retrofit Book, Renewable Energy in Canada, Toronto, 1981.

NCAT, "Moisture and Home Energy Conservation," National Center for Appropriate Technology, 1983.

Nisson, N., Dutt, G., The Superinsulated Home Book, John Wiley & Sons, New York, 1985.

NRCC, "Humidity Condensation and Ventilation in Houses," National Research Council of Canada, Proceedings No. 7 of the Division of Building Research, NRCC 23293, 1984.

Persily. A.K., "Outline of an Expert System Approach to Residential Air Infiltration," NBSIR 86-3323, National Bureau of Standards, 1986.

Socolow, R.H., ed., Saving Energy in the Home, Ballinger Publishing Co., Cambridge, MA, 1978.

Woods, A.A., Lovatt, J.E., "Twenty-Five Case Histories of Moisture Problems in Low-Rise Residential Buildings," Buildings Energy Technology Transfer Program, Energy, Mines and Resources Canada, 1986.

Table 1 Air Leakage Problems

Heat Loss/Gain:
- Excessive infiltration rates
- Air leakage decreasing the effectiveness of insulation systems

Thermal Comfort:
- Air leakage causing cold/warm interior surfaces
- Air leakage causing drafts

Moisture:
- Exfiltrating air contacting cold surfaces within the building envelope or living space and condensing (winter)
- Infiltrating air contacting cold surfaces within the building envelope or living space and condensing (summer)
- Inadequate attic ventilation
- Excessive moisture transport from the occupied space to the attic
- Excessive moisture generation and inadequate removal within the space

Indoor Air Quality:
- Excessive pollutant sources strengths
- Inadequate ventilation - whole building and/or local, and as a function of time

Table 2 Outline of the Knowledge Base

Factual Information

- Generic:
    - Housing styles
    - Floor plans
    - Roofs and foundations
    - Unheated spaces - basements, attics, crawlspaces
- Construction:
    - Envelope systems - framing, foundations, insulation
    - Details - joints, seams, interfaces
    - Accessories - doors, windows, dormers, overhangs
    - Mechanical equipment
- Problems: See Table 1
- Symptoms:
    - Heat Loss/Gain - Excessive utility bills
    - Comfort - Drafts
    - Moisture - Condensation, Mildew, Damage
    - Air Quality - Stuffiness, Lingering Odors, Chronic Respiratory Complaints

Heuristics

- Problem Specific:
    - Associations between building types and construction details
    - Associations between building types and air leakage problems
    - Associations btween construction details and air leakage problems
    - Associations between air leakage problems and symptoms
    - Associations between air leakage problems and appropriate retrofits
- Strategic:
    - Problem solving approaches

Table 3 Knowledge Base Resources

Documents
- Auditing and Retrofit Manuals
- Technical Reports on Retrofit Techniques and Demonstration Projects
- Energy-Efficient Construction Guides
- Home Construction Manuals
- Architectural Guides

Human Experts
- House Doctors and Other Expert Auditors
- Energy-Efficient Housing Designers
- Energy-Efficient Housing Builders
- Home Inspectors

DISCUSSION

Paper 1: 'Measurement techniques for ventilation and air leakage', presented by P S Charlesworth (UK)

R D Dawson (UK)
I am sure tracer gas techniques use 'small' amounts of freon, fluorinated hydrocarbons, fluorinated sulphur etc? Bearing in mind 'popular' criticism of these agents being dispensed in the atmosphere, what gases will be proposed and used to replace them? We cannot have one rule for environmentalists and one rule for ourselves?

P Charlesworth (UK)
The production of free radicals by the breakdown of carbon-halogen bonds in some tracer gases does no doubt contribute to the reduction of the ozone layer. However, the amount of tracer used in air change experiments is exceedingly small as compared to the amounts used in meteorological tracers (nanograms as compared to kilograms - an order of 10^{12}difference), that the problems created by air change tracers will be minimal. Where problems could occur is in background concentrations. If the background concentration of currently used tracer gases is increased due to other production sources then the accuracy of experiments may be affected, or it may be necessary to use an increased concentration of tracer gas in the building under examination. A return to previously used tracers would be hazardous as many of these were either explosive, poisonous or radioactive. Any quest in search of new tracers must take these points into account, and the effects of any gas must be carefully considered before releasing it into the atmosphere either directly or via the building envelope.

J Axley (USA)
(Comment) Regarding multizone tracer methods; these methods are based on the formulation and solution of the inverse contaminant dispersal equations that are, under the best circumstances, inherently illconditioned. For data reported by Dietz et al, the inverse equations formed were found, by our group, to have condition numbers in the order of 10-20 that, coupled with the uncertainty of the data, would indicate error bounds in the order of 200%.

D Harrje (USA)
(Comment) More than modelling alone, any of the measurement systems require extensive field testing to fully evaluate their capabilities. The PFT system has been evaluated in a number of studies, several of which will be reported at this meeting. These studies are helping to place in perspective the preferred applications of this approach.

Paper 2: 'Measurements of infiltration and air movement in five large single-cell buildings', presented by J R Waters (UK)

J Axley
(USA)

In the determination of multizone flows by inverse application of multizone contaminant dispersal equations one must be careful to use a tracer method that minimizes the ill-conditioning of the equations formed. Specifically one must carefully choose a system excitation and data measurement strategy to obtain the smallest condition number possible and not only compute the solution to the equations formed but also the condition number (or similar measure) of these equations. Did you compute the condition number for your studies?

J R Waters
(UK)

No, we did not do so for the present study, choosing instead to solve the equations by a constrained least squares approach that does not yield directly the condition number. In earlier studies we did consider the conditioning of the system.

J Lilly
(UK)

The improving agreement between the best value of air change with the interzonal flow airchange coincides with a reduction in the S.D. of the measurements. This would normally occur with improved mixing in the measurement volumes. (This would also ensure better uniformity of concentration in each hypothetical zone.) Do you have any measurement of turbulence or level of mixing in these tests?

J R Waters
(UK)

Yes, I agree with your point. No we have not made any independent measurement of mixing or turbulence, though we ought to do so in future measurements.

