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2nd AIC Conference

Building Design for Minimum Air Infiltration

Proceedings



Air Infiltration Centre

Old Bracknell Lane West, Bracknell, Berkshire, Great Britain, RG12 4AH



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Annex V Air Infiltration Centre

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2nd AIC Conference

Building Design for Minimum Air Infiltration

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Proceedings

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PREFACE

International Energy Agency

In order to strengthen cooperation in the vital area of energy policy, an Agreement on an International Energy Program 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 Program, 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 (CRD), assisted by a small Secretariat staff, coordinates the energy research, development, and demonstration programme.

Energy Conservation in Buildings and Community Systems

The International Energy Agency sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, etc. The difference and similarities among these comparisons have told us much about the state of the art in building analysis and have led to further IEA sponsored research.

Annex V Air Infiltration Centre

The IEA Executive Committee (Buildings 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 to 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 ground-work the experts group recommended to their executive the formation of an Air Infiltration 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 a firm basis for future research in the Participating Countries.

The Participants in this task are Canada, Denmark, Italy, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the United States.

PAPER 1

THE ROLE OF THE AIR INFILTRATION CENTRE

P.J. JACKMAN Air Infiltration Centre UK

1. INTRODUCTION

Significant energy wastage can result from the uncontrolled leakage of air into buildings. The inability to reliably predict the energy losses attributable to air infiltration led to the establishment of the Air Infiltration Centre (AIC) which provides technical support to those engaged in research in this specialised subject and to those seeking to apply the results of such research in building design and construction.

The trend towards better standards of thermal insulation in buildings has resulted in a significant proportional increase in the effect of air infiltration on energy usage. This in turn has led to an increasing programme of research and a growing urgency for the development of accurate methods of prediction. In this context, AIC is playing a vital role in providing a central source of relevant up-todate information and high-quality technical expertise with the aim of accelerating the effective application of energy saving measures in buildings.

2. BACKGROUND

In the wake of the 1973/4 energy crisis, the International Energy Agency (IEA) was established as an autonomous body within the Organisation for Economic Co-operation and Development (OECD). Its aims include the promotion of co-operation among IEA participating countries to reduce excessive dependence on oil through energy conservation, development of alternative energy sources and energy research and development. One of the early collaborative research projects related to buildings concerned the evaluation of analytical models, which had been developed for predicting energy consumption. It was soon apparent that one of the major causes of uncertainty in the models was the estimation of the energy losses attributable to air infiltration. To combat this problem, the Air Infiltration Centre was set up in 1979 to assist the international research community in its endeavour to improve the understanding of the complex air infiltration processes and so enable the prediction of the associated energy losses to a degree of confidence at least comparable with that for other building energy transmission.

3. ORGANISATION

The AIC is funded by eight of the member countries of the IEA; Canada, Denmark, Italy, Netherlands, Sweden, Switzerland, United Kingdom and United States of America. The services offered by the Centre are available only to the funding nations. Other countries have shown interest and it is hoped that some will become participants in the near future.

A Steering Group, comprising one representative from each of the participating countries, monitors and directs the work of the AIC with the Oscar Faber Partnership in the UK appointed as the Operating Agent.

The Centre is run as an autonomous unit by the Building Services Research and Information Association at their offices in Bracknell, UK. The full-time staff include two qualified scientists, a librarian and a secretarial assistant.

4. DESIGN DATA

The main emphasis of the work of AIC is in relation to the prediction of air infiltration in buildings. For the design of new buildings, reliable assessments of the potential rates of air infiltration are required for the proper analysis of the seasonal and peak energy consumption and hence, of the economic solutions for the provision of heating or air conditioning. For existing buildings, the requirement is particularly related to the economic comparison of alternative measures for reducing energy consumption. Without a proven method of predicting air infiltration rates, neither the physical implications nor the cost-effectiveness of the options can be evaluated correctly.

To meet these needs, AIC has been considering various important design aspects as detailed below. So far this work has been concerned mainly with dwellings but future studies will encompass commercial and industrial buildings as well.

4.1 Reliable Datasets

The basis of acceptable design techniques should be methods of prediction which have been verified by comparison with experimentally derived results. Many, if not all, of the available predictive models for air infiltration have a very limited basis of validation and so one of the major activities of AIC is to collect a number of comprehensive sets of numerical data derived from practical studies in real buildings of various types, and to make these available for comparison with the model calculations.

Each dataset consists of a detailed description of the building in question including the characteristics of the known air flow paths, information on the climatic conditions prevailing during the testing and, where possible, the pressures on the building surfaces. Results of leakage testing by pressurisation are also included. Some or all of this information may be used as input data depending on the requirements of the particular model under consideration. For example, some models are based on standard surface pressure coefficients and so the actual pressure data need not be used. Others may require little more than the pressurisation test results.

The datasets also include the results of the measurement of air infiltration by tracer gas methods so that the infiltration rates predicted by the models can be compared with the actual measured values.

To date, fourteen sets of data relating to houses and apartments have been evaluated and prepared in a standard format. These datasets have been circulated to model owners so that they can conduct their own validation trials. The particular value of this exercise lies in the wide range of experimental data which has been drawn from several countries and which relates to dwellings of various types and locations. This will provide a broad basis for validation and will enable the models so verified to be used with confidence over an extended field of application.

4.2 Design Calculations

Having validated models for predicting air infiltration rates, the next logical step is to develop them for use in design offices to complement other procedures for the estimation of building performance and energy consumption.

AIC will actively encourage this development and the effective integration of the air infiltration calculation procedures into design routines so that proper account can be taken of the energy implications of alternative building types and structural features.

It will also be possible to assess more reliably the costeffectiveness of alternative measures for reducing energy consumption in existing buildings. For such evaluations, data acquiried from the building in its existing state by measurement or observation can be used to advantage.

4.3 Structural Design

Another design aspect with which the AIC is involved, concerns the structural designs which are appropriate for the control of air infiltration in buildings. Until recently, very little attention has been paid to the leakage of air through the building envelope, other than that through doors and windows. Now, new structural designs and techniques for both new and existing buildings are being developed with a view to reducing the extraneous air leakage to an acceptable minimum.

In this context, the Swedish participant has accepted the leading role in the preparation of a handbook to be titled "Air Infiltration Control in Housing - A Guide to International Practice" which will provide detailed guidance on minimum acceptable rates of ventilation and on materials and methods of construction for achieving the required low levels of air leakage. This Conference has been called to provide a forum for discussing the general content of the handbook. The presentations and discussions here will help to ensure that the information produced will be directly appropriate to the needs of energy-conscious engineers and designers.

5. TECHNICAL INFORMATION

AIC provides a high-quality technical information service in the field of air infiltration in buildings and closely associated subjects.

Qualified staff respond to specific enquiries from participating countries and give technical advice based on their own expertise supported by close contact with sources of up-to-date information world-wide.

In its short history, AIC has gathered a comprehensive stock of relevant international literature which is available for reference or loan by enquirers. AIC also has compiled a versatile database, *AIRBASE*, which contains full bibliographic details of pertinent published papers, together with concise, informative abstracts in English. The main content relates to the prediction, measurement and reduction of air infiltration and leakage rates in buildings but *AIRBASE* also includes abstracts of papers on indoor pollutants and air quality, natural and mechanical ventilation, the character of wind and its influence on buildings, wind-tunnel studies and energy-saving measures such as the use of air-to-air heat exchangers.

The number of entries in *AIRBASE* is approaching 1000 and these can be rapidly searched by a free-text retrieval system to find papers on specific subjects, restricted if required by language or date of publication. On request, AIC additionally provides photocopies of papers of particular interest, subject to the usual copyright limitations.

A subject analysis of the content of *AIRBASE* incorporated by November 1980 has been published¹. In addition to a tabular classification by subject, the publication includes a listing of title, author and source of all the entries in numerical order. Since that time, a bi-monthly bulletin "Recent Additions to *AIRBASE*" has been distributed to interested organisations in participating countries. This bulletin keeps the recipients fully aware of the scope of the material being added to the database from sources throughout the world. This is of particular value in view of the rapid growth in the number of publications on air infiltration in recent years.

Enquiries for published information are efficiently handled by the AIC Librarian but facilities have also been provided to allow countries outside the UK to gain direct access to AIRBASE via the normal telephone network and suitable terminal equipment.

As an additional service to research and industry, AIC publishes bibliographies and digests of available information on specific topics. This provides, in a single document, a broad analysis of the scope and value of the available material together with a list of references for the reader who wishes to study the subject in greater depth. Examples of such review documents are References^{2,3}. To keep participants informed of the AIC publications and of international developments in the field of air infiltration, AIC publishes a quarterly newsletter "Air Infiltration Review" which is widely circulated.

The effective international communication of technical information depends on the correct understanding of the terms used. To facilitate this, AIC is producing a multilingual glossary of those terms which relate to air infiltration. Approximately 750 words and their definitions are being incorporated. These include scientific terms relating to the air infiltration process as well as descriptive terms for building materials and components which may be encountered by those concerned with controlling air leakage.

6. COLLABORATION

One of the underlying reasons for the establishment of AIC was the recognition that much of the relevant research was sporadic and unco-ordinated so its potential value was not being fully realised. Although the role of the AIC cannot extend to authoritarian control of international research, it is encouraging collaboration and technical interchange, not only between research experts but also between the research community and those concerned with the application of the results of research in the design and operation of energy-frugal buildings. This Conference is an example of the latter. A previous conference drew researchers together to discuss modern developments in instrumentation and measurement techniques⁴ and other conferences on topical subjects are planned for the future.

An important pre-requisite for collaboration is the awareness of the scope of the research being undertaken by others. To provide this, AIC conducts an extensive annual survey of current research and publishes an analytical summary of the results together with a synopsis of the many project details. As a result of the first survey conducted in 1980, details of 65 projects from 14 countries were collated and analysed. In the report⁵ the scope of these projects is summarised in terms of specific objectives, type of investigation and parameters with which air infiltration is related. A more detailed tabular classification by subject, building type, measurement techniques and parameters considered is also included. This can be used as an index to the project descriptions which are reproduced in full.

Information presented in this way not only promotes a general awareness of the scope of on-going research, it also encourages co-operation between personnel involved in research on similar subjects and highlights to engineers and designers with specific problems the potential sources of research data in advance of its formal publication.

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PAPER 2

INTRODUCTION TO THE AIR INFILTRATION HANDBOOK

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AIR INFILTRATION CONTROL IN HOUSING -A GUIDE TO INTERNATIONAL PRACTICE

A1 BACKGROUND AND INTRODUCTION

Energy for heating and ventilating buildings comprises a significant proportion of the total energy consumption in different countries. Traditionally, a building's energy status has been characterised primarily by the U-values - the coefficient of thermal conductance of different sections of the building. For this reason, there is a considerable amount of knowledge and detailed regulations in different countries as to how U-values are to be calculated and which maximum permissible values are accepted for the different structural components in a building. Energy consumption resulting from transmission through the building envelope is therefore relatively well-defined by the structural component's U-value and the indoor/outdoor temperature difference.

In contrast to energy consumption far more limited knowledge is available on the subjects of ventilation and airtightness. Standards and regulations are lacking to a great extent. In the research work that has been carried out over recent years, efforts have been made to consider air leakage and ventilation in more detail. To save energy, this has led, in many respects, to the development of completely new construction technology. The aim of this construction technology is to make the building envelope so airtight that undesirable air leakage can be minimized and to do so in a safe manner. In the same context, calculation methods have been developed which explain the mechanisms which govern the air leakage in a house. The driving forces for air leakage and ventilation are air pressure differences. These are made up of components from temperature, wind effects and fan effects when mechanical ventilation is used. In addition, the leakage characteristic for the building envelope is difficult to quantify. This means that sufficient accurate calculation of energy losses resulting from air leakage and ventilation is relatively complicated. Attention must be paid to attaining an acceptable air quality in dwellings by ensuring that a certain minimum ventilation is maintained independent of the effects of the outdoor climate. This can be achieved with mechanical ventilation or sometimes with controlled natural ventilation. Therefore it is becoming more and more important to consider the interaction between building technology and ventilation technology.

Several new measurement methods have been developed to check the airtightness of a building envelope. Some of these methods can be applied to determining air leakage and ventilation during different climatic conditions. Certain of the methods are suitable for production control - others for research purposes.

It has been considered a matter of urgency to consolidate available research results and other experience in the form of a handbook. This handbook, which forms part of the work of the AIC (Air Infiltration Centre) reviews the state of the art with respect to problems associated with a building's airtightness in the countries which take part in the work within the AIC. General principles, motives, standards, assumptions, climate, energy balance in a house, common recurring design solutions for both existing and new buildings etc are treated in the handbook's general section, Part A.

Part B of the handbook contains detailed information about the climate in different countries. Part B has a main section for each country. In each respective section there are several design examples showing how building structures can be produced to achieve a reasonable grade of airtightness. In general, these show examples of good design technology in the respective country.

By tradition, building technology differs from country to country and thus the design and grade of airtightness are also different. In some cases, new building technology is necessary to minimise air leakage. Using other solutions, better airtightness can be achieved with relatively simple measures. Several examples are shown whereby improvements are possible using such simple methods.

In most design, the design technology will be affected by new and more stringent requirements for building low-energy, ie well insulated and airtight, houses. The handbook also shows how thermal insulation demands are satisfied while retaining the goal of building problem-free houses with energy demands as low as possible.

NOTE: This handbook will be published in 1982

PAPER 3

INDOOR AIR QUALITY AND MINIMUM VENTILATION

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INTRODUCTION

Energy conservation efforts of past years have directed the attention towards <u>heat losses due to ventilation</u>. In this connection studies on indoor air quality became more important. Improved insulation of cracks and slits of doors and windows as well as the reduced operation of eventually available forced ventilation systems have led to reduced air exchanges and hence to the considerable <u>reduction</u> in supply of fresh air. From the hygienic point of view the questions are raised as to what are the effects of such measures on indoor environment and what are the minimum ventilation rates necessary in order to fulfil the hygienic requirements of indoor air quality.

The first part of this paper deals with an overview on important sources of indoor air pollutants. The second part discusses the ways and means of measuring the contaminants emitted by the very presence of man in a room (carbon dioxide and odors). Based on our own investigations we have made some recommendations on minimum ventilation rates or minimum supply of fresh air.

MAN AS A SOURCE OF AIR POLLUTION

Pollution of indoor air where the sources themselves are indoors depends on the furnishing of the room and the activities therein. Here one should concentrate on decomposition of building materials and their longterm effect due to daily exposure (WANNER, 1980). The effect on indoor air quality by man himself is not only due to his actions like smoking and cooking. Depending upon his activities the air quality will be affected by the temperature, the relative humidity, carbon dioxide concentrations, viable and nonviable particles emitted by the skin as well as perspiration - depending upon what he does in that room (BRUNNER, 1977). The number of persons in a given room or the space per person, and the supply of fresh air determine the effects of these parameters.

The subjective assessment of indoor air pollution caused by man can best be made by <u>odors</u> and objective assessment simply by <u>carbon dioxide</u>. Concentration of carbon dioxide in ambient air lies between 0.03 and 0.04 % which can reach up to double of this value in cities and in industrial areas. In European countries we have a recommended level of maximum 0.1 % CO_2 in indoor air of living places (so-called Pettenkofer-Number), and in some cases even 0.15 % CO_2 (BORNEFF 1974, RIGOS 1981). In the USA the MAC value of 0.5 % for workplaces is applied for the indoor air in living places as well (ASHRAE, 1980). Reduction of this limit to 0.25 % is under discussion. METHODS OF MEASURING CARBON DIOXIDE AND ODOR

Primary aim of this investigation was to study <u>carbon</u> <u>dioxide</u> and <u>odor</u> pollution caused by man. Carbon dioxide was measured by <u>physical</u> infrared method of gas analysis. Odor was measured by <u>sensory</u> method whereby selected test panel evaluated the instantaneous odor situation in our odor intensity measuring apparatus called GIMA (HUBER 1981 a). Here the perceived odor intensity of the air sampled from a test-chamber is compared with the odor intensity of reference substance pyridine at a known concentration. So-called annoyance level indicated the threshold limit of a substance above which its odor is perceived as a disturbing one.

TESTS AT STANDARD CONDITIONS

Twentyone runs were made	in a test-chamber of 30 m ³
volume (little more than	1000 cubic feet) by changing
the following variables:	
- Number of persons:	1, 2, or 4 (in other words,
	space volume per person: 30,
	15, or 7,5 m^3 , or about 1000,
	500, and 250 cft)
- Activity of persons:	Rest (50-70 W),
	Bicycle ergometer (250 W)
- Air exchange rate:	0.1, 0.2, 0.8, or 1.6 per hour

Each run took two hours and bicycle ergometer was used for 45 minutes. Odor intensity of the indoor air was evaluated at every 15 minutes. Temperature, relative humidity, and carbon dioxide concentrations were monitored continuously.

RESULTS AND CONCLUSIONS

Figure 1 shows carbon dioxide concentrations as a function of time and perceived odor intensity. Correlations between carbon dioxide concentrations and odor intensities for all the twentyone runs are shown in Figure 2 (HUBER 1981 b).

From the results of this study it can be concluded that in the rooms where no smoking is allowed, with space volume of about $12 - 15 \text{ m}^3/\text{person}$, at a carbon dioxide concentration of more than 0.15% an increase of annoyance due to odor can be expected. This limit of 0.15% CO₂ can be maintained in the rooms by supplying the fresh air of usual CO₂ content of 0.03 - 0.04% at the rate of 15 m³/h/person-assuming that only light physical work is performed in the rooms. This relationship between CO_2 and perceived odor intensity is not valid for the rooms where smoking is permitted. In order to ensure satisfactory air quality in such rooms, one must reckon with fresh air supply of double the above quantity (WEBER, 1981).

ABSTRACT

In a test-chamber the carbon dioxide and the odor intensity were measured as function of room occupancy and ventilation rate. When the supply of fresh air was $12 - 15 \text{ m}^3$ per person per hour, the carbon dioxide concentration was less than 0.15 % and the odor intensity was evaluated only as "slight annoyance". Higher ventilation rates are necessary if increased physical activities and smoking is done in the rooms.

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Figure 1: Carbon dioxide concentration and odor intensity as a function of time. Odor intensity was evaluated at the interval of 15 minutes during first hour and 30 minutes during second hour. Test conditions: 4 persons sitting in a room of 30 m³ volume with air exchange rate of 0.8 (corresponding to the supply of fresh air at the rate of 6 m³ per person per hour).



Figure 2: Relation between carbon dioxide concentration (in percent) and perceived odor intensity (100 units are equivalent to a reference odor of 365 ppb pyridine). Investigation in a test-chamber with variable occupancy and ventilation rates.

PAPER 4

EFFECTS OF ENERGY CONSERVATION MEASURES IN EXISTING BUILDINGS

A. ELMROTH, J. FORSLUND, C. ROLÉN

Royal Institute of Technology Sweden

EFFECTS OF ENERGY CONSERVATION MEASURES IN EXISTING BUILDINGS

Approximately 40 % of the total energy consumption in Sweden is used for the heating and ventilation of houses and premises. In 1978 the Swedish Parliament passed an energy conservation plan for existing buildings. Aiming at a gross energy saving of between 39 to 48 TWh per annum until 1988. This corresponds to a reduction of the total energy consumption in today's houses by 25-30 %.

Several different investigations formed the basis for the Energy Conservation Plan and the evaluation of the same. Essentially, these were of two types - substantial theoretical calculations of potential energy saving from different measures carried out and the evaluation of energy saving effects studied in individual housing groups or in a small number of houses under scientific control, and very accurate condition, so called Pilot-project. (e.g. Ulvsundaprojektet, Höglund et al 1981)

However, nobody in Sweden has earlier investigated the actual effects of different technical energy-saving measures on the basis of energy consumption, in a large number of houses selected at random, where different measures have been carried out. This has now been done in a research project at the Division of Building Technology, the Royal Institute of Technology in cooperation with the other institutes of technology in Sweden.