E Perera
(UK)

(1) During tracer injection, mixing fans are used. This should provide approximate uniform tracer concentration initially throughout the zones. Yet figure 2 does not show this. Can you explain?

(2) At what time points did you measure concentration gradients required for solving the interzonal airflows?

(3) How valid is the arbitrary choice of zones which has no physical boundaries? Tables 1 to 3 show several examples of two-way zero interzonal airflows. Is this physically realistic since there has to be some inherent air movement between non-physical artificial partitions?

(4) Could you please explain what you mean by rates calculated using averaged concentrations (AC)? Should not the whole building infiltration rate be the long term decay rates (as indicated by BRE's Simplified Technique) which can be determined if Figure 2 can be plotted semi-logarithmically?

J R Waters
(UK)

(1) Our objective is to begin the decay process with tracer gas in one zone only. To achieve this, we inject SF6 into one of the zones (zone 5 in the example shown in

figure 2) at a high rate, with mixing in that zone only. We have found that provided the injection and mixing process does not take more than about 3 minutes, our objective is substantially achieved, as figure 2 shows.

(2) Concentrations are measured in all zones at one minute intervals. Concentration gradients are obtained at every data point (except the first two and the last two in the time series) by taking 4th differences (see reference 1 of the paper). Therefore an equation can be written for the interzonal flows for each zone at every data point. All such equations are included in the constrained least squares solution technique.

(3) The purpose of dividing the building into hypothetical zones is to enable a methodology to be developed from which an estimate of the large scale movement of air within the building can be derived. The results show that this approach has been only partially successful, and the conclusions to the paper discuss some reasons for this. The existence of two-way zero interzonal flows does not by itself indicate that the choice of zones was invalid, but rather that the flows were too small, or the results too insensitive, for those flows to be detected.

(4)The method of taking averaged concentrations is explained in pages 5 and 6 of the paper. In a multizone building, or in a poorly mixed single zone building, the eigenvalue associated with the long term decay rate (ie the dominant eigenvalue) is <u>NOT</u> equal to the whole building infiltration rate. This eigenvalue will always underestimate the whole building infiltration rate, by an amount which depends on the degree of internal mixing. Thus, on a semi-log plot of the average tracer decay the long term straight line portion of the graph has a gradient which equals the dominant eigenvalue, but is less than the whole building infiltration rate. To take this value for the infiltration rate, as in the BRE simplified procedure, is in our view an unnecessarily poor approximation. By examining the whole of the decay curve one can obtain an upper as well as a lower bound on the true infiltration rate, and it is reasonable to hypothesise that the average gradient of the whole of the semi-log plot is closer to the actual value than either of the bounds.

<u>Paper 3</u>: 'Developments in a multi-tracer gas system and measurements using portable SF6 equipment', presented by <u>J Littler (UK)</u>

P Collet (Denmark) You asked for comments about the Figures for infiltration in two-floor houses. Our measurements show that in normal houses the fresh air intakes are through leaks in the bottom floor.

J Littler
(UK)

I agree.

B Kvisgaard
(Norway)

What size was your slot in the two storey houses? In Scandinavia we often use 30 cm^2, and it is normally insufficient.

J Littler
(UK)

Ground floor total length (made up of four sections in four windows) is ~ 1m; the same for upstairs. Slot width is about 15mm.

J Lilly
(UK)

In the house with the Genevex mechanical ventilation system, on what ventilation setting did the occupants use the system? What ventilation rate did this correspond to? Have you any information regarding window opening behaviour in this house?

J Littler
(UK)

We only fitted one Genevex, to a passive solar house occupied by our researchers. The setting most often used was 'normal'. The ventilation rate was 0.5 ach^{-1}. The windows were almost never opened. The floor plan is very open in the living area. Occasionally the bedroom windows were opened.

W Raatschen
(FRG)

Can you compare your natural ventilating systems with the mechanical ones? In Germany, room temperatures are usually 2-6°C higher with medi vent systems, as measurements showed, because occupants complained about draughts. What room temperatures did you have?

J Littler
(UK)

In the medi vent houses we had 20-21°C and low air velocities.

Paper 4:

'Tracer gas used to evaluate HVAC equipment', presented by B Kvisgaard (Denmark)

D Bohac
(USA)

Have you tried measuring the concentration in the house to look at the distribution of the infiltration flow?

B Kvisgaard
(Denmark)

No. We were only measuring on the main airflow. It could be possible to gain some information about the distribution of the air in the building, from the shape of the concentration/time curve in the extract duct.

P Charlesworth
(UK)

(1) What size were ducts in which concentration measurements were made?

(2) Was it necessary to measure concentration at more than one point in the duct?

B Kvisgaard
(Denmark)

(1) In one house the duct was about 12cm diameter, and in the other about 30cm - 50cm.

(2) No. When we dosed the tracer at a point before the

fan and measured it after the fan, there was no problem with non-uniform concentration.

D T Harrje
(USA)

In the example of the single family home you presented, six hours were necessary before an equilibrium condition was approached, isn't this unacceptably long for an analysis technique? Have you investigated ways to more rapidly bring about the equilibrium conditions?

B Kvisgaard
(Denmark)

How rapidly you reach the equilibrium condition depends on the airchange of the building. The single family house has a small airchange in comparison with a normal office building. We assume the equilibrium will be reached in less than 2 hours for an office building.

Maybe it is not necessary to measure until equilibrium is reached, maybe the equilibrium concentration can be predicted from the shape of the curve.

M J Holmes
(UK)

How practical is your method for use in large air conditioned buildings? In particular are there any air flow rate limits beyond which the method should not be used?

B Kvisgaard
(Denmark)

There is no problem in large building measurement. We have measured airchange up to 200,000 m^3/h. The limitation in the system is set by the sensitivity of the gas analyser.

E Perera
(UK)

You determine the airflow into the building by measuring the tracer concentration after it has passed through the supply duct. If either the duct length is too short or if there are leaks in the duct, then the airflow measured will be in error. What precautions do you take to minimise this error?

B Kvisgaard
(Denmark)

We normally dose tracer gas upstream to the flow, and measure the concentration downstream to the fan, to ensure uniform concentration in the duct.