The main purpose of this investigation has been to evaluate the actual effects of energy-saving measures by selecting a large number of houses at random where such measures have been carried out. The objects have been chosen statistically among houses receiving energy saving loans and grants in different provinces of Sweden. An on-site inspection has been performed of each house which was selected for the investigation. In total, 1144 buildings have been inspected comprising 944 single-family houses and 200 multi- family houses. When calculating the saving obtained, climate corrected energy consumption before and after measures undertaken has been com-

pared. The investigation was carried out in the following five counties: Norrbotten, Västerbotten, Stockholm, Göteborg-Bohus and Malmöhus. See fig. 1.

The measures and combination of measures studied in the investigation were selected because they had, to date, attracted most of the government support and/or were very common.

The following measures were studied in one or more counties:



Single family houses

Figure 1.

- additional insulation of external walls
- additional insulation of attics
- additional insulation of external walls and attics
- additional insulation of attics and the installations of radiator thermostatic valves
- installation of radiator thermostatic valves and motor shunt
- change to, or modification to, triple glazing windows
- additional insulation of external walls and change to, or modification to, triple glazing windows.

Multi-family houses

- additional insulation of external walls
- additional insulation of attic
- installation of radiator thermostatic valves
- installation of variator equipment

RESULTS

The following gives examples of some of the results. Importance is attached to comparing the theoretical savings with actual savings and showing the variations in actual savings in the modified houses.

Energy savings. External wall insulation

Results indicate that supplementary insulation fitted to external walls produced almost the intended theoretical savings in both single and multi-family houses.

TABLE 1. Modification: External wall insulation.

inergy	consumption	before	and	after	modifica	tion.	

Actual energy savings (A) and theoretical savings (T). Litres of oil per reference year and apartment for single family houses and per m^2 heated dwelling area for multi-family houses. (\bar{x} = average value, s = standard deviation)

ilouse type and county	No.of houses investigated	Heated dwelling area per apartment m ²	Modified area m ² /house for single family houses m ² /apartment for multi- family houses	Energy consumption litres oil/year, apartment, (single-family houses) litres oil/year, m ² (multi-family houses)				Energy saving litres oil/year, apartment (single-family houses) litres oil/year, m ² (multi-family houses)			
<u>Single family</u> houses				Before	Before retrofit After retrofit		A		Т		
				_ x	s	x	S	x	S	x	S
Norrbotten	25	128	124	3628	761	3300	526	327	566	456	236
Västerbotten	20	132	1 30	3871	842	3523	729	348	366	590	323
Stockholm ¹⁾	10	150	113	4234	1041	3839	964	396	479	414	2 30
Gbg and Bohus	41	143	125	35,38	1188	3054	1091	484	454	614	298
Malmöhus	34	139	97	4234	1303	3471	915	763	716	613	377
<u>Multi-family</u> houses											
Västerbotten	12	77	48	29.0	6.6	23.8	3.2	5.2	5.0	2.5	1.0
Gog and Bohus	18	55	- 28	25.7	7.3	23.2	5.1	2.5	4.5	2.9	1.9

The population of the group is too small for the results to be generally valid

Single-family houses

The actual energy savings varies for different houses within respective counties. Table 1. The reasons for the variations are many. Small or no savings can depend on no adjustments having been carried out on the heating system after modifications wherein the result may have been a higher indoor temperature after insulation. Actual savings greater than those expected were obtained in many houses which in turn may have resulted from the houses being made tighter after modification so that ventilation losses were less.

It is also possible that wall insulation has created conditions to allow a reduction in room temperature whilst still retaining the required comfort. The habits of occupants may have changed consciously or unconsciously as a result of information, cost changes etc.

Multi-family houses

The average actual savings are approximately equal, to or greater than, those calculated theoretically. Table 1. The greater savings than those expected might have occured when improvements other than those resulting from supplementary insulation have occured. Improved airtightness may be one example. Better maintenance of the heating system after retrofit cannot be discounted either. The variation in results in different houses is however considerable. The potential benefits of supplementary insulation have not always been realised since monitoring and adjustment of the heating system has not been carried out.

Energy savings. Attic insulation

Attic insulation in single-family houses resulted in the expected energy savings for the most part. In multi-family houses the actual energy savings were greater than the expected from installation of the actual insulation.

TABLE 2. Modification: Attic insulation.

Energy consumption before and after modification.

Actual energy savings (A) and theoretical savings (T).

Litres of oil per reference year and apartment for single family houses and per m^2 heated dwelling area for multi-family houses. (\bar{x} = average value, s = standard deviation)

House type and county	No.of houses investigated	Heated dwelling area per apartment m ²	Modified area m ² /house for single family houses m ² /apartment for multi- family houses	Energy consumption litres oil/year, apartment, (single-family houses) litres oil/year, m ² (multi-family houses)				Energy saving litres oil/year, apartmm (single-family houses) litres oil/year, m ² (multi-family houses)			rtment s))
<u>Single family</u> houses				Before x	retrofit S	After r x	etrofit s	ž.	s	T X	s
Sorrbotten ¹	13	164	93	4517	1182	4022	953	494	482	273	157
Västerbotten ¹	13	182	97	4454	1629	4115	1481	339	464	401	178
Stockholm	23	186	108	4576	788	4246	742	3,30	398	4 30	273
Gbg and Bohus	26	149	91	3491	1018	3100	890	391	524	372	364
Malmöhus	31	167	113	4463	2864	3897	2 380	566	728	769	542
<u>Multi-family</u> houses											
Stockholm	25	71	16	29.9	3.8	27.4	3.3	2.5	1.5	0.8	0.7

Single-family houses

The actual savings varied considerably between different houses which means that very good savings were measured in many whereas others indicated small or no savings. Table 2.

The savings achieved in individual single-family houses in the county of Stockholm are illustrated in figure 2.





Multi-family houses

The actual savings in multi-family houses were very good compared with the theoretical savings. Table 2.

In many houses with badly adjusted heating systems, the highest situaded apartments are designed in the basis of the radiator supply temperature. Apartments situated lower down in the building are thus supplied with too much heat. Attic insulation reduces heat demand in the highest apartments and this allows a temperature reduction thoughout the whole building. When assessing the effects of such a temperature reduction, the modifications are an added bonus since there was no possibility of measuring temperatures before and after insulation. Apart from a temperature reduction, better maintenance of the heating system can have contributed to a good savings result.

Energy savings. External wall and attic insulation

The combination of wall and attic insulation did not produce the theoretical energy savings.

TABLE 3. Modification: External wall and attic insulation.
Energy consumption before and after modification.
Actual energy savings (A) and theoretical savings (T).
Litres of oil per reference year and apartment.
$(\bar{x} = average value, s = standard deviation)$

llouse type and county	No. of houses investigated	Heated dwelling area per	Energy consumption litres oil/year, apartment				Energy saving litres oil/year, apartment				
Ciacle family		apartment m ²		Before x	retrofit s	After x	retrofit s	x	A s	T x	s
houses	·										
Norrbotten	19	1 39	201	4448	1242	3914	1063	535	571	662	289
Västerbotten	19	118	205	3707	1151	3379	1059	32.8	717	894	322
Stockholm ¹	12	148	184	4451	989	4054	841	397	670	736	360
Cbg and Bohus	24	152	174	3445	1148	3123	1011	322	525	740	305
Malmöhus	31	147	199	4419	1473	3782	1123	637	736	1554	978

¹ The population of the group is too small for the results to be generally valid
Single-family houses

The theoretical savings from wall and attic insulation was about the double of the average actual savings. Table 3. The actual energy savings in houses with combination insulation measured amount only to about the same as the houses that had been either wall insulated or attic insulated.

In this modification group the actual savings varied even more than houses where only one measure had been introduced. This means that the theoretical value has been achieved in some cases. The measured savings in several houses was very small or non-existant. Table 3.

The reasons for not achieving the theoretical savings can be many. Apart from the inherent uncertainties of the calculation methods, one cannot disregard the fact that part of the possible energy savings employed for increasing comfort have resulted in an increase in temperature after modification. One might assume that a reason for employing comprehensive measures was poor comfort (= low indoor temperature during the winter). When comprehensive measures were carried out, such as both wall and attic insulation, the building's heat demand was reduced considerably. This meant that the existing oil-fired heating system was oversized. the boiler was subjected to less load and full capacity was never used. Thus over the year the system's operating efficiency decreased. The results indicate that comprehensive measures should be combined with retrofits of the building services in order to achieve optimum energy savings.

No definite conclusions can be drawn as to why the combination of wall and attic insulation had not produced the anticipated savings. Further deeper studies are required.

Energy savings. Attic insulation and the installation of thermostatic valves

The actual energy savings for the combined measure of fitting attic insulation and thermostatic valves are considerable.

TABLE 4. Modification: Attic insulation and thermostatic valves. Energy consumption before and after modification.

Actual energy savings (A) and theoretical savings (T). Litres of oil per reference year and apartment. $(\bar{x} = average value, s = standard deviation)$

llouse type and county	No.of houses investigated	Heated dwelling area per	Modified area m ² /house	Energy consumption litres oil/year, apartment				Energy saving litres oil/year, apartment			
		apartment		Before	retrofit	After 1	cetrofit	-	A	Ţ	
<u>Single family</u> houses		•••			-	~	3	^ 	3	^	3
Norrbotten	17	155	102	4415	1026	3888	1041	527	542	257	164
Västerbotten	24	159	72	4857	1501	4146	1054	711	71,7	272	159
Stockholm ¹	28	151	99	4052	9.36	3654	945	407	621	430	2 36
Cbg and Bohus	37	153	86	4083	1013	3417	995	666	757	271	173
Malmöhus	34	145	97	4895	1090	4023	· 865	872	612	646	456
								1			

¹ The population of the group is too small for the results to be generally valid

Single-family houses

In houses fitted with attic insulation and thermostatic valves, the theoretical energy savings were calculated as though only attic insulated had been fitted.

The greatest savings in terms of litres of oil per apartment was achieved in the county of Malmöhus. Using radiator thermostatic valves and attic insulation, considerably greater energy savings were achieved than the case was for the group where only attic insulation was fitted. The so called free energy have been used more profitably and the periods of excess temperature reduced with the aid of thermostatic radiator valves. Variations in energy savings were also considerable in this group. Table 4.

Average actual savings effect of other measured studied

After having changed to triple glazing windows, the actual savings are equal to theoretical savings. When the measure was combined with wall insulation, the theoretical savings were greater than the actual savings. Thus a combination of measures did not realise the anticipated savings.

The installation of thermostatic radiator valves in multifamily houses in the counties of Stockholm and Malmöhus produced an average actual savings of approximately 6 % of the original consumption.

Thermostatic radiator valves and motor shunts in single-family houses in the county of Stockholm resulted in an average savings of 12 %.

Variator equipment in multi-family houses in the county of Stockholm produced an average energy savings of around 11 %.

The installation measures studied have on average led to satisfactory savings. (See table 5)

Actual energy savings (A) and theoretical savings (T). Litres of oil per reference year and apartmunt for single family houses and per m ² heated dwelling area for multi-family houses. (Ā - average value, s = standard deviation)											
House type, retrofit and county	No.of houses investigated	Heated dwelling area par apartment m ²	Modified area m ² /house for single family houses m ² /apartment for multi- family houses	Energy consumption litres oil/year, spartment, (single-family houses) litres oil/year, m ² (multi-family houses)				Energy saving litres oil/year, apartmet (single-family houses) litres oil/year, m ² (multi-family houses)			irtment es)
Single family houses				Before X	retrofit s	After x	retrofit s	x	5	x	s
Triple glazing ¹ Norrbotten	38	160	15,9	4506	987	4159	1030	347	440	2 82	91
Triple glazing ¹ Västerbotten	22	188	20,3	45,33	1 356	4176	1243	357	627	329	74
Triple glazing Malmöhus	• 51	170	16,6	3790	1164	35 30	1049	261	410	171	75
Triple glazing and wall insulation Norrbotten	17	144	102+13	3832	858	3452	970	380	464	623	150
Thermostatic valves and motorshunt Stockholm	. 32	180	-	.4675	1241	4106	1023	569	592	-	-
<u>Multi-family</u> houses			:								
Thermostatic valves Stockholm	29	70	-	26,6	5,8	24,8	5,2	1,8	2,3	-	-
Thermostatic valves Malmöhus	20	74	-	27,6	7,4	25,9	5,5	1,7	3,6	-	-
Variator equipment Stockholm	14	86	-	29,5	5,0	26,3	6,0	3,2	2,7	-	-

Energy consumption before and after modification.

TABLE 5 Other measures studied,

¹ The population of the group is too small for the results to be generally valid

A summary of comments and conclusions

The average energy consumption prior to retrofit was roughly the same in all modification groups in all counties. There was a tendency towards lower measured consumption in the county of Göteborg and Bohus.

Bearing in mind the differences in climate, it is surprising that consumption in fact certain groups in southern Sweden that had the highest consumption. This can be explained to a certain extent in that the houses in northern Sweden were better insulated. One can also assume that living patterns are different in different parts of the country.

Energy consumption varied considerably between houses within individual groups. Conclusions related to differences in consumption levels should therefore be viewed with a certain amount of reservation.

Building modifications such as wall insulation, attic insulation and changing to triple glazing windows have, in average, led to the anticipated savings when modifications were carried out individually. When more comprehensive building modifications were embodied, the anticipated savings were not always realized. That could for instance be explained by bad adjustment of the heating system to the building's new energy demand.

Good energy savings were achieved in houses where building modifications were combined with adjustment to the heat supply. The technical modifications in building service investigated had on average led to good savings.

Large variations in actual saving were noted. This means that many houses produced better savings results than the average. The revers also applies in that savings were small or none existant in many cases.

The houses design, age and sizes varied considerably in the different groups modified.

Houses in southern Sweden often have external walls of a noninsulated brickwork construction. These are often insulated at a later date by injecting foam. Plank, timber or framework walls were common in other counties and often had additional external insulation and a new facade leyer.

The houses in southern Sweden fitted with supplementary insulation all had bad high k values (= poor insulation) in walls and attics before retrofit. Walls and attics in northern Sweden however had relativiely low k values (= good insulation) before retrofit.

External walls had not been fitted with supplementary insulation to the extent that new building standards, according to current requirements in Sweden, had been achieved on average, table 6, whereas attics often achieved newbuilding standards after retrofit. Table 7.

TABLE 6. Modification: External wall insulation.

Change in thermal resistance (ΔM value), thermal transmission coefficient (k value) before and after modification, and change in thermal transmission coefficient (Δk value).

House type and county	Change thermal	in resistance W	Thermal transmission coefficient (k value) W/ ^O C, m ²								
	-,		Befor	Before		instice	Change				
	x	S	x s		x s		x	s			
Single family houses				· · · · · · · · · · · · · · · · · · ·		<u></u>					
Norrbotten	1.26	0.62	0.44	0.10	0.28	0.05	0.16	0.08			
Västerbotten	1.19	0.45	0.53	0.14	0.32	0.05	0.21	0.12			
Stockholm	1.00	0.59	0.60	0.18	0.36	0.08	0.24	0.17			
Gbg and Bohus	1.11	0.34	0.77	0.19	0.42	0.08	0.35	0.14			
Malmöhus	1.19	0.54	1.04	0.44	0.46	0.13	0.58	0.38			
Multi-family houses											
Västerbotten	1.17	0.24	0.55	0.04	0.33	0.03	0.22	0.08			
Gbg and Bohus	1.03	0.26	0.88	0.39	0.44	0.08	0.44	0.32			

(x	=	average	value,	S	¥	standard	deviation)
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TABLE 7. Modification: Attic insulation

Change in thermal resistance (ΔM value), thermal transmission coefficient (k value) before and after modification, and change in thermal transmission coefficient (Δk value).

House type and county	Change in thermal resistance °C, m²/W		Thermal transmission coefficient (k value) W/ ^O C, m ²								
			Before modification		After modification		Change				
	x	S	x	s	x	S	x	S			
Single family houses											
Norrbotten	2.50	1.01	0.29	0.07	0.17	0.04	0.12	0.06			
Västerbotten	2.73	0.84	0.38	0.09	0.19	0.03	0.19	0.07			
Stockholm	3.04	1.25	0.43	0.20	0.19	0.07	0.24	0.15			
Gbg and Bohus	2.73	1.15	0.47	0.16	0.21	0.06	0.26	0.15			
Malmöhus	2.49	0.73	0.88	0.46	0.27	0.08	0.61	0.42			
Multi-family houses											
Stockholm	2.44	0.54	0.44	0.22	0.21	0.05	0.24	0.19			

 $(\bar{x} = average value, s = standard deviation)$

Where future energy savings are concerned, more importance should be attached to combining the right modifications for each individual house and making sure that the work is carried out correctly. Poor houses should be insulated properly and the heating system should be adapted to the new heat demand. In houses of a good technical standard, only limited building modifications should be carried out for the time being. Instead, effort should be directed to improving installations.

MOISTURE PROBLEMS DUE TO ENERGY CONSERVATION MEASURES

Moisture problems in houses can be related to low indoor temperature and especially to low surface temperature on the inner surface of windows. Also high humidity in houses can during the winter time create such problems.

Some common causes when retrofitting houses which might increase the risk of moisture are for example:

- When houses are made more airtight the ventilation
 rate can be reduced and as a consequent of that
 moisture content might increase in the houses.
- o Additional insulation measures implies that the heating demand in houses can be reduced. It is also possible to decrease the room temperature without changing the indoor comfort for the people living in the houses. After measures being undertaken it is possible that the radiators below the windows cannot provide enough heat to keep satisfactory temperature on the inner surface of the windows why condensation will occur.

At the inspection of each house in the investigation the house keepers were interviewed about occurrence and extent of moisture before and after retrofit.

The evaluation of the information obtained shows in most of the cases that condensation problems did not increase after the insulation measures were carried out. Instead the condensation problems before retrofit in many houses had decreased in extent or compleatly disappeared after measures being undertaken (see table 8).

This can among other things depend on that the warm air from the room prevents to leak in between the window panes and condensate on the inner surface on the cold outer pane because

of better weatherstrips between the window-frame and casement after retrofit.

One must also bear in mind that, as mentioned above, when houses are made tighter moisture problems can occur due to insufficient ventilation. That can be an explaination to increased moisture problems in some of the houses in the investigation.

Extent of con- Con- densation densa- before tion retrofit after retrofit	More than after retrofit	Similar to after retrofit	Less than after retrofit	Condensation <u>dit not</u> occur before retrofit	No answer has been given
Condensation on windows	23	87	15	9	9
Condensation on other parts	2	9	-	2	-
Condensation both on windows and other parts	-	2	1	1	-
No condensation after retrofit	28			161	140

Table 3. Condensation

Occurrence of condensation after retrofits compared with extent of condensation before retrofit.

Retrofits: All additional insulation retrofits except groups with changing to triple glazing windows.

Single-family houses

Change to, or modification to, triple glazed windows would result in higher temperature on the inner pane so that the risk of condensation therefore is less after the measures were carried out.

When evaluating the measure changing to, or modification to, triple glazing windows the results also points out that condensation problems which occured before triple glazing windows were installed in most of the cases have decreased or entirely disappeared after measures being undertaken.

Though in some cases the occurrence of moisture have increased after modification. See table 9.

Extent of con- Con- densation densa- before tion retrofit after retrofit	More than after retrofit	Similar _{to} after retrofit	Less than after retrofit	Condensation <u>dit not</u> occur <u>before</u> retrofit	No answer has been given
Condensation on windows	22	6	3	2	2
Condensation on other parts	1	-	-	-	1
Condensation both on windows and other parts	1	-	-	-	-
No condensation after retrofit	40	\mathbf{X}	\mathbf{X}	21	32

Table 9. Condensation

Occurrence of condensation after retrofits compared with extent of condensation before retrofit.

Retrofits: o Changing to triple glazing windows

o Changing to triple glazing windows + wall insulation

Single-family houses

DIFFERENT TYPES OF WEATHERSTRIPS BETWEEN WINDOW-FRAME AND CASEMENT

Different types of weatherstrips seems to affect the energy consumption in different ways.

In the investigated single-family houses one can notice that expanded, angle - and tubular strips provide a lower energy level than weatherstrips made of foam and/or fibre.

There is a obvious difference in energy consumption after retrofit between houses where weatherstrips did not exist and houses where fixed windows were installed.

The results which are shown in table 10 corresponds quite well to the results of an earlier investigation¹ where different types of weatherstrips efficiency due to airleakage have been evaluated in laboratory tests. Though one can see a difference for expanded strips (see figure 3).