Paper 5:

'Appliance of infra-red thermography in examining air leakage of buildings', presented by O Adan (Netherlands)

D Harrje
(USA)

(Comment) I was surprised to see no reference to extensive past work on this project. The Swedish Council for Building Research in 1979 published the work of Axen and Petterson in the form of a handbook on thermography looking at air leakage and conductive losses. Thermosense (Bellview, Washington) in North America has held a yearly conference on this subject. Also the Canadian government buildings have been extensively surveyed by infra-red techniques looking for air leakage. The technique has even been extended to use helicopters to survey the building surface. Overflight and infra-red "van scans" have been used in the USA for the same purpose. There is an ISO standard that covers this topic area.

W Raatschen (FRG) How can you differentiate from the picture you get from thermography, whether you have a thermal bridge or losses by air exfiltration?

L Hendriks (Netherlands) With some experience you can decide these two things by the temperature gradients.

Paper 6: 'Draught measurements in ventilated and non-ventilated buildings', presented by E Mayer (FRG)

P O Danielsson (Sweden) Can your probe be bought on the market? If not, when will it be available?

E Mayer (FRG) As I hope, it will be available towards the end of this year by Thies (Klima-,Mess-und Regelgeräte) at D-3400 Göttingen, Postfach 3536, Federal Republic of Germany.

E Perera (UK) (1) A uni-directional anemometer rectifies negative signals into positive values so that an incorrect air velocity is obtained if the signal fluctuates about a mean of (say) zero. How do you cope with this?

(2) You have correctly identified two parameters, mean velocity and turbulence, which influence the heat transfer coefficient, α . A third, the length scale of turbulence (roughly the size of the energy-bearing eddy) is also important. If this length scale is of the same order of magnitude as the head size or body size, then heat transfer is increased. Have you considered determining this effect and would you not agree that it is important to do so?

E Mayer (FRG) (1) Of course you are right, for low mean air velocities with high fluctuation, we measured the vector air velocity incorrectly. It is measured correctly:

a) when fluctuation is low (e.g. in clean rooms) or
b) when this vector is always positive (higher main air stream as often in ventilated rooms).

But for draught investigations such as we do wouldn't it be helpful for simplification to analyse the amount (scalar) of an air movement?

(2) This effect correlates with the frequency of air velocities and I agree that this has to be studied too. We have just started with this.

Paper 7: 'Data needs for the purpose of air infiltration computer code validation', presented by J L Scartezzini (Switzerland & USA).

R P Dawson
(UK)

(1) What finish is applied to your wind tunnel model?

(2) Do you consider that more effort to more closely follow surface finishes in scale should be taken to obtain a better correlation between model and measurement?

(3) My experience of wind tunnel testing would indicate that the model presented will not correlate well.

JL Scartezzini
(Swi & USA)

(1) The walls and the roof of the building are made out of plexiglas. We did not change the finish of the material.

(2) We believe that the finish of the surfaces could have an influence on the value of the pressure coefficients. However, as we are not able to copy the surface of the building in detail, it makes no sense to apply a random roughness to the walls. From the results of our measurements we learned about the influence of the building's surroundings and the wind direction. This complicated dependency is not going to change qualitatively, independently of the roughness of the scale model. Furthermore, we are not aware of a detailed study on the above mentioned phenomena. Maybe you can help us with some literature references.

(3) As mentioned before, I would appreciate your help in finding the appropriate related roughness for our problem.

E Perera
(UK)

(1) Any validation requires correct input of meteorological data. In your validation, will you consider the joint probability of wind speed (with wind direction) and outside air temperature rather than individual probabilties?

(2) Will data from the LESO test facility be available, as a matter of course, for researchers (outside EPFL and LBL) to test their own multi-celled computer programs? Perhaps dissemination of this kind could be overseen by the AIVC?

JL Scartezzini
(Swi & USA)

(1) For the purpose of building energy analysis, we are developing a stochastic model based on the theory of Markod chain. Within their framework, we have already studied intercorrelation of the main meteorological variables (solar radiation, outdoor air temperature). Their analyser will be extended to the air infiltration main variables.

(2) To set up package data which can be used by everybody is a huge task which has not been scheduled yet. But in principle this could be done providing that the work is supported by some institution outside EPFL and LBL.

Paper 8: 'Applications of a simplified model for predicting air flows in multizone structures', presented by T Haugen (Norway & USA)

J Axley
(USA)

(Comment) I take issue with one of the fundamental premises presented for seeking a simplified model. You indicated that one of two disadvantages of using a detailed model was that a mainframe computer must be used. This is not so. For example, even a 100 zone model requires no more than 640K bytes (i.e. 100x100 terms x 64 bytes for double precision) of central storage term we have an IBM PC/MAC program AIRMOV at NBS that utilises dynamic array management and compact storage strategies and therefore can handle very large systems.

Paper 9: 'Use of statistics for predicting distribution of air infiltration', presented by A F Nielsen (Norway)

P Grabau
(Canada)

I did not understand the extra building height. What is that and why is it included as a parameter?

A F Nielsen
(Norway)

In the ELA-model we use the height of the structures as the height of the building (in this case 2x2.5m). If the house had a chimney the height would be higher. This is taken into account as called extra height. It can also be explained as a variation in exact height over the surrounding earth.

D Harrje
(USA)

It is nice to see that the prediction of air infiltration in Norwegian houses follows the same relationship found so useful for Swedish and US/Canadian housing, namely divide the ACH at 50 Pa by 20. Your figure to take into account the energy relationship is very useful but requires information on house volume so that a variety of house sizes can be evaluated. What has been your house volume in this paper? What other factors must be known to make it applicable for other countries, e.g. heating degree days, interior temperature?

A F Nielsen
(Norway)

The building is 600m^3. The indoor temperature is 21°C, as a mean value. I don't remember the degree days but the mean outdoor temperature in Oslo is 5.9°C. It has not been intended to use the results in other climates, but it is possible to make transformations if you know the sites, wind speed and temperature.

P Hartmann
(Switzerland)

(1) You spoke about the new Norwegian energy standard which depends on certain calculated infiltration rates. What is the purpose of this standard?