At this time there is some uncertainty about the results because of the great deviation in energy consumption between the houses in each group. The results seems to indicate that expanded, angle- and tubular weatherstrips prevent airleakage better than fibre and foam strips which in turn leads to a lower energy consumption.

¹ Höglund I, Wånggren B. 1979

TABLE 10 Other measures studied.

Energy consumption before and after modification. Actual energy savings (A) and theoretical savings (T). Litres of oil per reference year and apartment for single family houses and per m^2 heated dwelling area for multi-family houses. (\bar{x} = average value, s = standard deviation)

House type, retrofit and county	No.of houses investigated	Heated dwelling area per apartment x ²	Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Houses Heated Houses Heated Houses Heated Houses Heated Houses Heated Houses Heated Houses Heated Houses Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated Heated			Energy consumption litres oil/year, apartment, (single-family houses) litres oil/year, m ² (multi-family houses)					Energy saving litres oilygen, spartnam (single-family houses) litres oilygen, r' (multi-family houses)				
Single family houses				Before x	retrofit s	After X	retrofit s	ž	А Б	x 1	\$				
Triple glazing ¹ Norrbotten	38	160	15,9	4506	987	4159	1030	347	440	282	91				
Triple glazing ¹ Västerbotten	22	188	20,3	4533	1 356	4176	1243	357	627	329	74				
Triple glazing Malmöhus	51	170	16,6	3790	1164	3530	1049	261	410	171	75				
Triple glazing and wall insulation Norrbotten	17	144	102+1.3	3832	858	3452	970	380	464	623	150				
Thermostatic valves and motorshunt Stockholm	32	180	-	4675	1241	4106	1023	569	592	-	-				
Multi-family houses															
Thermostatic valves Stockholm	29	70	-	26,6	5,8	24,8	5,2	1,8	2,3	-	-				
Thermostatic valves Malmöhus	20	74	-	27,6	7,4	25,9	5,5	1,7	3,6	-	-				
Variator equipment Stockholm	14	86	-	29,5	5,0	26,3	6,0	3,2	2,7		-				

¹ The population of the group is too small for the results to be generally valid



Tubular and angle strips provide a high degree of airtightness in windows while airleakage is somewhat greater for expanded strips and considerably greater for foam and fibre strips.

Höglund I, Wånggren B. Weatherstripping windows and doors. Meddelande 126. Stockholm 1979.

PAPER 5

A SIMPLE METHOD FOR REPRESENTING THE TOTAL VENTILATION BEHAVIOUR OF AN APARTMENT BUILDING

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1. INTRODUCTION

The method, described below, may be applied for the determination of air leakage characteristics and for the assessment of energy saving measures. It was developed for four-storey apartment buildings with either natural ventilation (see Figure 1a) or mechanical extract ventilation (see Figure 1b). These building types are common in Sweden.

The air flow circuit for e.g. a second-storey apartment is represented in Figure 1c. It can be approximated by two resistances coupled in series.

The air flows through the two resistances must be the same and the sum of the pressures across the two resistances must equal the total driving pressure.

Since the flow through a resistance depends on its leakage characteristic, the total flow for the system can be represented graphically by plotting the leakage (n/p) curves "back-to-back" with a common axis for the flow rate (n) (see Figure 2).

2. THE DETERMINATION OF THE AIR INFILTRATION CHARACTERISTICS OF A BLOCK OF FLATS UNDER OPERATIONAL CONDITIONS

Pressurization tests in Sweden today are carried out at 50 Pa. This is well outside the normal range of operational conditions for a building.

When calculating air infiltration rates, the leakage characteristics for pressures within the normal range must be used.

This problem may be approached in one of two ways:

- a) Extrapolate the leakage curve determined at high pressures to lower pressures.
- b) Determine the leakage using operational pressures.

Accuracy is lost in both cases.

A method has been developed for estimating the leakage characteristics for an apartment in a four-storey residential building with natural ventilation. Each apartment may have 2, 3 or 4 ventilation channels running through a common stack to a vent above roof level (Figure la).

The resistance of the outside wall is high and, when the door and windows are closed and taped, forms a "bottleneck" in the flow so that most of the pressure difference is developed across it. The total driving pressure is the stack pressure. The pressure difference across the outside wall is measured and the outflows through the open exhaust vents are summed. This value is plotted on an n/p diagram, i.e. point A on Figure 3.

By sealing one or more of the exhaust openings with plastic film, the pressure differences across the outer walls is reduced. The outflow through the remaining open exhaust vents gives a new point B.

The characteristics of the ventilation shafts can be arrived at by carrying out a similar exercise with the shafts open and a door or window open to varying degrees. A partially open window yields point C. A fully open window or door yields point D for which the total driving pressure acts across the ventilation shaft alone.

The resulting curves can then be used in the manner of Figure 2 to find the air change rate for any given stack pressure.

The method was tested for several apartments during April-May 1981 as part of a larger research project involving measurements in 500 apartments. At this time, the weather became too warm for the method to be effective. The method has been employed and found very useful during the winter 1981/1982.

3. WHAT ABOUT THE WIND EFFECT ?

It can be demonstrated theoretically and in practice that for buildings with tight construction, and for the stack dominated weather conditions suited to this test, the wind effect is important for the flow through the walls.

However, wind does still affect the top of the ventilation shafts. The magnitude of this effect is not well known, and will be investigated as part of the current research programme with a view to modifying the design of the outlet to minimise the effects of wind.

4. <u>CONTROLLING THE VENTILATION RATE IN NATURALLY VENTILATED</u> FLATS

Some of the apartments in the project have been, or soon will be, fitted with a thermostatically controlled ventilation inlet valve for which the open area decreases as the outside temperature decreases. This provides an almost constant flow rate across the outside walls of the flat.

The flow for a range of outside temperatures normalised to the flow at 0° C is illustrated in Figure 4.

5. ASSESSMENT OF ENERGY SAVING BY SEALING THE ENVELOPE

The presentation of leakage data in the "back-to-back" form of Figure 2 can also be used if the natural ventilation channels are replaced by a mechanical extract system (see Figure 1b).

Thus the method can be used to investigate the effects of such practices as sealing the external walls of naturally ventilated and exhaust ventilated buildings.

The leakage characteristics for outside walls with an air change rate (at 50 Pa) of 1.5 and 0.75 air changes per hour are illustrated in Figure 5a.

The corresponding curves for the ventilation exhaust shafts for natural and extract ventilation systems are given in Figures 5b and 5c respectively. Figures 6a and 6b represent the effects of placing 5a "back-to-back" with 5b and 5c respectively. (Note the change of pressure scale).

It will be observed from Figure 6a that for the natural ventilation system, with the same total pressure difference (9 Pa), that there is a substantially reduced air change rate from 0.6 ach (air changes per hour) to 0.3 ach after sealing.

For the mechanical system, Figure 6b, the total driving pressure is 300 Pa. The effect of the exhaust fan predominates and the reduction in air change rate is very small or negligible.

6. COMMENTS

The above examples show that the air flow characteristics of a building and of its ventilation system must be regarded as an organic whole.

Lack of understanding of the effects of the interactions between the various parts of the total system on the functioning of the system poses a severe problem when seeking effective strategies for energy saving in buildings.



* p \simeq 0.04.h.(T_i - T_o)





Figure 1c Schematic diagram of the air flow circuit for the flat

- fixed resistances (e.g. wall)

- variable resistances (e.g. openable window)

- closure (e.g. damper, plastic sheet sealing an opening)

Figure 2 Graphical description of air exchange by total pressure difference



Figure 3 Leakage graphs of outer walls ① and ventilation channels ②



Figure 4 Temperature dependent flow characteristic of inlet valve





^{*}Note change of scale



a) Natural ventilation system



b) Mechanical ventilation system



PAPER 6

TRACER GAS MEASUREMENTS IN LOW LEAKAGE HOUSES

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INTRODUCTION

Air infiltration is an important component of energy loss in all buildings. Wind and temperature are the driving forces for this component. For given weather conditions the size of the air infiltration is determined by the air tightness of the building envelope. A promising technique to characterize this housing quality is air leakage measurements. An air leakage standard for new construction exists already in Sweden. Results from air leakage measurement can be used to predict the overall air infiltration for a building (1,2). Predictions will however not tell anything about the air infiltration in individual rooms. When this kind of information is needed tracer gas measurements using a special technique have to be employed. A technique for doing this has been developed and applied to a tight house.

The overall ventilation rate was very low for the test house, although it had mechanical ventilation (exhaust fan). This indicates that tight houses have to have a system for mechanical ventilation and that this system has to be efficient.

DESCRIPTION OF USED TRACER GAS TECHNIQUE

The basic principle of this method is the commonly used method of measuring the air infiltration using a tracer gas. Usually a tracer gas is injected into the house at one time and the following decay of the tracer gas is monitored. The result using this method will typically be the whole house ventilation.

In our case (3) we take air samples from every room and analyse them individually. The purpose of the method is to collect information about the ventilation of individual rooms i.e. the supply of fresh air to individual rooms. The method assumes negligible air flows between rooms and nearly perfect mixing. This is considered to be true for most of the residential buildings i.e. one-family houses or apartments. Air flows between rooms will add to the inaccuracy of the method. (This has been calculated in ref. 3).

A test is made in the following way. Every room to be monitored is connected to the sampling apparatus via tubing. The sampling apparatus is connected to an analyzer. The number of sampling points is maximized to 9. When choosing sampling points, locations close to inlets or outlets should be avoided. The sampling point are preferably chosen within the area where people normally stay and are located at mid height. The tracer gas is distributed manually and the following decay is monitored. It is essential that the tracer gas is uniformly distributed within the building at the start of a test. The sampling apparatus collects air samples following a preset schedule. Typically air will be sampled automatically at each individual sampling point every 3 to 7 minutes. The analyzer and the control apparatus are located in a van during the test. Tubing is run from the van into the house to be tested. The tubing is thermally insulated in order to avoid condensation at winter. The only disadvantage with having all instrumentation in a van is that it limits possible test sites to one-family houses and apartments in buildings with a maximum height of three storevs.

RESULTS

Measurements were made in a one-storey one-family house built 1977. When the house was built special care was taken during construction to make the house very tight. Standard building technique was used. The main idea was to be very careful about sealing all joints. The goal was to be better than the Swedish Building Code. A pressurization test was made, which showed that the house only leaked 1,5 ach at 50 Pa (see fig. 1). This value is to be compared with 3,0 ach in the Code. Most new Swedish homes meet this requirement and it is not unusual to find houses with 1,5 ach at 50 Pa.

In order to determine the ventilation rate the above described equipment was used. A typical winter day was chosen for the test. The temperature was -3 °C and a light wind prevailed. The house had mechanical ventilation i.e. air is exhausted using a fan. Exhaust air vents are located in bathrooms, laundry room, kitchen. Fresh air enters the house through cracks. This type of ventilation system is fairly common in modern Swedish housing. Nowadays this system normally also includes special supply vents.

The first test was done with the ventilation system in normal operating conditions. The average air infiltration for the whole house was shown to be 0,23 ach (see table 1). This value is clearly below the recommended value of 0,5 ach in the Swedish Building Code. There is a wide variation for different rooms. Only one room was above the recommended value, with a value of 0,64 ach. The room with the lowest ventilation rate had only 0,05 ach.

During the second test the fan was turned off and the air infiltration caused by natural means was studied. This time the average ventilation for the whole house was 0,11 ach. Some of the rooms seemed to have hardly any ventilation at all (se table 1).

In a final test the fan was turned on again and the ventilation was increased by opening a couple of windows on a slight angle. This way the ventilation rate became almost acceptable, reaching the value of 0,41 ach. There is a wide variation for different rooms; the highest value being 2,05 ach and the lowest value being 0,07 ach.

DISCUSSION AND CONCLUSIONS

The purpose of an exercise such as this is to attempt to find the ventilation rate for a tight dwelling. It was clearly shown in this home that relying on only natural ventilation is not sufficient for a tight house (0,11 ach). Adding mechanical ventilation for bringing out used air wasn't enough of a remedy for this particular house (0,23 ach). The reason being that the system wasn't properly adjusted, the fan wasn't powerful enough, there were no openings where air could come in. The best way of getting adequate ventilation is to install a ventilation system with built in routes where fresh air can enter the building. The system should either be a balanced ventilation system or an exhaust fan system with special vents to the outside for supplying fresh air. In order to save energy the first system can be combined with a heat exchanger and the second system with a heat pump for heating domestic hot water.

The difference in ventilation rate for different rooms was shown to be large. Some rooms were hardly ventilated at all judging from the measurements. It is obvious that in a tight house a great deal of attention has to be paid to supplying fresh air to every room.

The actual ventilation rate in tight homes has to be studied. Furthermore a better technique for evaluating the ventilation rate for whole homes and in individual rooms has to be developed.

A constant concentration technique is being developed for this purpose. The idea being to inject tracer gas continouosly into each room of an apartment or a house and to maintain a constant concentration of tracer gas in the whole house. By measuring the supply of tracer gas to each room the supply of fresh air to each room will be known directly. The only disadvantage with this system will be that no information as to the air flows between rooms is obtained. In standard buildings air flows between rooms will however have no effect on the measurement of the fresh air supply to an individual room. This is assuming perfect mixing within minutes. Problems with keeping a constant concentration may arise if there is an abrupt change in ventilation rate. In most houses this should normally not happen, this is especially true for houses with mechanical ventilation. An additional advantage with the system is the possibility of making long-term measurements of the ventilation rate.

Ventilation in modern tight housing is very often a neglected area. It is however possible to monitor the ventilation rate for whole homes and individual rooms in detail already today. Still better information will be available once the constant concentration tracer gas technique is developed.

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hr⁻¹

Ro	oom	Case 1	Case 2	Case 3	(m ²)
1	(kitchen)	0,16	0,18	0,25	21,6
2	(living-room)	0,18	0,16	0,33	31,5
3	(bedroom)	0,25	0,07	0,07	14,3
4	(den)	0,14	0,16	0,30	10,2
5	(bedroom)	0,16	0,05	0,16	12,5
6	(hallway)	0,07	0,16	0,34	15,8
7	(den)	0,10	0,38	2,05	10,2
8	(bedroom)	0,10	0,27	0,69	12,4
9	(storage)	0,01	0,64	0,28	21,6
1() (gameroom)	0,02	0,16	0,37	29,7
					180,0

Case	1:	Natural ve	ntilation (v	ents o	closed)			
Case	2:	Mechanical	ventilatior	n, all	windows	and	doors	closed

Case 3: Mechanical ventialtion, windows open on a slight angle

Case 1: Average 0,11 hr⁻¹ Case 2: Average 0,23 hr⁻¹ Case 3: Average 0,41 hr⁻¹



Figure 1. Air leakage vs. pressure difference inside-outside for the test house

PAPER 7

HOUSE DOCTORS PROGRAM --RETROFITS ON EXISTING BUILDINGS

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ABSTRACT

The needs, history, procedures, and past case studies for the house doctor approach are outlined. This program of individualized instrumented energy audits and retrofits has reached a stage in development where steadily increasing numbers of house doctors are envisioned for the years immediately ahead.

INTRODUCTION - THE NEED FOR DOCTORING HOUSES

In countries around the world, one question that is being asked more and more often is: What changes can I make in my home so that energy consumption will be reduced? The answer is often given in the form of lists of energy saving measures, but how many "solutions" apply to the home in question? We believe the question demands a customized solution -- one tailored for the particular house. The most common response to this question is a paper and pencil energy audit of the house. Such audits do not rely on any measurements of key variables that influence energy use. Our experiments have shown that an energy audit based on computation alone would miss some of the most effective energy conserving measures. Princeton University's House Doctor approach is based on an instrumented energy audit and leads to the identification of all the major energy defects in the house. The procedure generally includes a partial retrofit along with the instrumented audit.

The energy savings program is conducted by a house doctor team, which in our definition, is a well-trained two or three person crew to handle energy analysis and retrofitting. The house doctors use a carefully selected kit of instruments to speed their house diagnoses of energy loss. The end result is a prescription for appropriate retrofit measures that partly takes place during the visit of the team. Although a given house may call for a change in procedures to meet certain particular needs, there is a recommended approach that will be described.

HISTORY OF THE APPROACH

The beginnings of the house doctor approach may be traced to the Twin Rivers Project.¹ In a series of residential energy studies that extended over a period of more than six years, a number of experiments were conducted. The first experiment concentrated on three side-by-side townhouses instrumented to provide almost 200 channels of energy data. The object was to understand, in great detail, the way in which the occupants in these townhouses used energy. A complete weather history from a dedicated weather station nearby was a critical aspect of the study. The instrumentation continuously located in the house was supplemented by other portable measuring devices. Infrared scanning equipment was a principal tool. Other portable instrumentation included handheld temperature probes to measure a variety of air, water and surface temperatures, and hot wire anemometers to measure air flow in the warm air heat distribution system. An automatic air infiltration measurement device developed during this period was used extensively. The benefits derived from the detailed energy data were numerous, but the added information obtained from the portable instruments also proved to be significant.²

As the second series of experiments began, data logging was reduced to 12-channel tape recorders in more than 30 townhouses earmarked for retrofitting. Similar recorders were placed in ten homes heated and cooled with heat pumps. The use of auxiliary measurement techniques steadily increased during this experiment. The addition of the "Blower Door" pressurization device allowed the tightness of several Twin Rivers townhouses to be compared, and greatly expanded the versatility of infrared scanning.^{3,4}

The realization at that point in the research was that if larger numbers of houses were to be analyzed, emphasis on inexpensive portable instrumentation and streamlined analysis procedures were absolutely necessary.

THE PROCEDURE

The procedure that has been used in the house doctor approach begins with an external examination of the structure, sizing the house, and cataloguing its important features.^{5,6} The team makes use of simple measurement techniques and photography. The objective is to measure the size of dwelling and to photographically record the exterior details of the structure. These photographs include a clearly marked measuring stick so that measurements of windows and other features from the photographs are possible. The outside measurements allow a plan to be sketched accurately at the site. Using carbon sheets, multiple copies are produced so that a separate copy can be dedicated to the problems found on each floor of the house.

During the preliminary portion of the visit any energy problems encountered by the homeowners are also noted; cold rooms, localized draftiness, inadequate insulation, poor windows, etc. The final item is a room-by-room survey to determine how well the temperature is balanced and whether the thermostat(s) is functioning properly. A multiple setback clock thermostat may be installed by the house doctor so that temperatures can be programmed over the full 24-hour day (this includes daytime setback when appropriate). Setting the temperature back 1 degree C reduces space heating consumption by 7% in the average U.S. climate. Somewhat less than a third of this would be saved by an 8 hour night-time only setback. For residents not currently setting their temperature back at night (but would do so if a clock thermostat were available) these thermostats would be very cost effective.

The next priority is to determine the leakiness of the building envelope. A Blower Door, a large calibrated multispeed fan system, is installed in an exterior doorway and the house is pressurized.²⁻⁷ The amount of flow required to pressurize (or depressurize) the house over a range of pressure levels is recorded. This test not only indicates the amount of leakage, but rates the house with others as to tightness. Should the house be sufficiently tight (at Princeton we have set six air changes per hour at 50 Pascal as the temporary criterion) further leak sealing is not necessary. However, this degree of tightness is rarely found.

Leak site detection begins with the attic. A slightly pressurized house means that a greater than normal amount of air is forced through a variety of attic floor leakage sites. These leaks are detected by scanning the attic floor with portable infrared equipment. Even with insulation in place, the leaks are readily visible using the infrared technique. "Bypasses" from interior walls, plumbing stacks, electrical fixtures and wiring holes are just a few of the leaks that are detected.^{7,8} Often there are large energy loss sites due to lowered (soffit) ceilings, whole house fan openings, special piping or ducting chases, etc. These sites present leakage levels that demand immediate attention. Large openings are sealed with a plastic sheet placed over the Smaller openings are sealed with leak and under the insulation. foam, compressed fiberglass, caulking or tape. The access to the attic is often a major leak site and requires weatherstripping or perhaps an insulated sealing cover to cure the problem. Any sealing improvements can be measured while the Blower Door instrumentation is in place. In this way the house doctor knows that progress is being made - the patient is improving.