(2) Did you make similar calculations about the ventilation losses of your houses, which are mostly naturally ventilated?

A F Nielsen
(Norway)

(1) The standard is used in the design phase when you calculate the energy consumption taking into account infiltration, ventilation or transmission.

(2) The ventilation has not been taken into account, as the ELA-model does not include this. Results of variations in energy consumptions for typical houses can be found in reference 1, where we include the effect of inhabitants.

Paper 11:

'Ventilation rates and energy losses due to window opening behaviour', presented by P Wouters (Belgium)

P Charlesworth
(UK)

Is there going to be any feedback advice to occupants as to how they could use their windows in a more efficient manner?

P Wouters
(Belgium)

The 7th chapter of the final report of annex VIII deals with the problem of modifying inhabitants behaviour. It has been dealt with in the study by DeGids and Pfaff on the project in Schiedam. From the results one can see that modifying behaviour on window use is very difficult even when you confront people with their own measured behaviour. Speaking to them only made changes in the behaviour of the energy conscious group.

P Collet
(Denmark)

(1) Do you take into account in your calculation that the entrance door acts as a window size, which means that you also have around 6-10 openings a day?

(2) Have you measured the actual influence of window openings with the constant concentration method?

P Wouters
(Belgium)

(1) Several studies have shown that the effect of using doors on the total ventilation rate is very low: the instantaneous air flow rates are very high but the duration for one opening is expressed in seconds so that on a daily load the effect is very small.

(2) It has not been done in the Belgian enquiry.

G Fracastoro
(Italy)

When evaluating the energy losses due to airing by occupants, did you take into account the decrease of indoor temperature which takes place when you open a window for a while?

P Wouters
(Belgium)

This has not been taken into account. There are other similar phenomena which were simplified, e.g. we assume that the temperature was identified in all the rooms. It is clear that refinements are possible when better reliable input data become available.

J Lilly
(UK)

On what basis is the data base formed for your paper - was it the subjective response of occupants to questionnaires and all the associated assumptions, or the more objective automatic continuous monitoring of window opening?

P Wouters
(Belgium)

The results from the Belgian study were obtained from enquiries and associated assumptions. The details of this study were given in a paper at the 7th AIVC Conference.

A F Nielsen
(Norway)

Will you try to use your information on occupants behaviour using a statistical simulation, as it is not so useful in Figure 4 to get a very large interval for typical infiltration?

P Wouters
(Belgium)

It seems rather difficult to do a statistical simulation on window opening behaviour. What we did was combine answers in inquiries with some estimations on air flow rates which resulted in a frequency distribution (see paper at the 7th conference). We have divided the distribution into 3 categories for practical use by designers.

It is in principle, possible to do a statistical simulation for the rule of thumb $n_\beta=n_{50}/K$ (a similar approach to the one you presented but with a wider variety on the parameters).

Paper 12:

'Ventilation requirements and demand controlled ventilation', presented by L Trepte (FRG)

P F Collet
(Denmark)

(Comment) We have measured the influence of small openings like the French Humidity system. Such small openings do not work properly. You have to have a minimum to regulate an opening of 200-300cm.

G Fracastoro
(Italy)

In the evaluation of heat demand for ventilation should you not take into account also the effect of the moisture content difference? xipwv.(Ti-To)

Ex. $Q_L = \dot{m}\ (hi - ha) \simeq \dot{m}[c_p(Ti-To) + ro\ (x_i-x_o)]$

If $Ti = 20°C \quad rh = 50\% \rightarrow x_i \simeq 8 g/kg$

$To = 0°C \quad rh = 80\% \rightarrow x_o \simeq 2\text{-}3 g/kg$

Therefore $Cp(Ti-To) = 20\ KJ/kg$

$ro(x_i-x_o) = 2500\ (8-3)\ 10^{-3} = 12.5\ kJ/kg$

Where ro = evaporation heat

The order of the magnitude of the two terms is the same.

W Raatschen
(FRG)

Heat demand for ventilation is the heating power I need to bring the incoming outdoor air from outdoor to indoor temperature. You can do that very accurately using the formula

$$Q_L = m_{\text{air dry}}\ x[(c_{p\ \text{air}} + X_o .\ c_{p\ \text{vapor}})\ (Ti-To)]$$

In this equation I neglected the term Xo.Cp vapour as it is lower than 0.5%.

Therefore, the specific heat demand in figure 2 is the power to heat up the incoming air. You are of course right that the amount of energy needed to evaporate the liquid water in the room is considerable and this must show up, if you do an energy balance for the whole system, but this is not what I did in figure 2.

J Littler
(UK)

(1) You considered H_2CO, CO_2, H_2O etc, but not CO8 and NOx from gas burning appliances. Why?

(2) You used a calculated internal wall surface temperature, as a condensation criterion; but that ignores:

(A) Thermal bridges (e.g. concrete deck-access apartments).

(B) Windows (which are the common point for condensation).

W Raatschen
(FRG)

(1) For a demand controlled ventilating system in a naturally ventilated residential building we need very simple and cheap devices, which will give a good compromise between indoor air quality and energy savings. For smoking persons, the higher needed ventilation rates should not be realised by very sophisticated devices, but through manual handling devices.

You are right that I excluded burning appliances. My outlines do apply to any room in general, but burning appliances should have a separate hood to avoid CO or NOx in the occupied zone.

(2)(A) In appendix I, you can see how the surface temperature is calculated. The empirical formulae given there include geometric thermal bridges especially in 2- or 3-dimensional corners of rooms constructed within the current insulation standards.

(2)(B) These insulation standards say that we have to have at least double glazing, where condensation may never or very seldom occurs. If condensation occurs, this water will not cause damage, as it will stay and evaporate later.

P Wouters
(Belgium)

(1) The choice of the input data is very important for these calculations. Is it acceptable to use data in DIN 4108 and 4710 for these problems?

(2) e.g. DIN 4710: are the relative humidities mean values for these outside temperatures, or are they some well chosen values for other purposes (e.g. 95% value)?