Next the house is depressurized by reversing the Blower Door fan. Under these conditions ceiling leakage can be double checked from the inside. Now we are dealing with cooler surface areas (under heating season conditions) inadequate insulation and the presence of leaks are identified by cool patterns across the interior surfaces. The infrared viewer is used to survey all the interior surfaces of the house. Interior walls receive equal attention in this survey. Piping and wiring through the internal walls often are the cause of major leakage paths from the living space or basement to the attic. This condition results in characteristic cool stripes extending from floor-to-ceiling and indicate high priority sites for retrofitting. Soffit ceilings appear as cool areas in need of an attic seal. The floor is also scanned in the internal surface check. Often leakage along the floor-wall joint is a major source of air infiltration together with the electrical The latter leaks may be cured using closed-cell plastic outlets. gaskets as a retrofit measure. Transparent caulking on the joints along floor edges and around windows can prove to be very worthwhile. This tightening process typically yields 10-35% improvement in reduced air infiltration.

Having catalogued problems in the building envelope due to air leakage and insulation shortcomings, attention is next turned to the heating system. Both oil and gas fired systems have shown marked improvements through tune-up. Remember a 5% improvement on a heating system with a 70% seasonal performance translates into a more than 7% overall gain. The house doctor should use the best measuring equipment available for these tests. Direct readout of performance is helpful so that the tests, and adjustment if necessary, may be done in approximately 15 minutes. This can prove to be the conservation measure with the fastest payback. Since this check takes place after the Blower Door testing, the house has cooled down insuring reasonably long burner operation times.

Last, but not least, in the checklist for the house doctor is the inspection of major appliances. Generally additional insulation on the outside of gas and electric water heaters have a relatively short payback period. The hot water temperature should be set as low as possible to meet household needs. This setback can save as much as upgrading the insulation. Where needed, flow limiting devices should be employed in showers and sinks. The refrigerator may require some additional monitoring if questions arise as to its performance. We have developed a simple meter that provides such data by monitoring over a 24 hour period.⁶ This meter measures the cumulative, energy consumption and avoids the problem created by on and off cycles of the compressor, fans and other components.

FOUR HOUSES UNDER STUDY

The experience with townhouses, condominiums and single family detached houses built during the 1970's at Twin Rivers was revealing but that experience left many questions unanswered. Measurements of older homes, where a variety of style and vintage questions were relevant, was the next step.⁹ The techniques of the house doctor approach were employed.

Prior energy records were collected from two ranch-style (singlestorey) and two colonial-style (two-storey) homes. Wherever possible, an Energy Signature (a compilation of energy use plotted against outside temperature for the period) should be determined prior to a contemplated house visit.

Very evident from the house doctor visits to the four homes was that more than conventional retrofitting was necessary. Of particular interest was the amount of leakage in the band joist areas especially in the case of the two-storey houses. The use of depressurization and infrared scanning revealed these problems. The solution involved devising techniques to inject blown in insulation into these locations and make certain it would stay in place. Use of glue, cellulose, and a special spray nozzle were all part of this activity. Each of the houses received an attic insulation upgrading -- normally moving from 8 to 25 cm of equivalent mineral wool insulation (actually both fiberglass and cellulose blown in insulation were used). Basement band joists were upgraded through use of sealants, and 15 cm of fiberglass with vapor barrier. Craw] space walls were insulated as well. Electric outlets were gasketed; windows and doors were checked for leakage, and weatherstripped where economical; and other leakage sites, primarily in the ceiling, were treated with 0.15 mm plastic sheets, under the insulation. Each of the furnaces was checked with the highest gain being a 9% change due to increased steady-state performance in a modern oil burner.⁶

Certain of the houses required return visits to: monitor moisture problems in an underventilated attic where increased insulation had aggravated the situation; treat a local problem due to a missed envelope opening which was hidden by a bathtub; and vents blocked by insulation.

An appreciation for the saving potential of the house doctor approach can be gained from the Table.¹⁰ The first house is the Twin Rivers townhouse that received extensive retrofit treatment.¹ The last three entries are three of the four older houses just discussed. As an aid in visualizing the consumption, all energy for heating has been converted to liters per year and savings expressed in cost of energy saved (Dollars per 1000 liters.)

House (Year of Construction)	Heating Fuel	Energy Use b) (liters per year)		Retrofit	Cost of Saved
		Before Retrofit	After Retrofit	Cost (\$) ⁽⁵⁾	Energy ^a / (\$/1000 liters)
TR (1972)	gas	2207	522	30 00	119
HS 11 (1957)	gas	1624	973	700	72
HS 21 (1973)	סזו	3596	1703	1200	42
HS 22 (1963)	gas	3115	2290	1000	81

TABLE RETROFIT COSTS AND ENERGY SAVINGS

a) These data relate to four houses in New Jersey retrofitted by Princeton University's Center for Energy and Environmental Studies and local contractors.

b) Space heating energy use in equivalent fuel oil liters per year normalized to a standard year, based on a 10 year average of weather data.

c) Includes both materials cost and labor cost (computed at \$100 per person-day).

d) Cost of saved energy = <u>cost of retrofit</u>; for these retrofits a 15 life cycle energy savings

year life expectancy has been assumed.

STATEWIDE/NATIONWIDE

During the winter of 1979/1980 the four gas utilities of the State of New Jersey, in a model collaborative project with Princeton University, began a statewide experiment to conduct a large scale test of the house doctor concept.¹¹ The utility house doctor teams were trained at Princeton and received further field training at six housing sites. The experimental research plan involved 18 house modules which provided: six controls, six house doctor visits, and six houses that received major retrofitting following the house doctor visit. Energy signature data generally required R square fits better than 0.95 to qualify a house for consideration in the program. Since time did not permit the collection of preretrofit data, house/occupants that were not following a well-prescribed energy use pattern were excluded. As in the case of Twin Rivers housing (and a number of other housing sites where detailed measurements have been taken) there was again a more than two-to-one variation in gas use in the houses of each

of these groups of nearly identical houses.¹²

The data from this experiment have answered many questions but have posed new questions as well.

First the questions of training. The basis for training house doctors has been established, the conclusion has been that a minimum of five days of classroom and planned activities followed by a comparable field experience can satisfy the training needs. The savings due to both the house doctor and the visit plus retrofit have been documented as shown in the Figure. A subset of these data point out that improvements are evident as the team experience grows.





Some of the new questions that have arisen include the lack of benefit from the thermostat installation. Post retrofit interviews have revealed that the setback thermostats are only being used by those occupants that previously used manual setback. The interaction of the house doctor with occupant must include training and encouragement in the use of control systems. Another question deals with extreme outlying data points. In a period of rapidly rising fuel prices some of the homeowners are achieving major savings in their energy use, (10 percent reduction in gas use for the utility as a whole), the previous major change of this type was seen in the 73 - 74 period.

The house doctor activities of the utilities within the state involving some 130 houses have been mirrored in other regions throughout the country, e.g. Minnesota, New York, Tennessee and California. Full results of energy savings and costs are currently being analysed.

THE MARKET PLACE

The realization that a house doctors approach is needed and that the time has come is evident from recent events. The program at Princeton has received much publicity in the past but recent coverage¹³ has brought a virtual deluge of requests from prospective house doctors throughout the United States and many from other countries as well. Last year the level of interest was far lower.

A variety of groups in North America have come to the conclusion that the house doctor or similar technique is the way to approach home energy retrofitting. In the last few months many of these groups are moving to franchise the methods that have been developed. Unfortunately mixed in with the dedicated energy savers are groups that have only monetary gains in mind, offering inferior instruction and/or equipment of marginal value. Some have also become quite specialized, perhaps too specialized, in that they are concerned only with envelope tightening, neglecting furnace efficiency, and insulation questions. Others have become regionalized dealing with the specific problems of regional housing, this regional approach may be necessary in many instances.

THE FUTURE

In the United States and Canada there is considerable activity taking place in house doctoring. In New Jersey, a thousand house experiment to test new financing for house doctoring and other conservation measures is imminent. Judging from recent media pronouncements the groups now active in house doctoring activities are numbered in the tens, but predictions in the near future are for a thousand crews.¹⁴

One of the big questions is certification. Federal or State certification could greatly assist the program in making certain that high standards are followed in any house doctor activities. No such certification appears to be close at hand, at least in the United States.

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PAPER 8

INFLUENCE OF DIFFERENT PARAMETERS IN INFILTRATION HEAT LOSS

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INFLUENCE OF DIFFERENT PARAMETERS ON INFILTRATION AND INFILTRATION HEAT LOSS.

By: W.F. de Gids

SUMMARY

This parameter study with the IMG calculation model for ventilation is an attempt at forming some background for decisions relating to the preparation of a standard in the Netherlands.

From the results one can see that air tightness and the heat loss caused by infiltration cannot be considered as a simple linear relationship.

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INFLUENCE OF DIFFERENT PARAMETERS ON INFILTRATION AND INFILTRATION HEAT LOSS.

1. INTRODUCTION

Air infiltration plays an important part in our endeavour to save energy in dwellings.

Designing for minimum air infiltration sounds like a wish.

Considering the words design and minimum air infiltration, several questions arise:

- Where does one start?

Is it necessary to develop a complete new structural design for minimum air infiltration, or can the normal building practice be improved?

If improving the normal building practice, what details come first?

- How far must one go? There must be a minimum amount of ventilation, but infiltration may not disturb normal controlled natural ventilation.
 - Is it cost effective to improve the air tightness of dwellings?

- What are the consequences?

What are in the first place the effects on infiltration?

Second, what are the effects on air quality?

Third, what effects can be expected on man's behaviour as concerns his use of ventilation provisions such as windows, vents and grilles? Is adaptation in behaviour neccesary?

- What is the effect?

Do we save energy and how much?

In the Netherlands a standard on air tightness of housing is in preparation. This paper is an attempt to form some background for decisions.

2. INVESTIGATIONS

2.1 The calculation model

The investigation can be seen as a parameter study with the IMG calculation

model for ventilation and infiltration in buildings.

The principles of this model are described in literature [1]. The mathematical model is a simulation of all air paths in the building. For example, the cracks, joints and seams of windows, doors and other construction details, the grilles, vents etc. intended for ventilation and a mechanical ventilation system can be simulated. The input data concerning:

- wind pressures
- air temperatures
- characteristics of cracks, joints, seams, vents, windows, ducts and other openings.
- fan characteristics.

2.2 Present situation

The best estimate of the air tightness of houses in the Netherlands is given in figure 1 [2]. The mean value is $0,1 \text{ m}^3/\text{s}$ at 1 Pa, which means to an air change rate of about 12 at 50 Pa. In figure 2, the floorplan and the cross section of the reference house are shown. It can be considered a typical house in the Netherlands. For this house a model has been made as schematically presented in figure 3. Nine rooms with twenty-four air leakages make up the model. In figure 4, the assumed temperatures in the dwelling are shown. Figure 5 shows the distribution of the air leakage over the outside "shell" or building envelope [3]. With these figures in mind we start our parameter study.

2.3 Parameters

The following parameters have been studied:

- wind velocity (meteorological), 0 10 m/s
- wind direction, 0 360°, steps of 20°
- outside temperature, 0 15 °C
- air tightness, retrofitting of floor, roof and internal doors.

- surroundings, a house, exposed to wind.

a house surrounded in all directions by houses with the same height, a house surrounded by houses with the

same height and flatbuildings up to about 20 m (mild wind climate).

3. RESULTS

3.1 Wind velocity

In figure 6, the infiltration rates and infiltration heat losses are shown for the reference house in the exposed wind situation. Under average weather conditions, 5 m/s and 5 °C, the infiltration through the fabric is about 1 (h^{-1}). The basis or the dutch ventilation standard is 7 dm³/s per person [4]. Without opening any window, the infiltration has already a large overshoot in relation to the minimum fresh air requirements. An air infiltration rate of 1 (h^{-1}) equals a flow rate of 84 dm³/s, at a volume of 300 m³, which is sufficient for 12 persons. The corresponding infiltration heat loss is about 1,3 kW.

Between 0 and 2 m/s, buoyancy effects dominate. From about 5 m/s and up wind effects dominate. Between 2 and 5 m/s the influences of both buoyancy and wind interact.

3.2 Outside temperature

In figures 7 and 8, the air infiltration rate and the infiltration heat loss are plotted against outside temperature. For average weather conditions with a wind velocity of around 5 m/s and outside temperatures of 0 to 15 °C during the heating season, the rate of infiltration can be considered as linear to the outside temperature. For wind velocities lower than 5 m/s and temperatures between 10 and 20 °C, this relationship is non-linear. The relationship between outside temperature and infiltration heat loss can be considered as linear for temperatures lower than 10 °C.

3.3 Air leakage

In figure 9, the air leakage distribution is given after retrofitting the roof. The air leakage is reduced to 57 % of the air leakage of the reference house corresponding to an a_{50} of about 7. Figure 10 shows the air leakage distribution after retrofitting the floor. The air leakage is reduced to 85 % of the reference value. The corresponding a50 value is about 10. In figure 11, both floor and roof are retrofitted. The air leakage is 42 % of the reference value, which equals an a₅₀ of about 5. These three retrofits are assumed to reduce the original leakage to zero. This seems a bit optimistic. A more realistic air leakage distribution is given in figure 12. The air leakage of roof and floor has been reduced to 20 % of their original value. This leads to an air leakage value for the whole house of 54 % of the reference house, corresponding to an a co of about 6. Comparing the air leakage of such a house to the Swedish standard of a_{50} < 3, the air leakage of the whole house has to be reduced by that of the natural ventilation ducts (in this case 34), with an a_{50} of about 2,4 as a result.

The results of these retrofits in terms of infiltration rates and infiltration heat loss can be seen in figure 13. The realistic model gives under the average weather conditions (5 m/s, 5 °C) an infiltration rate of 0,5 (h⁻¹) and an infiltration heat loss of 700 W. In figure 14, the effect of air tight internal doors is shown. Air tight internal doors give a reduction of the air leakage value up to 20 %. The effect at this level of external leakages is relatively small.

3.4 Wind direction

The influence of the wind direction on the infiltration rate is given in figure 15.

For the house as a whole the variation is rather small. The highest value is about 1 (h^{-1}) , the lowest about 0,7 (h^{-1}) . Looking at two opposite bedrooms the effect of the wind direction is impressive. The low values of infiltration occured with the bedrooms situated at the leeward side. An example of the distribution of air through a dwelling can be seen in figure 16. These effects must be kept in mind when considering retrofits on air leakages. A consequent and conscious use of grilles and vents will be necessary to reach minimum ventilation standards. Enlightenment campaigns to occupants of these houses are necessary to avoid bad indoor air quality situations.

3.5 Surroundings

The effect of the surroundings on wind exposure and on infiltration rates is shown in figure 17. This figure teaches us, that the effect of surrounding buildings in an absolute sense is more important for leaky houses then for air-tight houses.

4. DISCUSSION

In the figures 18 and 19, the infiltration and infiltration heat losses are plotted against relative air leakage. These results are calculated in the situation with all windows closed, a wind velocity of 5 m/s and an outside temperature of 5 °C. As can be seen from figure 18, there is no linear relationship between air infiltration rate and air leakage [5]. If there is no leakage in the floor the relative air leakage is 85 % and the air infiltration rate is 0,7 (h⁻¹). Reducing the air leakage through the roof to zero gives a relative air leakage of 57 % and also an air infiltration rate of 0,7 (h⁻¹). The corresponding infiltration heat losses are 900 W and 1000 W, respecively . The higher heat loss applies to the lower air leakage ! The reasons for this are :

- distribution of air leakage over the building envelope in relation with
- distribution of air pressures over the building
- temperature distribution in the house.

The overall conclusion of this consideration must be:

Different retrofits with the same effect on air leakage can have complete incomparable effects on air infiltration and infiltration heat loss.

5. CONCLUSIONS

- The effects of wind velocity and temperature difference on infiltration are both non-linear. However, within certain limits and with some inaccuracy they can be considered linear (figures 6,7 and 8).
- 2. Under average weather conditions, 5 m/s and 5 °C, the air infiltration exceeds the minimum fresh air requirements, even in a mild wind climate (see figures 6 and 17).
- Because wind direction is a predominant factor for the infiltration rates of individual rooms conscious behaviour is neccessary to reach minimum ventilation standards (see figures 15 and 16).
- 4. Under average weather conditions, 5 m/s and 5 °C, the infiltration heat loss can be reduced from 1300 W in the reference situation to 700 W in the realistic model situation (see figure 13).
- 5. It seems possible to reach reasonable air leakage values by improving normal building practice in the Netherlands (see figure 12).
- 6. There is neither a simple linear relation between air leakage and air infiltration rates, nor between air leakage and infiltration heat loss (see figures 18 and 19).

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7. NOMENCLATURE

7.1 Symbols

С	Air leakage coefficient	$(m^3/s \text{ at } 1 \text{ Pa})$
vmet	Meteorological wind velocity	(m/s)
a	Air infiltration rate	(h^{-1})
V	Volume	(m ³)
Q	Infiltration heat loss	(W or kW)
Т	Standard deviation	(-)
n	Number	(-)
^a 50	Air infiltration rate at 50 Pa pressure difference	$(h^{-1} \text{ at } 50 \text{ Pa})$

7.2 Abbrevations.

INF	Infiltration
MET	Meteorological
L	Living-room
В	Bedroom
BR	Bathroom
К	Kitchen
Во	Boiler



Figure 1 Distribution of air leakage for 130 dwellings in the Netherlands









Figure 2 Floorplan and cross section of the reference house



Figure 3 Scheme of the model



Figure 4 Temperature distribution in the dwelling



Reference 100% C = 0,1 m³/s at 1 Pa a₅₀ ≈ 12



Distribution of air leakage



Figure 6 Infiltration rates and infiltration heat losses versus windvelocity



Figure 7 Infiltration rates versus outside temperature



Figure 8 Infiltration heat losses against outside temperature













Figure 11 Air leakage distribution after retrofitting floor and roof













Figure 14 Effect of airtight internal doors on infiltration and infiltration heat losses



Figure 15 Infiltration rates versus winddirection for the whole house and for two opposite bedrooms







─► Flow l/s or dm³/s 5 m/s

Figure 16 Distribution of air through a dwelling







Figure 18 Relative air leakage against infiltration rates



Figure 19 Relative air leakage against infiltration heat losses

PAPER 9

AIR FLOWS IN BUILDING COMPONENTS

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Knowledge of air tightness behaviour of buildings and building components is essential if a proper climate protection is to be achieved. Attempts to predict air infiltration rates and air flows in building components on the whole, and also intentional flows, have hitherto been difficult to perform. Therefore, often rough methods of calculating air flow rates have been used. Knowledge of surface roughness and the magnitude of the influence of this property for different flow cases has been poor. Permeability data concerning building materials have been - and still are - uncertain.

Quite a lot of effort has been spent on research concerning natural convection, both in building components and rooms. Apart from only a few early works, the concept of forced convection has been investigated just little until very recently, say the last five to ten years.

In Kronvall (1980) the aim has been to:

- o investigate how, and to what degree the concept of fluid mechanics can be applied to problems concerning air flows in building components caused by forced convection
- o produce calculation routines capable of handling also large and complex flow and pressure distribution problems
- o investigate and interpret present knowledge of air leakage behaviour of buildings and building components
- o investigate the influence of non steady state pressure difference acting on a building component
- o design and test an experimental procedure for determination of surface roughness of plates
- o expand the knowledge of the magnitude of the surface roughness
 of building materials
- o study experimentally the magnitude of entrance and bend losses in duct flow.

In this paper two important sections of the report mentioned above has been selected for presentation - one dealing with computorized analysis of flow resistance networks and another one dealing with different ways of describing air leakage characteristics of building envelopes. Reports on computer calculations of air flows in building components are extremely rare. In most cases the reported works have been limited to a certain flow problem and the calculation procedures have been designed exclusively for the problem in question. Hence the computer programs used normally are afflicted by severe lacks of universal applicability.

Calculations of great complex networks of flow resistances are very timeconsuming and sometimes impossible to perform by hand. A systematic computerized calculation procedure can be obtained by means of a proper computer program. Such a one, called JK-CIRCUS, was written for this research project. Parts of the computer program originates from a program designed for analysis of electrical circuits; Anderson (1978). The solution procedure involves the following stages:

- o The flow problem geometry is split up into finite parts components.
- o The admittance, defined below, of each component is calculated.
- o The computer calculates the potentials, p(Pa), in all nodes and flow rates, $q(m^3/s)$, through all components.