W Raatschen
(FRG)

(1) It is important to get an idea of in what range e.g. outdoor humidities are. In DIN 4710 this range is given for 13 locations spread over the FRG. For my estimations here I used the maximum and minimum values to cover the whole range. In figure 1 therefore this range is given by the shaded areas.

The outdoor humidities given in DIN 4710 are based on hourly measurements of air temperature and relative humidity during 1951-1970. I didn't use any information from DIN 4108 directly. Indirectly I used an empirical equation from Erhorn and Gertis to calculate surface temperatures, which can occur at critical locations in a building which has been built due to the DIN 4108.

J Timusk
(Canada)

If condensation on exterior walls is the criteria for ventilation control, how can we justify the highest ventilation rate when indoor and outdoor temperatures are the same?

Take it a step further - would the curve continue to rise when outdoor temperature is higher than indoor - common when air conditioning is used as without but with large diurnal fluctuations?

L Trepte
(FRG)

As long as there is a positive difference between Xi-Xo, a necessary air change rate to remove moisture can be calculated. This difference is also positive when indoor and outdoor temperature, and therefore surface wall temperature, are the same, because relative outdoor humidity is almost always below 100%.

For German weather conditions and ventilation rates for German dwellings, which this paper is aimed at, there is no need for air conditioning.

Paper 13:

'An overview of the R-2000 home program design and installation guidelines for ventilation systems', presented by M Riley (Canada)

D Harrje
(USA)

(1) First, congratulations on a very successful program, I only wish the US had a comparable program. Currently - 10 Pascal is the diagnostic approach used to achieve winter radon levels year round. Since the R-2000 homes cover a wide range of Canadian locations what problems do you anticipate?

(2) What are your reservations with regard to ASHRAE 62-81R since your designs have made excellent use of the ASHRAE 62-1981 ventilation standard?

M Riley
(Canada)

(1) To date we have not seen any problems related to this specification but we are continuing to monitor levels to determine whether levels become elevated. For leakier

conventional homes it is anticipated that the allowable pressure differences will be only 5 PA for continuous operation when the national standard is issued.

2) My major reservation is that the target audience we are dealing with needs an extremely simple procedure that addresses both overall requirements and distribution with the same calculation and a procedure that can be easily verified by inspectors. A volume or per occupant calculation introduces greater problems with interpretation or calculations of the ventilation rate and the distribution of air. The per room calculation addresses both the requirement and distribution in a simple way.

J Littler
(UK)

(1) Did you consider ventilation controlled by a broad band detector (e.g. doped solid state) responding to H_2O, CO, smoke etc?

This avoids the need for occupant action, particularly action in turning boost mode back to background mode.

(2) I was impressed by the speed with which Canada managed to introduce a new standard.

M Riley
(Canada)

(1) High speed operation is now controlled automatically when humidity levels exceed a preset level. Other detection devices could also be used. In addition, some systems use timers that are set by the occupant, which return to background ventilation rates automatically.

(2) This was made possible because the initial work was carried out under a "voluntary" demonstration programme to verify the approach and gain a degree of acceptance before the standard is considered for widespread application. This was an effective approach to avoiding negative reaction to the introduction of new requirements.

E Perera
(UK)

(1) Whereabouts do you take the supply air for a balanced mechanical ventilation system? Do you ensure that exhaust air does not come anywhere near the intake location?

(2) Can you describe (or reference) the flow measuring devices you permanently fix to the ducts?

(3) You say that formaldehyde levels in Quebec houses for 1987 are lower than the other three regions you considered. Is this difference statistically valid?

M Riley
(Canada)

(1) These issues are covered in the standard. A minimum spacing between the supply air inlet and exhaust air outlet is stated (≃2 meters). The airflow is measured near the outside wall to ensure we are measuring only fresh air.

(2) I will reference a report on the sensor testing and send you a copy.

(3) The drop between years is "statistically valid" but we have not done tests for differences between regions. This information will be the subject of a separate report. I will again send this report for review.

H Phaff
(Netherlands)

Is recirculation from bedroom to living room allowed, as 5 L/s for a two person bedroom will be low?

M Riley
(Canada)

The requirements are being revised to require 10 L/s from master bedrooms. In addition, most houses have a recirculation system that ensures good mixing of air throughout the building.

W Raatschen
(FRG)

(A) Very wise precaution. You said that peaks in room contamination are handled by the occupants. This may be for smoke, is that also true for moisture because we know that persons are not sensitive to moisture?

(B) (Remark to answer A). This is very good and I fully agree that this is the best way to handle this problem. My next question is what kind of humidity sensor do you use?

(C) How cheap is your device to measure the air velocity or air flow rate?

M Riley
(Canada)

(A) Moisture is handled automatically by use of a (de)humidistat set to activate when humidity levels exceed a preset level.

(B) A (de)humidistat wired to the ventilation activates the high speed mode when humidity exceeds a preset level.

(C) The airflow sensors cost approximately $25. This is expected to be reduced with mass production to under $20.

Paper 14: 'Design, construction and performance of a dynamic wall house', presented by J Timusk (Canada)

M Holmes
(UK)

Your wall would appear to be a filter. Do you see any problems in respect to particles etc being drawn into and retained by the wall?

J Timusk
(Canada)

We do not know. The openings in the membrane could become filled with airborne particles. (This we plan to monitor over a long period of time in the field.) Within the insulation we have no concerns in that we have improved on the performance of normal glass fibre insulated walls with which we have some 50 years of experience.

If air is to be exhausted through the wall, filters must be installed before air is taken into the wall.

H Phaff (Netherlands)

(1) Did you try to connect all cavities (between wind/rain barrier and installation) to guard all wind pressure at zero?

(2) Could such a guard ring with an extra foil over the ground stop all of the radon infiltration?

(3) By using a fan to extract the "heated" air between the insulation and the inner wallboard, can the short circuit effect of all window leaks (and open windows) be minimised?

(4) How far can energy consumption drop by using an optimal dynamic wall, and using a heat pump to extract heat from exhaust air into the low temperature wall heating?

J Timusk (Canada)

(1) No. There is no continuous cavity.

(2) Do not know. Would like to install a system which is not workmanship sensitive or if tied to the ventilation system, it is coupled to a necessity like domestic hot water production. Experience has shown that occupants do not always maintain mechanical ventilation equipment.

(3) Yes - would the building cost be justifiable?

(4) The wall recovery would depend on the design - how much air is dynamic, how much is through ordinary cracks, how far above the optimum point we are, or how much solar energy we collect. With heat pump heat recovery we could justify ventilation rates above those needed for air quality. Also, shoulder months (spring or fall) and summer operations represent new problems as well as opportunities.

Paper S.1: 'Ventilation technology - aims of the Federal Ministry for Research and Technology in Research and Applications'- Keynote speech, presented by H Hlawiczka (FRG).

P Charlesworth (UK)

The projected 1990 energy saving was achieved in 1982. Has the energy consumption improved since then?

H Hlawiczka (FRG)

Yes. But more attention is now given to internal environment quality.

Paper S.2: 'Evaluation through field measurements of BNL/AIMS, a multiple tracer gas technique for determining air infiltration rates', presented by N Bergsoe (Denmark)

P Charlesworth (UK)

(1) What was the average period for PFT?

(2) Was temperature monitored?

N Bergsoe
(Denmark)

(1) Approximately 1 week.

(2) Yes, and found to be constant.

M Liddament
(UK)

From a practical side these measurements were made in Denmark and the results analysed in the United States.

How long did analysis take?

How expensive was it?

N Bergsoe
(Denmark)

Analysis of CATS were made by Brookhaven National Laboratory, in the United States. The waiting-time for the results was approximately 3 months.

The recent price we have been informed is $35 per CATS analysis, but newer and more detailed information can be obtained from Russell N. Dietz at BNL.

E Perera
(UK)

(1) Could you please describe the 'passive sampler' in slightly more detail - e.g. adsorbent used, polymer through which permeant diffuses?

(2) What multiple PFT's did you use?

N Bergsoe
(Denmark)

The 'passive samplers' and the PFT's used are developed and described by Russell N. Dietz and manufactured at BNL (see ref. 1).

Adsorbent in the CATS is Ambersorb, type 347.

The PFT's are fully fluorinated organic compounds of the perfluoroalkylcycloalkane family.

PDCH is Perfluorodimethylcyclohexane
PMCH is perfluoromethylcyclohexane
PMCP is perfluoromethylcyclopentane
PDCB is perfluorodimethylcyclobutane

C A Roulet
(Switzerland)

(PFT-methods, average concentration, passive sampling) PFT really measures the average concentration (or effective ACH [Sherman]), and constant concentration tracer really measures the airflow rate.

Do these differences in results explain the poor agreement observed between these methods, when used in inhabited dwellings, where the airflow rates are not constant?

N Bergsoe
(Denmark)

Yes. The PFT-method has a definite negative bias, and as seen from Figure 2 significant fluctuations in the air infiltration rate did occur, during the measuring period.

JL Scartezzini
(Swi & USA)

Do you use a fan during your experiments with PFT?

N Bergsoe
(Denmark)

Yes, the goal was to test the effect of using one method (PFT) or classical method (constant concentration).

The results are in this way better than in the reality where no fan exists.

Paper S.3:

'Simplified technique for measuring infiltration and ventilation rates in large and complex buildings: protocol and measurements', presented by E Perera (UK)

J Axley
(USA)

To underscore the comments of the speaker, the proposed method depends critically on the degree of communication between zones. As noted, a dead zone poorly coupled to the rest of the system may introduce a dominant response not well correlated to infiltration. One can find examples of well-ventilated subsystem of building systems that are not well coupled to the rest of the building system (e.g. the Columbia Plaza building studied by Persily at NBS). For these cases the proposed simplified method should be expected to fail.

Two additional problems exist in principle if not in fact. One may find systems having imaginary components associated with their time constants that result in oscillatory decay response (see for example data reported at this conference by J R Waters). That may tend to introduce additional error. It is also possible to conceive of so-called degenerate systems whose decay response cannot be expressed as a sum of simple exponential terms.

E Perera
(UK)

(a) Comment is fair - method would fail if applied to whole building. However, one can still get useful results by reducing the building into large subsystems and dealing with these in isolation.

(b) Agree - we have, however, not found these problems in real-life measurements.

P Collet
(Denmark)

I think that the difference in slope in those three room models are due to the internal infiltration from the highest source.

E Perera
(UK)

We do not have a simple two-cell building as used for your illustration - there are many cells. It is this feature which gives the opportunity for the technique to work; i.e. a range of plausible conditions as explored in Ref. 4 of our paper.

D T Harrje

Having long been an advocate of simplified container sampling and having observed the ability of tracer gas to reach equilibrium on a single floor I must question exactly what a measurement means five hours later. Must you assume long-term weather stability? What exchange rate is assigned to what weather conditions?

E Perera
(UK)

If the tracer distribution has reached an approximate state of equilibrium, then you use the weather conditions prevailing at the time that you take samples. If the weather conditions are indeed changing significantly, then the results can be considered to be suspect. The same criteria that we use in regular decay experiments apply.

J R Waters
(UK)

(1) Degenerate solutions will usually occur when one (or more) zone(s) receives air from the outside, feeds air to one or more other zones, but does not receive air from any other zone. The zone on the windward side of a building may cause this.

(2) If the tracer is distributed approximately uniformly, "steady-state" decay will be established rapidly, probably in a fraction of a time constant.

E Perera
(UK)

(1) Comments similar to those for Axley (part 'b') apply. We have, however, covered a situation (Ref 5 in paper) similar to the one you mention. There was no occurrence of any degenerate solutions.

(2) This is not so. The seeding strategy that will expedite dominant decay requires an initial distribution pattern similar to the ratios of the final steady state concentrations.

Paper S.4:

'Field study comparisons of constant concentration and PFT infiltration measurements', presented by D Bohac (USA)

J Axley
(USA)

(1) Errors in the use of the PFT method can be due to the combined effect of those errors introduced by flow variation and those "perturbed" by errors in the data set. Errors due to flow variations depend in principle on the magnitude and spectral content of the flow variation. Have you considered the spectral content of the flow variation?