The computer program works with the concept of admittance. This property, A, is defined by:

 $q_{v, x} \left[m^3/s \right] = A_{x} \left[m^3/(s \cdot Pa) \right] \cdot \Delta p_{x} \left[Pa \right]$

Hence the admittance, A, is a linear operation on the pressure difference, Δp , across a component returning the flow rate, q.

In the case of (air) flow problems a component may be either of

o a pressure difference between two nodes (active component)

o a piece of permeable material (passive)

o a piece (in the flow direction) of a duct (passive)

o a single resistance (e.g. entrance, exit, bend loss) (passive).

A flow chart of the computer program is shown in FIG. 2.a.

Example:

Cavity brick wall with beams penetrating the inner leaf.

This is a typical design in many countries. If the cavity wall has a bad air tightness and the clearance around the beams is large there is a certain risk of discomfort in the house caused by movements of cold air in the intermediate floor.

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A part of the wall (height 3.00 breadth 0.30 m) was chosen to represent the "flow area" of the wall corresponding to the clerance on one of the two long sides of the beam end. The back wall itself is assumed to be air tight. The network used for the analysis is outlined below.



The roughness, ε , was put at = 0.005 m in the cavity and 0.001 m in the interstice. Test pressure difference was 20 Pa.

The resulting flow rate through the interstice around the beam is shown in the following figure as well as the percentage of the pressure drop across the interstice compared to the total drop. An alternative wall material (wood panel) is added too as comparison.



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The building envelope is here considered to consist of the total climatic shelter of a building. The knowledge of air leakage characteristics of building envelopes of different buildings has been extended substantially during the last few years. This is due to a high degree to the rapidly increasing use of the pressurization technique to test the airtightness of whole buildings.

The pressurization procedure establishes a relationship between pressure difference across the building envelope and resulting leakage rate.

In most cases the result is given as a leakage curve.

From pressurization practice it can be observed that the shape of the leakage curve differs from house to house. The extremes of the shape are a parabolic curve on one hand and a straight line on the other. It is tempting to claim that this corresponds to complete turbulent flows in the flow paths of the envelope and complete laminar flow respectively. While the second statement is reasonable, the first one is quite dubious, since other phenomena than turbulence may cause the flow rate to be proportional to the square root of the pressure difference. Obviously, since single resistances like entrance, bend and exit losses operate on the square of the average velocity in the flow path, turbulence is not the only reason. This will be discussed more in detail below.

A versatile way of describing the relationship between leakage rate and pressure difference is to use a power function

 q_v , tot = $\alpha \cdot \Delta p^{\beta}$

(3.a)

where

 α is a flow rate coefficient, $m^3/(s~\cdot~Pa^\beta)$

 β is a flow exponent, 0.5 < β < 1

It is sometimes claimed that this expression is in conflict with a proper description of the physics of the flow. Of course, such an objection is correct and perhaps it would have been wiser to use a quadratic equation of the form

$$\Delta p = c_1 \cdot q_v, \text{ tot } + c_2 \cdot q_v^2, \text{ tot}$$
(3.b)

where the relative contributions of laminar flow on the one hand and orifice and single resistances and turbulent flow on the other could be shown.

A third way of making the description, used especially in the Anglo-Saxon countries, is by using the concept of <u>equivalent</u> <u>leakage area</u>, A_{eq}, defined as follows i.e. an equation for turbulent flow through a sharp-edged opening in a thin wall.

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 $A_{eq} = \frac{q_{v, tot}}{c_{d} \cdot \sqrt{\frac{2 \Delta p}{\rho}}}$

Thus the leakage behaviour of the building envelope is described as an area, A_{eq} , producing a certain flow rate q_V , tot, at a certain pressure difference, Δp . The choice of Δp seems to be rather arbitrary. C_d is a coefficient of discharge usually given the value of 0.6. A_{eq} has a constant value in an interval of Δp only if the leakage flow is proportional to the square root of the pressure differences in the interval.

Some researchers use a leakage function, $f_1(\Delta p)$ defined as:

 $q_{v, \text{tot}} = f_1(\Delta p) \cdot \Delta p$

(3.d)

(3.c)

The observant reader realizes of course immediately that this is nothing but an "overall" admittance of a building envelope.

The leaky envelope of a building may be considered to consist of a rich variety of different flow paths from tiny cracks and airpermeable material to relatively large (hidden) openings. It is possible to simulate the air leakage characteristic of a house by assuming arbitrary combinations of different flow paths. For the case of pure crack/duct flow, an example of such a simulation is shown in FIG. 3.a.

Perhaps the most astonishing thing about this simulation lies in a comparison between the leakage rates of different leaks. Though quite long - 20 to 70 running-metres - the narrow cracks No. 1-6 with widths between 0.075 and 1 mm create only minor contributions to the total leakage. Wider cracks, (5 to 10 mm), however, have a substantial influence on the total leakage, even though their lengths are quite small (1 to 5 running-metres).

The total leakage curve of figure 3.a will be analysed in accordance with the four different ways of description reviewed above.

Power function approach

The result of a least squares curve fit to a power function was:

 $q_{v, \text{ tot}} = 0.047 \cdot \Delta p^{0.57} (m^3/s)$

In addition, for each 5 Pa-interval (except the first one - being 1-5 Pa) the exponent β is displayed in the figure.

The exponent, β , was calculated as

$$\beta = \frac{\ln(\frac{q_{v,1}}{q_{v,2}})}{\ln(\frac{\Delta p_1}{\Delta p_2})}$$
(3.e)

Thus the exponent of the potential expression seems to have a rather constant value for all pressure differences. High leakage rates seem to be caused by quite few, large leaks. The dimensions of these are big enough to create either turbulent flow or a flow such as in and outlet effects become considerable. It is obvious that the duct width has a very great influence on the leakage rate. Once a leak of large dimension is introduced:

- o the total leakage rate increases strongly,
- o the exponent β of the total flow curve is altered,
- o the value of β in the total flow curve does not vary much in different pressure difference regimes.

Quadratic equation approach

The result of a least squares curve fit to a quadratic equation was:

 $\Delta p = 16.7 \cdot q_{v, \text{ tot}} + 238.1 \cdot q_{v, \text{ tot}}^2$

which shows that the influence of the second term is considerable.

Equivalent leakage area approach

The equivalent leakage area can be written:

$$A_{eq} = \frac{1}{C_{d} \cdot \sqrt{\frac{2}{\rho}}} \cdot \frac{q_{v, tot}}{\sqrt{\Delta p}}$$
(3.f)

For $C_d = 0.6$ and $\rho = 1.25$ kg/m³ the equivalent leakage area was calculated for different pressure differences. The result is shown in FIG. 3.b.

From the figure it can be seen that at low pressure differences the equivalent leakage area decreases strongly. The value of A_{eq} at 1 Pa differs from that of 50 Pa by around 25%. This is the case even though the exponent formula in the power expression approach was found to be quite close to 0.5. If $\beta = 0.5$ the A_{eq} -value must be constant by definition. For narrow cracks the deviations from a constant A_{eq} value are likely to be larger still, of course.

Leakage function approach

According to definition the leakage function $f_1(\Delta p)$ simply equals the ratio between leakage rate and corresponding pressure difference. The resulting curve for the present example is shown in FIG. 3.c.

Obviously the leakage function varies within a large interval, and it seems to be rather high at small pressure differences. This behaviour was also found in field studies reported from the Lawrence Berkeley Laboratories, Grimsrud et al (1979).

The results may be explained if different basic duct/crack flow cases are studied. The figures 3.d-f are based on calculations of flow rate through ducts of different widths and with different values of total single resistance loss factors.

The figures show distinctly the influence of single resistances such as entrance, bend and exit losses. From figure 3.f in which $\Sigma\xi_{single} = 0$ it is obvious that the leakage function has a constant value until the flow turns over from laminar flow at Re > 2300. This will not happen at all at low pressures provided the ducts are not too large (< 10 mm). Real ducts/cracks in fact have entrances and exits and the flow direction may be changed too. Thus the assumption of $\Sigma\xi_{single} = 0$ cannot hold in practice.

The figures 3.d and 3.e show how different magnitudes of $\Sigma \xi_{single}$ influence the shape of the leakage function curves. Introducing single resistances implies that:

- o the value of the leakage function for a specific crack width decreases
- o the leakage function can become non-linear and non-constant even though Re > 2300
- o the maximum value of the leakage function occurs at $\Delta p = 0$ and equals the value corresponding to the case when $\Sigma \xi$ = 0.

General remarks

The analysis above show that there is a relationship between leak dimensions and degree of discrepancy from linear flow characteristic. Hitherto this has not been taken into account as far as pressurization test practice is concerned. Instead of concentrating the effort on giving a leakage rate value at 50 Pa only, it would be worthwhile to investigate the shape of the leakage characteristic too. If considerable deviations from linearity is observed when the pressurization test is performed, a short time spent on looking around in the house in order to detect some few leak paths with large dimensions could in many cases probably be very profitable.

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FIG. 2.a. Computer program JK-CIRCUS. Flow chart.



DESCRIPTION OF FLOW PATHS :

FLOW PATH NUMBER	1	2	3	4	5
LENGTH IN FLOW					
DIRECTION (m)	0.25	0.225	0.20	0.175	0.15
WIDTH (m)	0.000075	0.0001	0.00025	0.0 005	0.00075
LENGTH (m)	70	60	50	40	30
ROUGHNESS (m)	0.000075	0.00001	0.000025	0.00005	0.000075
FLOW PATH NUMBER	6	7	8	9	
LENGTH IN FLOW					
DIRECTION (m)	0.125	0.10	0.075	0.05	
WIDTH (m)	0.001	0.0075	0.005	0.01	
LENGTH (m)	20	5	2	1	
ROUGHNESS (m)	0.0001	0.00075	0.0005	0.001	

FIG. 3.a. Simulated leakage characteristic of a house assuming crack/duct flow only. $\Sigma \xi = 1.5$.













FIG. 3.d.



FIG. 3.e.

FIG 3.d. - 3.f. Air flow through ducts of different widths with length 0.2 m in flow direction for different single resistance values from 0 to 3.5.

FIG. 3.f

PAPER 10

AIR INFILTRATION SITE MEASUREMENT **TECHNIQUES**

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AIR INFILTRATION SITE MEASUREMENT TECHNIQUES

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Abstract

A summary of the existing types of air infiltration measurement techniques and instrumentation using tracer gases is presented. Automated air infiltration instrumentation used by researchers in the United States, Canada, the United Kingdom, Denmark, Sweden and Switzerland are described. The equipment can operate in the dilution (decay) mode, constant flow mode and the constant concentration mode. Most of these instruments are microcomputer or microprocessor based and capable of performing real time determination of the air infiltration rate in multizone buildings and monitor the state of additional parameters such as temperature, wind speed and energy consumption. Two simple techniques, the air bag or container method and the average infiltration monitor, developed by researchers in the United States are summarized.

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1.INTRODUCTION

The important missing ingredient in the energy use analysis of buildings, from the smallest house to the largest building complex, is often the energy lost to ventilation and air infiltration. It is not that measurement methods are unavailable, but rather that the importance of the air exchange measurement has not been given proper emphasis in the past. The subject of this paper is to provide a perspective as to where we stand today in air exchange measurements on site and to provide an overview of where we may be heading in this rapidly advancing field.

At the First Air Infiltration Centre Conference [1] it was evident that research groups were working with two air infiltration measurement techniques -pressurization and tracer gas. Both techniques had received wide acceptance and had been used together or separately by the groups in field studies.

The simpler method relies on pressurization of the building to supply information on the relative tightness of the building, and with the addition of ancillary equipment such as infrared imaging systems or smoke injection techniques, leakage site determination. To achieve the pressurization/depressurization of the building, a fan system of various forms can be used. Access to the building is usually gained by replacing a door or window with a panel through which a measurable flow is induced. Vital to the approach is the accurate measurement of air flow which may be achieved by an on-site measurement device attached to the fan or by calibrating the fan in the laboratory and using the rate of rotation and pressure difference across the fan to determine the volumetric air flow. To use the data from this test method for predicting the air infiltration under natural conditions, additional data such as the site location, building details and weather data are required. Thus a model is an integral part of this approach in order to arrive at reasonable predictions of what level of natural air infiltration will occur in the building. Such a model has been developed by the researchers at Lawrence Berkeley Laboratory (LBL) and other laboratories [1]. Field testing of the model has been encouraging in many instants.

The tracer gas technique is the method most widely used for determining the actual air infiltration rate at a specific instant of time in the building. The use of a tracer gas, as the name implies, provides a method by which the air in the building can be tagged and thus

identified so that an accounting can be made as to how much outdoor air replaces it. Only a small quantity of tracer gas is required, usually at concentrations in the parts per million, parts per billions and sometimes in the parts per trillion range. A wide choice of tracer gases is available today but based on the criteria of detectability, safety, simplicity, quantity and cost certain gases have proven to be preferable. Some common choices are sulphur hexafloride (SF₆), nitrous oxide (N2O), carbon dioxide (CO2), and ethane (C2H6). This paper discusses the various types of methods and equipments now in use in various parts of the world for the measurement of air infil[^]tration by the tracer gas technique. Automated equipment for measuring the air infiltration rate by the decay (dilution) method, the continuous flow method and the constant concentration method developed by laboratories in the United States, Canada, the United Kingdom, Sweden, Denmark and Switzerland are described. Two simple and inexpensive techniques developed in the United States which do not require the deployment of on-site gas monitoring equipment are described. The first, called the air sample bag or container method, uses air grab samples collected after the injection of the tracer and which are analyzed in the laboratory for determination of the air infiltration rate by the The second method, called an dilution method. averaging infiltration monitor (AIM) by its developers at LBL, uses a constant injection/constant sample techinque to provide a measure of the average air infiltration rate experienced by the building over an extended period of time.

2. THEORETICAL BASIS FOR THE MEASUREMENT TECHNIQUES

The theoretical basis for the tracer gas measurement techniques lie in the continuity equation:

 $\frac{dC}{dt} = (C_0 - C) \frac{v(t)}{V} + f(t)$ (1)

where: C₀, C are the outdoor and indoor concentrations of the tracer at time t v(t) is the rate at which the air enters (or leaves) the building f(t) is the rate per unit volume of production (or absorption) of the tracer gas inside the building V is the volume of the building. The quantity v(t)/V is the air exchange rate of the building (AI) usually expressed in air changes per hour. Equation 1 is nothing more than a global conservation of mass equation for the gas tracer. However, it is based on the important assumption that the building is a single chamber in which the tracer gas concentration is uniform throughout; i.e. there is perfect mixing. A discussion of the errors in the determination of the air infiltration using equation 1 when the mixing is not uniform can be found in reference [2]. For building evaluations the tracer gas is always chosen such that $C_0 = 0$. Equation 1 can be solved exactly to give:

$$C(t) = C_1 \exp \left(- \int_{t_1 V}^{t} \frac{v(s)}{v} ds \right) + \int_{t_1}^{t} Q(t,s) f(s) ds \quad (2)$$

where:

$$Q(t,s) = \exp(-\frac{\int_{t}^{t} \frac{v(y)}{t_1 V} dy)$$

and $C_1 = C(t_1)$.

Decay (Dilution) Method

In the decay (dilution) method the tracer gas is injected at certain intervals of time, allowed to mix and the decay of the tracer is observed. In this case f(t) = 0 and the solution 2 reduces to:

$$C(t) = C_1 \exp(-\int_{t_1}^{t} \frac{v(s)}{v} ds)$$
 (3)

Therefore the average air infiltration rate in the period (t,t_1) can be obtained from the relation:

$$AI(t,t_1) = \frac{1}{DT} \ln (C_1/C)$$
 (4)

where $DT = t-t_1$

In most applications v(t) is almost constant in the interval on measurement (t,t_1) and the decay of the tracer gas is approximately exponential (see figure 1).

Constant Flow Mode

In the constant flow mode of tracer gas measurements, the injection flow rate f(t) is specified at a known constant value F. In this case the solution 2 to the continuity equation reduces to:

$$C(t) = C_{1} \exp(-\int_{t_{1}}^{t} \frac{v(s)}{v(s)} ds) + F \int_{t_{1}}^{t} Q(t,s) ds$$
(5)

In general there is no simple way to solve (5) for v(t); however in most applications v(t) is treated as a constant Q and equation (5) reduces to:

$$C(t) = \frac{F}{Q} + (C_{1} - \frac{F}{Q}) \exp[-\frac{O}{V}(t-t_{1})]$$
(6)

For times $t >> t_1$, equation (6) becomes the simple relation:

$$Q(t) \simeq F/C(t)$$

It should be pointed out that equations (6) and (7) are strictly valid only for constant air infiltration rates Q.

Constant Concentration Mode

The reason that many researchers are using the constant concentration mode comes from a multichamber treatment of tracer movement in a building. The continuity equations in this case for the tracer concentrations $C_i(t)$ in the ith chamber are [3,4]:

$$\frac{dC}{dt} = \frac{v_i}{v} C_i + \sum_{i \neq j} v_{ij} (C_i - C_j) + f_i$$
(8)

The terms v_i represent the air infiltration from the exterior into the chamber and the terms v_{ij} are the flow rates from the jth chamber to the ith chamber. Due to stability difficulties in using the solution to equations (8) for determining the coefficients v_i and v_{ij} , these flow rates cannot in practice be determined by measuring the concentration decays in each chamber with a single tracer gas [4]. This can only be done using multitracer gases and still some knowledge as to the direction of the interroom air flowsis useful. However, if one can kept the concentrations in each chamber the same and at a constant level by controlling the injection flows f_i , then the air infiltration rates

into each chamber can be determined by

 $v_i/v = f_i(t)/C_0$

(9)

where C₀ is the constant level of tracer concentration. Thus the air infiltration rate is determined by measuring the amount of tracer injected into each chamber required to maintain a constant level. The major criticism of this mode of using a tracer gas is that there is no stable control scheme which will do this [3] and therefore the level of tracer is never really constant.

3. AUTOMATED TRACER DECAY EQUIPMENT

Automated air infiltration measuring equipment using the tracer decay method has been developed by researchers at the National Bureau of Standards (NBS) and Princeton University and have been in use since 1974 in the United States. These systems use an electron capture gas chromatograph which can measure SF6 in the ppb range. The earlier versions of these systems used mechanical sequencing timers to control the sampling and injection and recorded the output on a strip chart recorder [5,6]. Later electronic control circuits replaced the mechanical timers and an electronic peak detector was incorporated into the unit and thedata were recorded on a magnetic cassette in ASCII code [7]. Figure 1 shows a sample of data collected by this equipment in a seven storey administration building at Princeton University. The latest version of this series of equipment consists of a S-100 Buss microcomputer with two 5 1/4 inch dualsided floppy disc drives, a real-time clock, a CRT terminal, an electron capture detector gas chromatograph, a ten port sampling manifold, five injection units and interfaces for both analogue and digital data [8]. This system has been used in air infiltration studies in large buildings. Figure 2 shows a schematic of a twenty-six storey, 450,000 m³ office building in which air infiltration measurements are being made. Two such systems are deployed in this building. One measures the air infiltration rates in the tower (floors 3 to 26) portion of the building and is located in the mechanical equipment room of the 26th floor. The sampling network for this sytem is shown in figures 3 and 4. This system also measures the outdoor environment from a local weather station on the roof and the interior temperatures on each of the sampled floors. An exterior pressure measuring system will be added to this instrumentation. The second system is located in the lower mechanical equipment room and monitors the four lower zones of the building and the adjacent four storey Plaza Building. A typical trace of data from the tower is shown in figure 5. Injection occurrs 10 minutes before each hour. Note that the tracer is fairly well mixed after twenty minutes. Figure 6 shows the average daily air infiltration rates for the months of April and May of 1981. Days on which there are no data are usually weekends or holidays when the HVAC systems in the building are not operating. These air infiltration measuring systems have operated 18 days without human attention and 30 days without loss of data.

Hartman and Muhlebach [9] of the Swiss Federal Laboratories for Material Testing and Research have designed a tracer decay system controlled by a special controller. Data from this unit is analyzed off line on a central computer. This system uses N_{20} as a tracer and an infrared analyser (MIRAN) operating in the 10 to 20 ppm range. This system can handle up to six rooms and also measures air temperature, humidity, wind velocity, wind direction and wind pressure.

4. CONSTANT CONCENTRATION TRACER GAS EQUIPMENT

Automated air infiltration measuring equipment using the constant concentration method has been developed in the United Kingdom, Denmark, Sweden and Canada. The U.K. automated air infiltration unit called Autovent [10] developed by Alexander, Gale and Ethridge of British Gas to acheive constant tracer gas concentration is based upon a microprocessor and a rapid analysis of the individual samples. The $\rm N_2^O$ detector with a two second rise time allows that a room or zone may be analyzed every 6 seconds. The sampling is through tubes of equal length and the recorded concentration value (together with the previous reading) is used to vary the amount of N₂O injected prior to the next sampling. The nominal concentration is maintained at 50 ± 2 ppm. Injection takes place for durations up to half of the period (to a maximum of 30 seconds) between samples. Each of the injection lines is calibrated prior to the experiment so that the injection rate can meet local needs. The range of air infiltration that can be accomodated after calibration is from four or five to one. This equipment has been used over a period of almost two years with up to 12 rooms measured simultaneously. Overall accuracy of 10% is reported. Six houses have been carefully analyzed using this equipment. Futhermore, the analyzer has a second channel allowing CO₂ tracer gas analysis. Using two tracer gases simultaneously, exchange rates from the living area to the attic have been determined.

The Danish automated air infiltration system is microcomputer based and has been developed by Collet and McNally of the Institute of Technology in Taastrup. There are many similarities to the U.K. system in this new research effort focused on occupant activities such as opening and closing of windows and doors and their effect on air change rates in each of 10 rooms in a house south of Copenhagen. The injection of N2O can take place essentially on a continuous basis, hence more than 10 to 1 variations in air change rates can be accommodated (from a few tenths to five or more air changes per hour with an accuracy varying from ±5% to +10%). Small (12 cm dia.) silent fans are spotted near the N₂O injection port in each room to promote rapid mixing of the tracer gas. Ten solenoid values are used to control injection, and another ten control sampling to the URAS-7N infrared detector. The experimental design also provides a tank of N2O reference gas at 48 ppm to periodically check the design value of 50±2 ppm N2O concentrations within the home. Temperature and hūmidity sensors are being added to further increase reading accuracy. Since the study emphasizes occupancy effects, the tubing that runs throughtout the house has been kept as unobtrusive as possible (only 3-4 mm dia.). At the doorways metal tubes near the hinge are used to provide the tubing paths so that the door operation is unaffected. The N₂O injection orifices for each room were carefully designed to provide choked flow and were subsequently calibrated. The system can operate for up to six days unattended. Records are maintained on floppy disc, with a viewing screen provided to check on-site operation. Also a statistical package can be used on site to further provide system checks.

The use of similar concepts to measure air infiltration automatically have been used in the Swedish unit for tracer gas measurements reported by Pettersson of the Swedish National Testing Institute. The short response time of the N_{20} analyzer has made it possible to collect a large number of samples per unit time. In the case of field measurements on a variety of buildings the problem of the two hour equipment warm-up time for the URAS-7N analyser has been solved by a 12V/220V transformer in the instrumentation van and warming up is accomplished in transit. An alternate MIRAN 101A analyzer requires 10 minutes or less to warm up. The arrangement of the 10 tubes to the analyzer allows 9 air samples and one fresh air purge. The fresh air must be raised to room temperature to avoid analysis problems. The pumping system moves the samples to the analyzer through 10 meter long, 6mm diameter plastic tubes within the house. When operated from the van, special 25 meter tubing is used to thermally insulate

the enclosed 9 plastic tubes. The measurements are made at a certain definite frequency, treated by the microprocessor, and recorded as air changes per hour for the individual points.

Up to this point the emphasis in this section has been on the use of N₂O as the tracer gas. Dumont of the Natinal Research Council of Canada reports on a Canadian constant concentration air infiltration apparatus that is based on SF₆ as a tracer gas and used an electron capture gas chromatograph. The apparatus has been functioning for three years and is now available as a commercially packaged unit [1]. The unit has demonstrated the ability to hold SF_6 concentrations in a house constant to within $\pm 4\%$ over 15 minute intervals and ± 2 % over a one-hour interval. The controller feedback loop uses a proportional plus integral action. Unattended the unit has run 72 hours. Operating in the "sample" mode using the ITI detector, generally a level of 15 ppb of SF_6 is maintained. Consequently, the amount of tracer gas used during an experiment is very small. At the start of the experiment, it usually takes about 1 hour to reach the desired setpoint level of SF6. To date more than 20 houses have been tested using this equipment.

The major weakness of the apparatus has been in the operation of the detector. With the very high usage that it is subject to, the column and the electron capture detector require considerable maintenance, cleaning and calibration. Zero drift of the detector is an ongoing problem. In addition, the switching valve, which uses a spool valve arrangement with O-rings, requires maintanence. Small leaks from the pressurized SF₆ supply have also been a source of difficulty. Normally the equipment is placed within the house being measured and consequently small SF₆ leaks will give a false indication of the air change rate. Comparing experience with other investigators, the maintanence problems sited here tend to favor a choice of infrared equipment if the higher concentrations (50 ppm range) are tolerable.

5. CONTINUOUS INJECTION TRACER GAS SYSTEM

Continuous infiltration monitoring system using the continuous injection mode has been developed at Lawrence Berkeley Laboratory in the United States to permit automated measurement of infiltration in a test space at half-hour intervals. This design decision was based upon stability considerations in the feedback loop of the controller. This unit originally used N₂O with an infrared analyser but later, due to

environmental requirements in the U.S., was modified to use SF6 with an infrared analyser. The system was designed to permit researchers to carefully examine the mechanisms that drive infiltration, i.e. the effects of weather and mechanical systems. The system is designed around a microcomputer that (1) controls the injection of tracer into the test space, (2) selects the sampling port used during an interval, (3) processes and records weather and system operation data, (4) calculates and records half-hour average infiltration values and (5) computes a new injection flow rate based upon the calculated infiltration to keep the concentration level in the test space within a particular target range. The calculation of infiltration is made using equation (6). In practice equation (6) is solved numerically by the microcomputer using a search algorithm that finds the set Q, C1 and V having maximum likelihood consistent with the measured values of C and F for the time interval. The flow rate is then increased or decreased to a new value for the next half-hour interval to keep the concentration within a particular range.

6. SIMPLE AND LOW-COST TRACER GAS TECHIQUES

In an effort to develop simple and inexpensive methods which can be used by inexperienced personnel, researchers in the U.S. have developed two techniques which can determine the natural air infiltration rates with a minimal effort. The main reasons that the tracer gas methods are complicated and expensive are: (1) the concentration monitoring equipment is costly, (2) its use requires highly trained technicians, and (3) the duration of the test is usually 2 to 4 hours. However, if one is not interested in a detailed history of the air infiltration rate, but wants only the total air exchange rate over a period of specified time, then it is possible to remove the tracer gas monitoring equipment form the field site and use air sample bags or containers to collect the concentration levels of the tracer at specific instants [7-11]. This method has been used by NBS to evaluate the air infiltration rates in a national sample of over 200 homes in the United States. The method is shown schematically in figure 7. The tracer gas (SF6) is initially injected into the dwelling using syringes. After a mixing time of about 1/2 hour, an initial air sample is taken on each storey of the building. The tracer gas is allowed ot decay for a period of 1 to 2 hours and a second set of air samples is taken on each storey. The air samples are shipped to a laboratory and analyzed for their concentrations. The air infiltration rate is determined by equation (4). Figure 8 shows the results of these tests for the first heating season of the project [12].

For comparison figure 9 shows the induced air flow at 50 Pa for the same set of homes. Princeton University has also used this method in their field studies. The individual floor readings in figure 1 were obtained by this method. During the performance of this test, local weater data are usually recorded. The secret to implementing this procedure successfully are: (1) developing an accurate and simple identificatin label for each container, (2) slow and uniform injection of the tracer, usually accomplished by having the person performing the test walk slowly around the dwelling gradually depressing the syringe while waving his arms and (3) obtaining an integrated sample by walking around each storey slowly filling the air sample container. The accuracy of the method is assured by waiting more than 1 hour between samples [13].

An average infiltration monitor (AIM) has been developed at LBL to permit simple, unattended measurement of the long-term infiltration rates of a house. This monitor produces a measure of the average air infiltration rate of the house during the time the equipment is in the dwelling. Typical long-term infiltration measurements require significant amounts of patience on the part of the building occupants. In addition, standard long-term systems require skilled personnel for installation. The AIM system minimizes both the inconvenience to the occupant and the technical skills required to install the system. The AIM consists of two small suitcases, outwardly identical, called an injector and a sampler. Each contains a small positive-displacement solenoid pump that is pulsed at a rate controlled by an internal timer. The pump connected to gas sample bag, is either slowly emptied, injecting tracer gas into the space to be tested, or filled, sampling the mixture of tracer gas and room air present in the space. Using equation (7), the average air infiltration rate can be determined by measuring the concentration in the sample bag. A determination of the concentration of tracer gas collected in the sample bag is a measure of the time average concentration over the duration of the test; knowing the the time interval of the constant injection and the total volume of tracer gas injected into the test space gives the injection rate, F. It is important to note that the AIM system measures the total ventilaton rate. This means that ventilation changes due to occupant behavior (using mechanical spot ventilation, opening windows, etc.) are included in the measured air exhange rates. Consequently, combining the AIM mesurement system with fan pressuriztion tests of the building tightness (which can be used to predict the infiltration of the closed shell of the structure) allows a researcher to extract information about the occupancy contribution to the ventilation in the

building.

7. CONCLUSIONS

The state of the art in measuring air infiltration in buildings has progressed rapidly in the last several years and it is now possible to measure the air infiltration rate in a building by means commemsurate with the effort required to determine the other parameters which influence the energy performance of the building. It is possible to deploy automated air infiltration monitoring equipment which automatically collects and analyzes air infiltration rates using microcomputer and microprocessor based equipment. It is also possible to use low-cost methods in audit type applications for determining the air infiltration in large samples of buildings.

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Figure 1. Decay Mode Tracer Concentrations in Test of Seven Storey Administration Building at Princeton, University







Figure 3. Schematic of Sampling Network for Tower of Park Plaza Building







Figure 5. Typical Sequence of Test Data From Tower of Park Plaza Building.



Figure 6. Daily Average Air Exchange Rates For Park Plaza Building.



Figure 7. Schematic of Air Infiltration Measuring Technique Using Air Sample Containers.



Figure 8. Histogram of Air Infiltration Rates in Homes in CSA/NBS Weatherization Demonstration Project.



Figure 9. Histogram of Induce Air Exchange Rates at 50 Pa in Homes in CSA/NBS Weatherization Demonstration.
PAPER 11

LONG-TERM INFILTRATION MEASUREMENTS IN A FULL-SCALE TEST STRUCTURE

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INTRODUCTION

Researchers, for some time, have been working on the problems of measurement and modeling of infiltration in residential structures. Basic research, however, has been hampered by the lack of long-term data from a fully-instrumented, full-scale structure. The Mobile Infiltration Test Unit (MITU) was designed and built at the Lawrence Berkeley Laboratory (LBL) to meet such a need. MITU spent the 1980-1981 winter in the field collecting the data required for infiltration modeling. This data includes: measured infiltration rates, surface pressures, wind velocities, indoor and outdoor temperatures, leakage area and leakage distribution.

Analysis of the MITU data has allowed us to, (1) evaluate models of envelope leakage using surface pressure and infiltration data, and (2) evaluate a model which uses the concept of effective leakage area, along with weather data, to predict infiltration rates.

MITU TRAILER

MITU¹ is a commercially available construction-site office trailer that was modified and instrumented by researchers at LBL. Illustrated in Figure 1, MITU is a portable self-contained test structure designed to perform extended infiltration field studies in a variety of climates, allowing complete control of building parameters and site parameters. It is instrumented to provide for validation of both long-term average and hour-by-hour infiltrationmodel predictions. The trailer is also designed to test various components of the model individually (i.e., translation of airport wind data into wind at the structure, reduction of wind-induced pressures due to localized shielding, etc.).

MITU is a wood-frame structure, 4.9 meters (16 ft) long, 2.4 meters (8 ft) wide, and 2.4 meters (8 ft) high. It contains both heating and cooling systems and requires only electrical power from each site. The walls and floor of the trailer contain a total of sixteen window openings that can be fitted with interchangeable calibrated leakage panels for controlling total leak-age, leakage distribution, and leakage type (i.e., narrow cracks, large holes). The trailer shell is sealed with a continuous vapor barrier, and perforations are caulked with silicone sealant to minimize the leakage. The leakage of the panels and the trailer shell are determined with a specially designed fan pressurization system that fits into one of the window openings and measures air flow using an orifice plate.

Air infiltration, weather data, and surface pressures are sampled, reduced, and recorded on floppy disk by a Z-80 microprocessor-based computer.

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<u>Air infiltration</u> is monitored with the Continuous Infiltration Monitoring System (CIMS) developed at LBL.² This system computes and stores half-hour average infiltration rates.

Windspeed and wind direction are measured at two heights, 5.5 meters (18 ft) and 10 meters (33 ft) above the ground. The sensors are mounted on collapsible weather towers that are permanently affixed to the rear of the trailer. Outdoor temperature is monitored by a sensor mounted 7 meters (23 ft) above the ground. Speeds, directions and temperatures are checked every 10 seconds and recorded on disk as half hour averages.

Surface pressures from 82 taps located on the walls, floor and ceiling are measured with differential pressure transducers. Taps are opened and closed by computer-controlled solenoid valves. During sampling, each tap is kept open for ten seconds. The pressure signal, sampled 40 times per second, is electronically filtered using a one-second time constant in order to eliminate any ringing in the pressure lines due to solenoid operation. The pressures are monitored with pressure transducers on six levels. Four of the transducers are on the walls at 0.23m (0.75 ft), 0.90m (2.95 ft), 1.57m (5.15 ft) and 2.24m (7.35 ft) above the floor of the trailer, while the remaining two transducers are for the ceiling and floor. All pressures, including inside pressure (measured with an additional transducer), are measured relative to a pressure reservoir that communicates with indoor pressure with a two minute time constant. This system allows for direct measurement of stack-induced pressures and the height of the neutral level. The zero of each transducer is checked every thirty minutes and subtracted from the surface pressures, which are then stored as thirty-minute averages.

LEAKAGE MODELS

The most important factor for determining natural infiltration is the resistance of the building shell to air flow. The flow resistance, or leakage, is measured with a technique known as fan pressurization. This involves pressurizing and depressurizing the structure to known pressure differences and measuring the resulting flow response. In order to determine the curve relating the pressure drop across the envelope to the flow that it induces, the flows at each pressure differential are plotted on log-log paper. In the pressure region used (10 to 60 Pa) the data generally form a straight line; i.e., the data are well represented by the empirical (power fit) relationship:

$$Q = K \Delta p^{n} \tag{1}$$

where

Q is the volume flow rate of the fan $[m^3/s]$,

K is a constant,

- $\underline{\Delta} P$ is the absolute value of the pressure drop across the building envelope [Pa] , and
- n is an exponent in the range 0.5 < n < 1.0.

Researchers at LBL characterize the flow resistance of the cracks and openings in the building shell in terms of the effective leakage area. The concept of effective leakage area approximates flow resistance using square-root flow; i.e., it assumes that the flow through the apertures in the building shell is similar to orifice flow, where the flow rate is proportional to the square root of the pressure drop across the opening. This implies that the flow through the building shell can be represented by:

$$Q = L \sqrt{\frac{2}{\rho} \Delta P}$$
 (2)

where

 ΔP is the pressure drop across the building shell [Pa],

L is the effective leakage area $[m^2]$, and

 ρ is the density of air [kg/m³].

To use fan pressurization data to determine leakage area, the flows in Equations 1 and 2 are equated at a reference pressure:

$$L = K \sqrt{\frac{\rho}{2}} \left(\Delta P_r \right)^n - \frac{1}{2}$$
(3)

where

K is the graphically determined constant, L is the effective leakage area $[m^2]$, ρ is the density of air $[kg/m^3]$, and

 ΔP_r is the reference pressure [Pa].

The reference pressure we have chosen, 4 Pa, is typical of weather-induced, infiltration-driving pressures.

MITU FIELD TRIP

The Mobile Infiltration Test Unit was stationed in Reno, Nevada for the past winter (December, 1980 - March, 1981). The site was chosen for its low temperatures, high winds, and lack of shielding from the wind (see Figure 1). During the four-month period, data was collected under a variety of conditions; the quantity, shape and distribution of leakage area were varied, as well as the orientation of the trailer on the site.

INFILTRATION FROM SURFACE PRESSURES

The measured infiltration rates and surface pressure data collected during the MITU field trip can be used to compare the hypothesis of square-root flow to the more exact power-fit leakage model. Since the location and flow characteristics of all of the leakage sites are known, measured surface pressures can be used to predict the flows in and out of the trailer shell. We made these predictions using our square-root flow leakage model (see Equation 2), and using the power fit leakage model (Equation 1) with a flow exponent of 0.65. A flow exponent of 0.65 was chosen for two reasons: the measured flow exponents for the leakage panels were between 0.6 and 0.7; additionally, 0.65 is the quoted flow exponent in many leakage studies. Figures 2 and 3 are plots of measured infiltration, infiltration predicted by square-root flow (n= 0.5), and infiltration predicted with a 0.65 flow exponent. The flows are calculated assuming a normal (Gaussian) pressure distribution over time, using measured mean pressures and standard deviations. Infiltration is determined by integrating flow times the probability density function between zero and positive infinity, while exfiltration is determined by integrating between negative infinity and zero. The plotted curves represent the average of predicted infiltration and predicted exfiltration. In Figure 2, both square-root and power fit predictions track measured infiltration quite well. As one might expect, the flows predicted with a flow exponent of 0.65 exceed square-root flows at high infiltration rates (high pressure differences), and are lower than square-root predictions at low infiltration rates (low pressure differences). In general, at pressure differences below 4 Pa (the pressure at which leakage area is determined), square-root flows will be higher, while above 4 Pa, power fit (n=0.65) flows will be higher. Despite these differences, the square-root and power fit models give very similar results over the course of the test. Although square-root and power-fit predictions show good agreement in Figure 3, they both underpredict considerably during the high infiltration periods near the end of the test. A possible explanation is suggested when one examines a plot of wind direction over the course of the test. During the entire period of underprediction, the wind direction varies between thirty degrees east and thirty degrees west of north. Wind tunnel studies of pressure coefficients on structures with similar aspect ratios have shown that for winds from these angles, the pressure coefficients change sign as one proceeds along the east and west faces. Since the measurement system physically averages the pressures across a given face, it will sum positive pressures with negative pressures, resulting in an underprediction of pressures and therefore flows.

Although they should agree, the <u>average</u> predicted infiltration and exfiltration disagreed by as much as 25% for many data sets. One cause could be an offset in the measured pressure differences, possibly caused by stack effects in the vertical lines connecting the pressure reservoir to the pressure transducers. By adding a uniform pressure offset to the measured pressures it was found that a 0.1 to 0.3 Pa offset (corresponding to a few degrees C temperature difference) resulted in flow equalization for all data sets. Although the difference between infiltration and exfiltration was significantly affected by the pressure offset, the average value did not change.

INFILTRATION MODEL

A residential infiltration model has been developed at LBL^{4,5} using the concept of effective leakage area. It uses building and site parameters to make infiltration predictions from available weather data. The model was specifically designed for simplicity; that is, precise detail was sacrificed for ease of application. The functional form of the model, along with some important assumptions, is presented below.

The basic form of the infiltration model is:

$$Q = L \sqrt{f_s^2 \Delta T + f_w^2 v^2}$$
(4)

where

Q is the infiltration $[m^3/s]$, L is the effective leakage area $[m^2]$, ΔT is the indoor-outdoor temperature difference [K], f_s is the stack parameter $[m/s/K^{1/2}]$, v is the wind speed, and f_w is the wind parameter.