(2) Solving the inverse problem transforms concentration data to flow results and also transforms uncertainty in concentration data to uncertainty in flow results. For the problems at hand there will be an amplification of data uncertainty that will be system dependent, that can be expected to be very large. Given a system and a measured data set one can, and should, not only compute and report the air flow solution but also the uncertainty in these flows. Perturbation analysis, formal or numerical (e.g. Monte Carlo methods), provides one means to achieve this end.

D Bohac
(USA)

(1) We have not investigated the spectral content of the flow variation; the constant concentration method, used as the standard against which the PFT method was compared, provides results averaged over approximately one hour and therefore do not provide sufficient detail for complete spectral analysis.

We have performed further studies which also indicate that the underprediction error is a function of the spectral content (i.e. period of the oscillation) and relative magnitude of the oscillation. In addition, the error is a function of the magnitude of the average infiltration rate (higher rates give larger errors). We have not examined the spectral content of our data. However, the simulations we performed with the CCTG data directly take into consideration the spectral content, relative magnitude of fluctuation, and the average infiltration rate.

We presently use a perturbation technique to compute the uncertainties in the flow rates. This technique has been shown by the researchers at BNL to be accurate in most situations (it was compared against Monte Carlo simulations of error). The results are conservative when two zones are well coupled. A paper by BNL explains the use of a condition number for the concentration matrix to indicate when the uncertainties may be larger than computed by our present method. We will soon be incorporating the calculation of the condition number into our PFT analysis.

P F Collet
(Denmark)

How do you cope with results from big samples, when you do not know if the specific house has a big airing frequency or not and how do you make a questionnaire without changing the behaviour of inhabitants?

D Bohac
(USA)

The results of our study show that there must be some documentation of the level of airing in order to achieve accurate infiltration measurements. For a large study it seems that the most efficient way to do this is to distribute surveys or questionnaires with the instructions for the test. In addition, research must be done to correlate the reported amount of airing in a house and the PFT underprediction error.

The occupant behaviour could be affected by both the PFT test and the airing survey. The instructions would have to stress that the occupants should not alter their normal routine during the test. It will be interesting to see how effective this will be.

E Perera
(UK)

(1) Emission rates of your passive sources is a function of ambient temperature and you, rightly, make a correction for it. But this presupposes that temperature equilibrium has been obtained. Even though you allow for

this in your calibration procedure (by allowing the emitters to equilibriate for 7-10 days in a water bath), you cannot do this during field measurements. How do you allow for this? Does this not explain the wide discrepancy in your comparison between the PFT technique and constant concentration measures in the 'over-aired' building?

(2) Could you describe how you prepare your reference 'CATS' and how you compare them with the performance of the 'CATS' that you use?

D Bohac (USA)

The temperature response of the emitters is somewhat complicated. We have not studied it in detail but Russell Dietz has indicated that about 50% of the equilibrium value is reached after a couple of days. Complete equilibrium is reached after 10 to 14 days. We believe that this long time constant will smooth out short term (i.e. the brief temperature drop that occurs during night setback) variations in the temperature so that the source rate will be fairly constant. Long term variations in the temperature that may occur from the start to the end of the test period will be more of a problem.

Our reference CATS are made from our calibration gas cylinder. Gas from the cylinder flows through the CATS which adsorbs the PFT gases. The computer controls the exposure time of the CATS and a gas flow meter (accuracy of 1%) is used to measure the flow. We have found that flow rates below approximately 45 cc/min must be used or there will be some breakthrough of the PFT gases (i.e. the entire amount of PFT gases will not be adsorbed). However, we have increased the amount of ambersorb in the reference CATS so that higher flow rates can be used without breakthrough.

H Phaff (Netherlands)

PFT does not say so much about ACH. This was calculated before and we can see it in your measurements.

I think here, there are two kinds of goals for ventilation measurements:

1. Ventilation energy loss
   flow rates, ACH

2. Indoor air quality
   pollutant doses, concentrations, daily intake (human).

- PFT will be an ideal method for determining the indoor quality capability of different buildings and systems. Emphasis must be on the normalisation of source strengths, a standard procedure and personal sampling.

- PFT must not be used (in the first place) to produce energy loss, ACH figures.

D Bohac (USA)	We agree that PFTs are useful for indoor air quality studies. The results from our tests in the radon houses have allowed us to measure the radon entry source rate over an entire year for seven houses. We disagree that PFT measurements cannot be used to measure infiltration rates. They provide a simple method of measuring infiltration in multiple house studies. The underprediction error due to weather changes and occupant effects is an important problem. However, with further studies we believe that it will be possible to properly account for this underprediction effect.
Paper S.6:	'Simulation of CO_2, concentration for determining the air change rate', presented by T Baumgartner (Switzerland)
P Charlesworth (UK)	Have you tested, or do you intend to test this model in other buildings?
T Baumgartner (Switzerland)	If the new IEA-school annex is selected and Switzerland joins the annex, we intend to do more measurements in schools without mechanical ventilation systems.
H Phaff (Netherlands)	Calculating the ventilation from the CO_2 level one should take into account the size (Dubois area) of the persons. Data about this exists. Doing this the error in the ventilation can be less than ± 10%.
T Baumgartner (Switzerland)	Yes, this comment is correct, if you don't know the absolute value of the CO_2 production in the room.
C A Roulet (Switzerland)	Is it possible to use your model to measure the air change rate from occupancy level and CO_2 concentration indoors and outdoors?
T Baumgartner (Switzerland)	Yes, when there are no plants in the room and you know the outside CO_2 concentration level.
Paper S.7:	'Estimating air infiltration in multi-storey buildings using wind tunnel tests', presented by P Grabau (Canada)
J Axley (USA)	The study is based on a power law relation for infiltration - an elevation that reasonably represents the steady state case. You conclude that the influence of turbulence can be significant especially under pressure control. As one may expect, the turbulence driven flow is an unsteady phenomenon; then would you believe that your study exaggerates the importance of turbulence?
P Grabau (Canada)	I don't think that this study exaggerates the importance of turbulence. Full scale studies and wind tunnel studies on porous models could help to verify the mathematical models.

P F Collet
(Denmark)

You showed the difference between the more and less complicated models. How do you verify the difference to show that the more complicated models are more accurate in practice and therefore are worth the extra effort?

P Grabau
(Canada)

The simple approach appears to be quite adequate under most situations. The exceptions arise under special internal pressure control when infiltration due to turbulence may become significant.

GV Fracastoro
(Italy)

You said that the overall air infiltration rate is affected both by the building shape and by the surrounding terrain, through changes in wind direction. Have you tried to split the two effects?

Which one of the two is prevailing?

P Grabau
(Canada)

Although we have not tried to split up the two effects in detail, overall the surrounding terrain (exposure) is the predominant.

M Holmes
(UK)

Wind tunnel tests are used to obtain data on the response of structures to pressure fluctations. Do you think it possible to combine the power spectrum associated with measured pressure coefficients and a building transfer function to obtain realistic ventilation rates under non-steady conditions?

P Grabau
(Canada)

The turbulence effects are generally small and the additional infiltration due to turbulence can, it seems, be estimated quite well with the simple statistics rather than the spectrum.

E Perera
(UK)

Could you please explain why Figure 4 shows a sizable infiltration caused solely by turbulence even though Figure 3 shows no difference between rates obtained with and without the addition of fluctuation pressures to the mean pressures?

P Grabau
(Canada)

Figure 4 reflects a hypothetical situation in which the internal pressure of each point is held steady at the mean pressure for that point. The infiltration is then due exclusively to the fluctuating components. The model complies also that the internal ventilation system adjusts itself to the resulting internal flows.

H Phaff
(Netherlands)

Did you take into account the dynamics of the internal pressure fluctuations (in the rooms) due to the fluctuating wind pressures?

If you did; do you have information on how simultaneously the pressures on the different pressure taps go up and down (phase and frequency of the fluctuations)?

P Grabau

No, the internal pressure was taken to be uniform. The

(Canada)

buildings are very big, and since the same internal pressure is used for the entire building (not in model 3 though), it is not likely that the internal pressure fluctuations will be big compared to the external pressure fluctuations. No, we don't have any information, since the only values we have used so far are the RMS, mean, and peak pressures.

JL Scartezzini
(Swi & USA)

Stack effect for such a huge building is often dominating wind effect. Do you account in your wind tunnel experiment for the stratification of air temperature (by use of a stratified temperature wind tunnel experiment)?

P Grabau
(Canada)

No. The wind tunnel experiments were carried out in a neutrally stable flow (representing stronger winds). Stack effect can be included in the calculations where necessary.

Paper S.8:

'The moisture load in dwellings as a function of the layout of the rooms shown by ground plans', presented by K Hain (FRG)

H E Feustel
(Switzerland)

In buildings with different types of mechanical ventilation systems (here one balanced, and one exhaust system) there is the danger of a strong interaction between the ventilation systems. If your exhaust system is powerful enough to suck air through closed windows from the leeward side of the building, it will be obviously strong enough to overcome the floor resistances of the two internal doors between the two considered flats (see Feustel/Lin2 HLH 4/87).

K Hain
(FRG)

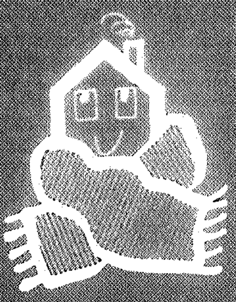
In one apartment there is a balanced ventilation system and therefore there is no influence on the internal door of this flat. The volumetric flow of exhaust and supply air here are coincident. We know that this is not always in balanced ventilation systems, but this was a r+e-project. In the other flat there is an exhaust ventilation system. There is not air coming through the closed windows only, but also through the internal door of the flat as shown in the pictures 1-4. But this stream is overlooked in the pictures 9-11. But the staircase with the front door has a much lower flow resistance as the other internal door of the flat with balanced ventilation. Therefore there is no interaction between ventilation systems.

W Raatschen
(FRG)

In figure 11 you showed an exhaust system, where the ventilator is so powerful that even at high wind speeds the air is infiltrating from all sides. If this is the design point for your ventilating system you will have much too high air flow rates at calmer weather conditions. Do you think that this is an energy efficient way to ventilate a residential building?

H Trümper
(FRG)

No.



INTERNATIONAL ENERGY AGENCY
energy conservation in buildings and
community systems programme

8th AIVC Conference

Ventilation Technology Research and Application

Supplement to Proceedings

Air Infiltration and
Ventilation Centre
Old Bracknell Lane West, Bracknell,
Berkshire RG12 4AH, Great Britain.

This report is part of the work of the IEA Energy Conservation in Buildings & Community Systems Programme.

Annex V Air Infiltration and Ventilation Centre

Document AIC-PROC-8-S-87
ISBN 0 946075 34 4

Participants in this task:

Belgium, Canada, Denmark, Federal Republic of Germany, Finland, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and United States of America.

Distribution: Unrestricted

Additional copies of this report may be obtained from:

The Air Infiltration and Ventilation Centre,
Old Bracknell Lane West,
Bracknell, Berkshire
RG12 4AH, Great Britain.

THE AIR INFILTRATION AND VENTILATION CENTRE was inaugurated through the International Energy Agency and is funded by the following twelve countries:

Belgium, Canada, Denmark, Federal Republic of Germany, Finland, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and United States of America.

The Air Infiltration and Ventilation Centre provides technical support to those engaged in the study and prediction of air leakage and the consequential losses of energy in buildings. The aim is to promote the understanding of the complex air infiltration processes and to advance the effective application of energy saving measures in both the design of new buildings and the improvement of existing building stock.

Air Infiltration and Ventilation Centre

Old Bracknell Lane West,
Bracknell, Berkshire,
Great Britain,
RG12 4AH.

Tel : National 0344 53123
International + 44 344 53123
Telex: 848288 (BSRIAC G)

ISBN 0 946075 34 4

Operating Agent for International Energy Agency, Oscar Faber Consulting Engineers, Upper Marlborough Road, St. Albans, Herts, Great Britain.

Printed by Information Printing Ltd., Oxford, England