In this expression, f_w and f_s , the wind and stack parameters, essentially convert the wind speed, v, and the indoor-outdoor temperature difference, ΔT , into equivalent pressures across the leakage area of the house. The terms inside the square root actually have the units of velocity squared, i.e., pressure over density. The wind and stack parameters are weather independent quantities that depend upon the distribution of leakage area, the degree to which the house is shielded from the wind, and some geometrical parameters.

INFILTRATION MODEL VALIDATION

Half-hour average infiltration predictions were made for 34 days of data from the MITU field trip, using weather data and appropriate values for each of the model parameters. A compact method of displaying this large data set is with a histogram of the ratio of predicted-to-measured infiltration; Figure 4 shows the distribution of this ratio. Although this plot shows a symmetric (lognormal) distribution about the mean, it also indicates that the average ratio of half-hour infiltration predictions to the measured infiltration rates is 1.23. Although one would like the data to be centered about unity, this mean ratio does not imply that the average predicted infiltration will be 23% high. A histogram of ratios weights all infiltration rates equally, implying that a systematic error at low infiltration rates, although small in absolute value, will have a large effect on the mean ratio. The average predicted infiltration for this data set (1600 measurements) was 34.4 m³/hr, while the average measured infiltration was $32.5 \text{ m}^3/\text{hr}.$

Although the histogram is useful for presenting the entire set, a plot of measured and predicted infiltration against time provides information about the tracking ability of the model. Figure 5 is a plot of air infiltration rate vs. time for a three-day period and Figure 6 displays the results of a four-day test using a different leakage configuration. In both figures, the model predictions track measured infiltration quite well. Although the infiltration rate changes by a factor of ten over the course of the four-day test, the model falls short only at some of the higher Both plots show a slight overprediction at infiltration rates. lower infiltration rates. These results encourage using the model to provide short-term infiltration predictions in situations that require hour-by-hour infiltration measurements, e.g., measurement of the thermal characteristics of buildings, indoor air quality tests, etc.

The data sets plotted in Figures 5 and 6 correspond to the same dates as Figures 2 and 3, respectively. Comparing Figures 2 and 5, the average flow rate predicted by the infiltration model agrees remarkably well with the square-root flow prediction from measured pressure differences. A comparison of Figures 3 and 6 reveals some interesting discrepancies. At high infiltration rates, the infiltration model tracks the measured flow rate quite well, yet both square-root and power fit flows underpredict considerably. The close agreement of infiltration model predictions with measured infiltration rates supports the earlier hypothesis of pressure measurement system inaccuracies as the cause of these underpredictions.

CONCLUSIONS

The Mobile Infiltration Test Unit has been an excellent source of field data, allowing us to carefully examine the problems associated with infiltration in residential structures. Comparisons of measured infiltration rates with values calculated from surface pressures have shown no decrease in accuracy when a square-root flow model is used instead of the general power-fit model of leakage. We therefore conclude that the square-root flow leakage model is preferable to a power-fit model, because of its direct physical interpretation.

The measurement results have clearly demonstrated that great care must be taken when making surface pressure measurements: temporal and spatial pressure averaging can lead to significant errors in infiltration predictions. Additionally, very small temperature differences in the pressure measurement system can cause large apparent disagreements between infiltration and exfiltration. Combining these difficulties with the successful predictions of the LBL infiltration model, we conclude that the determination of infiltration from surface pressures has provided both a validation of the LBL model, as well as a justification for the use of predictive infiltration models.

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Figure 1. Mobile Infiltration Test Unit in Reno, Nevada test site.



Figure 2. Plot of measured infiltration and infiltration predictions from surface pressures vs. time: Three-day test in MITU.





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Figure 5. Plot of measured infiltration and infiltration model predictions vs. time: Three-day test in MITU.



Figure 6. Plot of measured infiltration and infiltration model predictions vs. time: Four-day test in MITU.

PAPER 12

CONTINUOUS MEASUREMENTS OF AIR INFILTRATION IN OCCUPIED DWELLINGS

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Continuous measurements of air infiltration in occupied buildings

The measurement system, developed by the Institute of Technology at Tåstrup, Denmark, is a microcomputer-controlled system for registering air change rates using tracer gas according to the constant concentration method.

The system is designed for measuring and metering tracer gas in up to ten separate rooms. The air change rate to outdoors is measured on the basis of the amount of tracer gas supplied to maintain a constant concentration.

The system operates through automatic data logging on a floppy disc and can run without supervision for extended periods (up to six days).

Background

In conjunction with energy saving measures, both in existing buildings and in new buildings, there is a natural desire to build as airtight as possible.

There has been a considerable amount of measurement of natural ventilation in buildings in Sweden and Denmark but such measurement has been of instantaneous values where outside doors, windows etc have been closed. This does not give any indication of the air change rate when the building is occupied, ie when the occupants open and close windows, go in and out of the building etc.

The prerequisite for being able to measure a building's airtightness in relation to

a: the building's air change rate when occupied

b: the building's content of gases and allergens

c: the building's energy consumption

is being able to measure the true air change rate over an extended period (1-2 weeks) while the building is occupied.

As an example, one could expect that the reason for the differences in formaldehyde concentration in the air and air change rates in Swedish and Danish investigations could be attributed to air change rates not being measured while the building is occupied.

Correspondingly, it can be shown that by making the building tighter, the frequency of the occupants opening windows etc increases so that the effective air change rate is greater than that demanded by the tightness. Thus there is a real risk of increasing the air change rate instead of reducing it.

Design of the system

The measurement system comprises a central unit in which the dosage, control and measurement units are housed (see figure 1).

From the central unit, 2 hoses go to each of the measurement rooms. One hose is used for dosing the gas while the other is used for collecting room air for central concentration control.

The dosing unit:

The dosing unit comprises a bottle of tracer gas (N_2O) , 10 solenoid values, 10 metering jets and a pressure gauge.

The dosage to individual rooms is determined by two parameters:

1. The pressure in the jet.

2. The opening period of the solenoid valve.

To be able to calculate the flow through the jet simply and satisfactorily, the pressure and the jet size are selected so that there is an over-critical flow in the jet's smallest cross section - "the mill". At an over-critical flow, the maximum possible velocity in the mill is the speed of sound.

Over-critical flow is achieved when the ratio between the available pressure and the exit pressure at the jet exceeds approximately 1.9.

When increasing the available pressure in excess of this ratio of 1.9, the mass flow is proportional to the available pressure and independent of the exit pressure.

In other words, when there is over-critical flow in the jet, the mass flow varies linearly with the pressure at the input side (the pressure used is in the region of 3 bar).

The room is dosed every 30 seconds. The dosage time can vary between 0 and 30 seconds but is set so that the minimum dosage is 2 seconds.

The jets used (see figure 3) have a very fine quadratic characteristic. 10×2 second doses provide the same amount of gas as 1×20 second dose.

The measurement unit:

The measurement unit comprises 10 3-way solenoid valves, a Uras 7 n infrared gas absorption detector and a gas suction pump.

The concentration of N_2O in the room air is measured with the aid of a two beam infrared gas absorption detector (see figure 6), and the measurements are expressed as the difference between the absorption of light in the two beams. The reference cell contains nitrogen, which does not absorb light in the measurement range of the detector. The measurement cell contains the gas to be measured. A single measurement takes 30 seconds. Thus if 10 rooms are connected, the tracer gas measurement in the rooms can be determined every sixth minute.

There are two components in the room air in addition to N_2O that absorb light in the detector's measurement range. The effect of CO_2 is removed by inserting a filter in Uras and the effect of moisture in the air is eliminated mathematically.

In order to get "fresh air" in the measurement apparatus a pump is installed which pumps from the hoses not used in the measurement process.

To eliminate drift at the 0 point, a test gas with a 50 ppm N_2O concentration in N_2 is measured at fixed intervals. The measurement apparatus's O drift point'is corrected mathematically.

Control and registration unit:

A microcomputer is used as a control and registration unit (SORD MARK II).

Results

The results of one day's measurements in a house are shown in figures 4 and 5.

The house is of a timber construction on two floors located in $K\phi ge$.

Measurements were taken in all rooms while in use.

Room number	Description	Volume	Window open	Mixing fans
1	Living room	84m ³	No	Yes
2	Kitchen	22m ³	No	Yes
3	Hall	9m ³	No	No
4	Bathroom	9m ³	No	No
5	Stairwell	32m ³	Yes	Yes
6	Bedroom	25m ³	Yes	Yes?
7	Room	38 m ³	No	Yes
8	₩C	7 m ³	To 3	No

The greatest problem encountered during measurement is maintaining a constant concentration of N_2O in rooms.

Different conditions limit the extent to which the concentration can be regulated:

- 1. The facility for mixing air in the room. For example, in bedrooms it is not possible to use mixing fans for mixing the room air at night.
- 2. The rooms are measured at fixed intervals of up to 6 minutes. If a window or door is opened, a certain time elapses before this is registered.

The discontinuation of strong ventilation can result in an extended period of increased concentration in a room.

Figure 2 shows the result of a trial using two different types of control. The momentary concentration of N_2O was measured every minute.

Further development of the measurement system

Futher endeavours to improve the system will be to register temperature and moisture content in parallel with air change rate measurement. This will provide a better illustration of the indoor climate and will permit continual monitoring and correction of the effect of moisture on the URAS 7n.

We also hope to improve the dosage procedure so that even small rooms with a considerable air change rate can maintain a stable concentration of N_2O .



Uras sample: Computer off

FIGURE 1

Design of the measurement apparatus, principle





FIGURE 1a



TI office, room no. 2055 with I and PIA Measurements from a 53m³ adjustment of jets

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FIGURE 2



FIGURE 3







- E Receiver E1 Condenser diaphragm Counter electrode E2 E3 Receiver shutter Filter cell Direct voltage source Measuring cell F GQ Μ MI Analysis chamber Reference chamber M2 R High-impedance resistor St1 Radiation sources St2 Shutter wheel St3 Shutter wheel motor V Amplifier
- N Mains stabilisation

FIGURE 6

Measurements taken while house was occupied on 10-11 September 1981 between 10.00 and 11.00



FIGURE 7

PAPER 13

CHANGING THE VENTILATION PATTERN OF A HOUSE

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CHANGING THE VENTILATION PATTERN OF A HOUSE

By

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1. Introduction

Two series of pressurisation and ventilation measurements have been made in a low-energy house. One of the objectives of the work was to assess the extent to which the ventilation pattern of the house could be improved by modifying its leakage distribution. The first series of measurements was interpreted to understand the ventilation pattern and to make recommendations for the modifications. The second series was used to find out the effects of the modifications.

Throughout this paper the term ventilation rate is used to denote the volume flow rate of air entering a room (or the whole house) directly from outside, divided by the volume of the room i.e. the ventilation rate of the room is the fresh air change rate.

The term stack effect denotes the temperature difference between the inside and the outside of the house.

2. Description of the House and the Measurement Methods

The house, built on split levels on a hillside, is part of a long terrace within an estate. It has a brick outer wall and an insulating block inner wall, with an insulated dry lining. The design heat loss is 5kW and the house is centrally heated by a gas-fired boiler. A plan of the house and its spatial orientation The lowest level contained a utility room are given in Fig.1. and entrance hall. Stairs led to the first landing, the kitchen and lounge; further stairs reached the second landing and the bathroom and toilet, these being directly above the utility room and entrance hall. A third set of stairs extended to the top landing and 3 bedrooms, these being above the kitchen and lounge. There were two separate attic spaces accessible from the bathroom and bedroom 2 respectively. The house was at the end of the terrace and was exposed, in varying degrees, to winds from the East, South and West. The volume of the house, excluding the utility room and internal cupboards which were kept shut, was 160 m⁵. The windows were adequately weatherstripped but that on the doors had deteriorated.

Pressurisation measurements were made on the whole house and on individual rooms using a technique described previously (1). Ventilation rate measurements for the whole house and individual rooms were made using Autovent, the automatic monitoring equipment developed by British Gas for ventilation studies in dwellings (1).

The Autovent apparatus provides detailed information on the volume of fresh air entering each room of the house. By studying this data as a function of measured wind conditions and stack effect and using our knowledge of the leakage of the house and the rooms, we built up a picture of the ventilation pattern. We had precise knowledge of the entry points for fresh air, but exit routes were inferred. The results are described below.

3. Before Modification

3.1. Leakages

The leakage distribution is shown on the left hand side of Fig.2. It can be seen that the biggest measured leakages are in the bathroom, hall and bedroom 1, but the biggest actual leakage was due to the stairwells and landings which was determined by subraction of the measured room leakages from the total.

Smoke flow visualisation was performed during the tests to indicate large sources of leakages. The major leakages in the bathroom were at floor level and around the bath and those in the hall were around the door and door frame.

3.2. Ventilation rates

In all there were 132 separate half-hourly average ventilation rates determined. Of these 122 were for wind directions lying in the range 230° c through North to 180° . For this range it was found that stack effect was a very important determinant of the whole house ventilation rate R_H. A regression analysis of the results showed that R_H was seven times more sensitive to $\sqrt{\Delta T}$ (ΔT is the internal/ external temperature difference, ^oC) than to wind speed U (m/s).

However, for the small range of wind directions from 180° to 230° R_H showed an almost equal dependence on wind and stack effects, and this manifested itself in relatively higher ventilation rates for a given $\sqrt{\Delta}$ T. This directional effect is shown in Figure 2 where R_H is plotted against wind directions for a fairly narrow band of wind speeds and a roughly constant stack effect.

Additional information on the ventilation pattern of the house came from an anlysis of the room ventilation rates. The mean ventilation rates of the hall and bathroom were by far the largest (expressed in room volumes per hour). They were roughly ten times larger than those of the kitchen, living room and toilet. The mean rates in the bedrooms were very low (less than 0.1 h^{-1}). In many instances the bedrooms had no fresh air entry i.e. only air from other parts of the house entered the bedrooms.

4. Modification to leakage distribution

From the results of the first series of tests it was decided that the average of the whole house ventilation rate was probably satisfactory, but the pattern of ventilation was open to improvement. Briefly summarised, the objectives were

- (i) to maintain the average whole house ventilation rate,
- (ii) to increase the ventilation rates in the living room and the bedrooms,
- and (iii) to decrease the ventilation rates in the hall and bathroom.

With these aims in view, the following modifications were carried out.

- (a) All of the rooms and the landing were fitted with (closeable) strip ventilators.
- (b) Gaps in the joins between floors, walls and ceilings in the hall, bathroom and toilet were sealed with tape. The hall door was weatherstripped with durable material.

5. After modification

5.1. Leakages

Figure 2 compares the leakage distribution measured after the modification with that measured before. It can be seen that the total leakage after modification is about 10% less than that measured before. The leakages of the hall, bathroom and toilet have been substantially decreased, whereas the leakages of the kitchen, living room and the three bedrooms have been increased, presumably due to the installation of the strip vents. In the hall, bathroom and toilet the sealing measures were sufficiently effective to more than compensate for the installation of the vents.

5.2. Whole House ventilation rates

Figure 4 compares the values of $R_{\rm H}$ before and after modification, plotted against wind speed. For clarity, no distinction has been made between different wind directions, or between those results which have different arrangements of open vents and open internal doors. These differences are the main reasons for the apparent scatter in the results. All of the results however correspond to the range of stack parameter indicated in Figure 4.

It can be seen that, despite the greater leakage before modification, the whole house ventilation rates have generally been increased by the modifications. These increases are however relatively small when compared to the changes observed for some of the rooms.

FIGURE 1 PLAN OF THE HOUSE SHOWING ROOM VOLUMES



not to scale

FIGURE 2. LEAKAGE DISTRIBUTION BEFORE AND AFTER MODIFICATION



LEAKAGE AT $\Delta P=20Pa$

FIG.3 VARIATION IN WHOLE-HOUSE VENTILATION RATE WITH WIND DIRECTION



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Fig.4 COMPARISON OF WHOLE-HOUSE VENTILATION RATES



Fig.5 COMPARISON OF BATHROOM

VENTILATION RATES






PAPER 14

DESIGN AND CONSTRUCTION OF LOW ENERGY HOUSES IN SASKATCHEWAN

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DESIGN AND CONSTRUCTION OF LOW ENERGY HOUSES IN SASKATCHEWAN

by

H.W. Orr

As a result of the need to reduce energy use there has been an interest on the part of government and some private individuals in constructing super-insulated houses, sometimes called low energy houses. In these houses, thermal resistances of the walls and ceiling are typically RSI 7 (R 40) and RSI 10 (R 57), respectively; special efforts are usually made to keep air infiltration to a minimum.

It should be noted that these are unusual buildings; only two or three hundred such houses have been built in Canada. Thus they represent a small fraction of one per cent of dwellings constructed in this country in the past two or three years. Observation of some of these houses indicates that, when compared with conventional houses, significant reductions in energy consumption have been achieved. Continued observation of their performance and documentation of details of construction constitute an important contribution to the development of housing in Canada.

This report provides some of the background of this development on the Prairies. It describes details of wall and foundation designs that have been used. It does not address the question however of whether these details are justifiable from an economic standpoint.

The dimensions of wall studs in houses are usually governed by structural needs. The amount of thermal insulation required by current building regulations can be fitted into the 89 mm $(3\frac{1}{2}$ -in.) wall space provided by 2 x 4 studs. This space, filled with 24 kg/m³ mineral wood, provides about RSI 2.1 (R 12); taking other wall components into account produces RSI 2.5 (R 14.2).

In the past few years, several innovations in wall design have appeared which provide for greater thermal resistances. In some new houses, rigid insulation, usually 38 mm (1.5 in.) thick, is applied outside of 38 x 89 mm (2 x 4) wall studs. In some others, 38 x 140 mm (2 x 6) studs are used. When filled with mineral wool or equivalent insulation, these produce a thermal resistance of about RSI 3.7 (R 21).

The desire to incorporate still more insulation has led to the development of the double framing system in which two sets of wall studs are used, one at the outside and the other at the inside of the wall. In this way, walls of almost any thickness can be built without adding significantly to the cost of wall framing material. Also, in this system, the studs do not extend through the wall and thermal bridging is therefore reduced.

Studies have demonstrated the importance of a complete air-vapour barrier in controlling wall condensation and heat loss due to air infiltration. Traditionally, air-vapour barriers are placed between the drywall and the studs. Faults in the air-vapour barrier membrane occur at joints at the top of the interior partitions, around floor joists in each floor system, at the top and bottom of exterior walls, around windows and doors, and around penetrations for electrical fixtures and wires, vent stacks for plumbing, and chimneys and attic hatches. These deficiencies can be attributed in part to poor application of the air-vapour barrier, damage by other trades, wood shrinkage and to the design which often makes good application extremely difficult to achieve.

These deficiencies in the air-vapour barrier in walls can be largely avoided in the double frame system. The air-vapour barrier is located at the outside of the structural framing members, thus providing a space for electrical wiring and outlets, and other mechanical installations to be installed without penetrating it. Further, its installation as an integral part of the wall avoids the application problems inherent in the traditional method, and allows detailed inspection of the air-vapour barrier before it is covered.

The double frame system requires construction procedures different from those used for conventional walls. A procedure that has been found in the field to be convenient is as follows:

1. The wall is built in the horizontal position on the house floor. The interior structural frame is constructed first. It is straightened and squared in preparation for the sheathing.

2. The 150 μ m (6 mil) polyethylene is placed on the cold side of the inner frame and laps over the top and bottom plates and end studs (Figures 1, 2 and 3).

3. The sheathing is applied to hold it in place, care being taken to protect the air-vapour barrier when the sheathing is cut to size and to ensure its integrity at window and door openings.

4. The exterior frame is then constructed on top of the sheathed interior wall. Window and door openings are constructed to match exactly the openings in the interior frame. The inner frame provides the structural strength, therefore the outer one does not require structural headers or cripple studs for the windows and doors, or double plates, and can be made of 38 x 38 mm (2 x 2) or 38 x 63 mm (2 x 3) material.

5. When the exterior frame has been completed it is squared. It is then raised onto temporary supports so that the space between inner and outer frames can be set. Plates of plywood, 7 mm (5/16 in.) are used to hold the walls at the correct spacing. They are nailed or stapled to the top and bottom plates to complete the framing of the wall. This holds the frames in their proper, relative positions, and provides final straightening.

6. When the wall is raised to the vertical position, properly located on the floor and nailed in place, it is necessary only to brace the wall at the ends. No further straightening is necessary before putting on roof trusses or floor joists for the next stage of construction. The continuity of the air-vapour barrier is provided by a bead of acoustical sealant, which is added when the polyethylene is applied to the ceiling or over the joist headers for intermediate floors.

The air-vapour barrier is located well away from the inner face of the wall and will be somewhat colder than in more common designs. It has been assumed that at least 2/3 of the thermal resistance should be placed on the cold side of the air-vapour barrier. If the interior stud space contains insulation of RSI 2.3 (R 13) the total resistance of the wall would have to approach RSI 7 (R 40) to achieve this.

In conventional house design, the space between the top plate and the roof is not large enough to allow much insulation to be placed on top of the plate. In low energy houses, high lift trusses are used. Insulation 250 to 300 mm (10 to 12 in.) thick can be placed directly over the plate and still permit air to flow from the soffit into the attic for attic ventilation. Plywood sheathing and/or cardboard soffit baffles, made for this purpose, prevent this insulation from falling into the soffit space. The "high lift" effect is obtained by using trusses 1200 mm (4 ft.) longer than normal or by using specially designed roof trusses.

Basements are used in some cases; in others a crawl space is employed. In both instances large amounts of insulation have been installed. Special designs may be needed for basement walls to accommodate the large amount of insulation and at the same time to meet the structural requirements imposed by horizontal soil pressures.

Three different double stud wall designs are shown in Figures 1 to 3. One or more houses have been built following each of these designs.

Energy consumption data have been obtained for the house represented in Figure 2. It has two storeys, no basement, and a total floor area of approximately 250 m^2 . The estimated annual energy consumption for space heating based on the measured energy input to the house was 35 GJ. The estimated space heating energy consumption for a conventional house of that size would be 210 GJ. Both values are based on 5600 $^{\rm O}$ C heating degreedays - the number measured in the test year. A preliminary report on energy consumptions in other houses of similar type has been prepared.¹

Pressure tests have been carried out on a number of houses, including 21 low energy houses. Nine were of double stud construction with the vapour barrier placed in the wall as shown in Figures 1 to 3. In the twelve other houses, which had been constructed with careful attention to the vapour barrier, it was placed in the normal location -- behind the dry wall. The air leakage rates at a pressure of 50 Pa were compared. For the double stud walls the average leakage rate was 0.78 air change per hour (ach) with a standard deviation of 0.32 ach; for the other houses the average leakage rate was 1.80 ach and the standard deviation was 0.88 ach. For these cases it appears that the double stud design resulted in significantly lower air leakage rates and suggests that air tightness is more easily achieved with this design than with other types of construction.

Construction costs for a double stud wall will be significantly higher than those of conventional houses. Tests indicate that with proper construction practices the expected savings in energy for space heating are achieved. The economics cannot be properly assessed at this time since a simple comparison of construction costs and energy saved does not include the benefits to the country of savings in non-renewable resources or reduced cost to municipal and provincial governments of services required to supply energy to the houses.

Reference

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FIGURE 1 Wall section - grade beam and piling foundation



FIGURE 2 Wall section - pressure treated wood foundation



FIGURE 3 Wall section - concrete wall and footing foundation

PAPER 15

AIRTIGHTNESS IN TERRACED HOUSES

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INTRODUCTION

Testing detached houses using the pressurization technique, applying a negative and a positive pressure, is nowadays an accepted test method. The test is simple to perform and the obtained test results are a measure of the air leakage through the climatic barrier of a building.

When pressurizing a terraced house two kinds of air leakage will be measured; firstly the air leakage through exterior walls, ceiling, and certain parts of the floor over the crawl-space will be measured, secondly the air leakage through walls common with the neighbours i.e. from one apartment to another. These two leakage paths have different signification from an energy point of view.

The air leakage through the facade, the ceiling, and certain parts of the floor is unfavourable because it will result in important energy losses. The indoor climate can also deteriorate if the air leakage is extensive. The air leakage from one apartment to another will however not influence the energy consumption to any noteworthy degree. The air leakage through walls separating apartments is anyway small for normal running conditions. The reason being that as the temperature difference between different apartments is small, the driving forces for air leakage are almost nonexistant.

From an energy point of view it is therefore above all the air leakage through the surfaces of the apartment facing the outside which should be stopped and a pressurization should therefore only include these parts of the building.

Several different methods for only measuring the air leakage through the exterior surfaces have been tried out with varying success. It has been shown that a theoretical determination of the different leakage paths is very difficult because construction techniques and production techniques vary very much.

For certain constructions more attention is paid to sound transmission problems than to airtightness. Other constructions are primarily designed to suit the production techniques of the site. The discrepancy in constructional design is as can be seen large. The Testing Institute therefore chose to develop instrumentation for the simplest principle of measurement. This means that the apartments adjoining the apartment which is to be tested is depressurized or pressurized to the same pressure as the test apartment. No air leakage between the apartments will occur during the test. The only air leakage will be through exterior walls, ceiling and if there is a crawlspace the floor.

INSTRUMENTATION

The instrumentation consists of the following parts: (see figure 1)

- a) Fan with measuring duct for measuring air flows.
- Two fans for obtaining negative or positive pressures in adjoining apartments.
- c) Micromanometer for measuring the pressure difference between the inside and the outside.
- d) Micromanometer for reading air flows.
- e) Three doorleafs with connections for the fans.

The measuring fan (a) is driven by a DC motor and is connected to one of the two measuring devices, which have a range of $0 - 1100 \text{ m}^3/\text{hr}$ and $700 - 4000 \text{ m}^3/\text{hr}$.

The measuring ducts work on the pitot tube principle where the dynamic pressure is measured with a punched cross tube in the air flow and the static pressure is measured at four points on the wall of the tube.

The two pressure supporting fans (b) are axial-flow fans without any air flow measuring device. The micromanometer (c) for measuring the pressure drop across the exterior wall is connected to a manifold with valves. Three apartments can be connected to the manifold. One at a time can then manually be connected to the micromanometer.

The micromanometer (d) is used for measuring the dynamic pressure in the measuring duct. The registered pressure corresponds to a specific air flow.

The micromanometers (c) and (d) can be connected to a x/y-plotter. The doorleaf (e) are made of aluminium frames with reinforced plastic foil. The frames can be expanded with screws in order to tighten against a door frame. The complete instrumentation has been put together in a rig which is located in one of the vans belonging to the Testing Institute.



Figure 1



PROCEDURE

All the openings for controlled ventilation should be tightened before a test can be started. Windows, shutters and exterior doors are closed. The doorleafs are mounted and the fans are connected.

The pressure is then adjusted step by step to +10, +20, +30, +40, +45, +50, +55 Pa. After that the fans are turned around and the pressure is adjusted to -10, -20, -30, -40, -45, -50, -55 Pa. When a pressure has been adjusted in the apartment which is being tested this apartment is disconnected from the micromanometer. One of the adjoining apartments is connected to the micromanometer and the pressure is adjusted to the same pressure level as in the test apartment. The pressure is adjusted in the same way for the other adjoining apartment. The pressure in the test apartment is read once again and adjusted if necessary. When the pressures in all three apartments are equal then the air flow through the fan is registered. The air flow is a measure of the air leakage through exterior walls, ceiling and for certain constructions also the floor above crawlspace in the apartment. The test method is also useful for pressurization of semi-detached houses. In the following results from measurements in two different terraced houses are presented. The results include measurements with and without supporting fans. In house A there is a continuous air/vapor barrier in the envelope. In house B the vapor barrier is non-continuous, but breaks occur at walls separating apartments.

A pressurization test whitout supporting fans in the adjoining apartments was made in test house A (see fig. 2). The test results (3,1 ach at 50 Pa) show that the tested apartment is not very tight, the value is however close to the code value. Next step was to perform a pressurization test with supporting fans in the adjoining apartments (see fig. 3). The result was now 2,5 ach at 50 Pa. The difference in air changes rates (0,6 at 50 Pa) depends on the fact that the supporting pressures prevented any air flow through walls separating apartments from occuring.

The pressurization tests in house B was performed in the same way as in test house A. The two results from house B are close to each other in this case and that is the point (see fig. 4 and 5). In test house B the air/vapor barrier in the exterior walls is cut and folded into the joint between the exterior walls and the apartment separating walls. The results show that the air/vapor barrier does not cover the part of the apartment separating wall wich is part of the exterior wall. This design principle for wood frame house cause serious air leakage to occur.

The test method described above could be a helpful tool to point out leaky constructions. It could also change the design principals to either constructions with continuous air/vapor barrier or construction where each apartment is a separat unit seen from an airtightness point of view.

A continuous air/vapor barrier must cover all the inside of the wooden frame i.e. apartment separating walls must be connected to the inside of the exterior walls. This will mean just a minor change in the production methods of today and it is probably the simplest way to reach the goal 2 ach at 50 Pa wich was the primary recommendation given in the Swedish Building Code.



+ = pressure, - = depressure Volume of building: 297 m³ Indoor temperature: +15 °C Outdoor temperature: +15 °C Average airflow at 50 Pa: 911,2 m³/h Air changes per hour at 50 Pa: 3,1

FIG 2



+ = pressure, - = depressure Volume of building: 297 m³ Indoor temperature: +15 ^OC Outdoor temperature: +15 ^OC Average airflow at 50 Pa: 753,2 m³/h Air changes per hour at 50 Pa: 2,5

FIG 3





+ = pressure, - = depressure Volume of building: 290 m³ Indoor temperature: +15 ^OC Outdoor temperature: +15 ^OC Average airflow at 50 Pa: 982,4 m³/h Air changes per hour at 50 Pa: 3,4



+ = pressure, - = depressure Volume of building: 290 m³ Indoor temperature: +15 ^OC Outdoor temperature: +15 ^OC Average airflow at 50 Pa: 925,5 m³/h Air changes per hour at 50 Pa: 3,2

PAPER 16

AIR LEAKAGE THROUGH CRACKS

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AIR LEAKAGE THROUGH CRACKS IN CONCRETE ELEMENTS

(Summary)

Alf Jergling

1. INTRODUCTION

A desired restraint of energy use in buildings makes demands upon the tightness of the house envelope. Swedish Building Code gives the maximum values of allowed ventilation rates in buildings. Concerning building components maximum values are given without further statements of the construction of the component. The building material concrete is applicable for wall constructions in one-family houses as well as in blocks of flats, at which air exchange at normal pressure differences between the inner and the exterior side of the wall occurs only through cracks in the concrete material (windows etc are disregarded here). Of great interest is therefore the knowledge of leakage rates through cracks in concrete structures. This investigation deals partly with leakage through cracks in concrete elements, partly with cracks in joints between concrete elements.

2. EXPERIMENTAL INVESTIGATION

2.1 Test equipment and test methods

Determinations of air leakage dependence on pressure difference, crack width and crack depth have been carried out on laboratory manufactured test specimens and on test specimens composed of parts from prefabricated concrete elements. The solid concrete specimens were made in the dimension 300 x 500 mm and the different thicknesses 100, 150 and 200 mm. The prefabricated elements constituted standard elements with thicknesses 150 and 265 mm. Tha magnitude of the air leakage at different pressure differences was determined for cracks through the concrete specimen and for cracks in joints between concrete elements. Measurements were made for crack widths 0.1, 0.3, 0.5 and 0.7 mm and pressure differences 25, 50, 75, 100, 300 and 500 Pa. Air leakage through cracks in solid concrete elements with thicknesses 100, 150 and 200 mm was determined by mean of a test equipment. fig. 1. Some of the test results are shown in fig 2, where the mean values for



Fig. 1 Test equipment

- (1) pressure box
- (2) slot
- (3) micromanometer
- (4) flowmeter
- (5) U-tube (manometer)
- (6) pressure regulator
- (7) connection with compressed air
- (8) specimen



Fig. 2 Air-flow through cracks in 100 mm solid concrete elements, mean values for all measurements (hatching denotes 95% interval)



Fig. 3 Crack surfaces of 100 mm concrete element

The crack width in a test specimen was changed in three steps from 0.1 mm to 0.7 mm, through which the crack surface has to change its appearance, fig. 3. The variations of air leakage rates for different crack widths are illustrated in fig. 4.



Fig. 4 Relationship between air leakage and crack width for element thicknesses 100 mm.

2.3 <u>Air leakage through cracks in joints between prefabricated con-</u> crete elements

Air leakage through cracks in joints between concrete elements was determined for both 150 mm wall elements and 265 mm floor components. The test results for joints between wall elements show the same pictures of the relations between air leakage and pressure as in 2.2.

3. ANALYTICAL DETERMINATION OF AIR FLOWS THROUGH CRACKS

3.1 General expressions for the air-flow

The course of the flow through a concrete crack is complicated. A fictitious "tube of flow" has irregular shape and area, some parts of the boundary area touch upon concrete, some parts border on more or less stationary air.

Air-flow through a slot is often estimated by the simple expression

$$q = C_0(\Delta p)^n \tag{3.11}$$

Eq. (3.11) is based on a rough picture of pressure conditions for airflows through cracks.

The pressure difference across a crack is obtained from pressure losses at entrance and exit, which together with friction losses yield a relation of the form

$$\Delta p = \xi_1 \lambda \left(\frac{t}{d_h}\right) \frac{m_\rho v^2}{2} + \xi_2^{\frac{1}{2}} \rho v^2$$
(3.12)

where ξ_1 , $\xi_2 = 1$ oss factors

In this investigation the tubes of flow have irregular shapes and the crack surfaces are very rough, wherefore the loss factors ξ_1 and ξ_2 have been introduced. Eq. (3.12) can be transformed into

$$\Delta p = A_{b_3}^t q + B_{b_2}^1 q^2 \text{ or } q = \frac{At}{2Bb} \left[\sqrt{1 + \Delta p} \frac{4Bb^4}{A_t^2} - 1 \right]$$
(3.13)

Calculations according to eq (3.13) give approx. for air leakage through cracks in oncrete

q = 14
$$10^{6} \frac{b^{3}}{t} \Delta p$$
 för b = 0.1 10^{-3} m (3.14a)

q = 0.010
$$\frac{t}{b}$$
 k $\left[\sqrt{1 + \Delta p \frac{b}{t^2}} + 1.5 + 10^9 - 1\right]$ (3.14b)

for
$$0.3 \ 10^{-3} \le b \le 0.7 \ 10^{-3} \text{m} (q \ m^3/\text{mh})$$

where
$$k = 1$$
 for $t = 0.10$ m
= 0.85 for $t = 0.15$ m
= 0.7 for $t = 0.20$ m
b = crack width

Eq (3.11) gives n-values between 1.0 to 0.882.

For air leakage through joints between concrete elements (t = 150 mm) eq 3.13 gives

$$q = 10^{-3} \frac{k}{b} (\sqrt{1 + 220 \ 10^9 b^4 \Delta p} - 1) \ m^3/mh$$
 (3.15)

where k = 1 for $b = 0.3 \cdot 10^{-3}$ m k = 0.7 for $0.5 \cdot 10^{-3} \le b \le 0.7 \cdot 10^{-3}$ m

Eq (3.11) gives in this case n-values between 0.996 to 0.778. Eq (3.14) and (3.15) fit the curves of test results with a good accuracy.

4. ESTIMATION OF CONCRETE STRUCTURES ACCORDING TO DEMANDS OF TIGHTNESS IN SWEDISH BUILDING CODES

According to Swedish Building Codes a building must have a satisfactory degree of airtightness. For building with ≥ 3 storeys the maximum air exchange rate is $0.2 \text{ m}^3/\text{m}^2\text{h}$ for 50 Pa, which corresponds to $1.8 \text{ m}^3/\text{h}$ for an assumed wall area of $3.6 \times 2.5 \text{ m}$ (normal wall area for a dwelling-room). Some examples of crack lengths corresponding to the tightness demand and caluclated by means of the test results are presented in Table 1.

crack Wall width mm thickness m	0.3	0.5	0.7
0.1	25	5	2
0.15	38	.9	3
0.20	70	14	5

Table 1 Maximum crack length/outher wall area of a dwelling-room. Cracks through solid concrete

Comment: The crack lengths are calcualted from the mean flow values The contribution from slots in and around window-constructions has been disregarded in the calculations of the crack lengths given in Table 1.

DISCUSSION

Ist Discussion Session

Monday afternoon - 21st September 1981

Chairman Ingemar Höglund (Sweden)

- J. Kronvall In the calculation of energy balances, how do you take (Denmark) into account the influences of inhabitant's bevaviour ?
- A. Elmroth (Sweden) Energy balances are calculated in different ways in different countries. In the draft Handbook, we have tried to indicate the methods by which the energy balances are calculated. Concerning your specific question on the influence of inhabitants' behaviour, this was not considered in the pilot studies of single family dwellings that I have described. In repeated measurements on these well-sealed, mechanically ventilated buildings little difference in the rate of ventilation was found. It seems, therefore that in such buildings predictable ventilation rates have been achieved. There may well have been some influence of open windows but this was not monitored.
- W. de Gids (Holland) The Dutch energy balance is based on measurements made over a period of 3 months during which the positions of all doors and windows were monitored. The flow rates through the windows and doors were then calculated on the basis of previous infiltration rate measurements through such openings.
- P. Burberry (U.K.) In the United Kingdom, the savings from insulation measures on the whole have been much less than was theoretically anticipated. This is very different from the picture that was presented earlier this afternoon. Part of the reason is that the comfort temperature increases because either the occupants deliberately choose to have more comfort rather than save energy or the house mean temperature rises as a result of the insulation measures and consequently the actual savings are far less than those theoretically anticipated. This seems very different from your experience and I wondered whether the authors could comment on that difference.

H. Orr (Canada) I would like to comment on your supposition and I think that we have found generally the same sort of situation when people have insulated basements. The actual savings are not as great as we would expect them to be, primarily because the temperature in the basement rises quite substantially. P. Collet (Denmark) The airtightness measurements described were first made in October and subsequently in February. Could some of the differences in the results be due to seasonal variations in the structure ?

- A. Elmroth (Sweden) The moisture content in the timber construction was measured in the 15 month period between the October and February tests of airtightness. It was found that the moisture content decreased which suggests that there may also have been some shrinkage of the wood. I agree that weather conditions can influence airtightness but we have no measurements to demonstrate this.
- D. Harrje (USA) We have made an extensive series of fan-pressurization tests on a house throughout an entire winter period. Measurements were made every three days and there were 10% variations between the results of tests made in a dry spell and those made during wet weather. There seems to be a correlation between leakage and the condition of the wood and the sealants.
- P. Collet I have a second question which I wish to ask Ake (Denmark) Blomsterberg. Are you aware that, with the method of air infiltration rate measurement you were using, under certain conditions errors of between 30 to 100% may occur because of differences in the tracer gas concentrations in different rooms ?
- A. Blomster- I know there are problems with this method and for this berg reason we are now developing a new method based on (Sweden) constant concentration.
- D. Harrje I have a question for Dr Wanner. The study of odours (USA) has always been on a very subjective basis and I am pleased to note the scientific basis of your studies. Your tests have shown that observers outside the test room are able to detect odours reasonably consistently, but can people in the room itself detect a slow buildup of odour concentration ?
- H. Wanner As we know from our own personal experience, the (Switzerland) perception of odours by people in the room is quite different from those outside. Whereas people in the room may feel an increase in temperature, they are not sensitive to a change in odour level. In our tests we asked the persons in the room to give their impression of the odour level, but their response is not as reproducible as that of the test panel outside the room.
- P. Hartmann I have an additional question in this context. We have (Switzerland) Seen that Dr Wanner has by his recent experimental work confirmed one of the curves on the Swedish diagram which gives the air quantities required in occupied rooms for various levels of activity and for the smoking and non-smoking situations. Has any work been done recently in Sweden to verify any of the other curves ?
| A. Elmroth
(Sweden) | The data we have used is based on published literature.
I know of no projects being conducted to verify these
graphs. | | | |
|------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|--|--|
| D. Etheridge
(U.K.) | I have a question for Arne Elmroth. Is the Handbook
going to include designing for natural ventilation as
well as for mechanical ventilation systems ? | | | |
| A. Elmroth
(Sweden) | In the draft Handbook, no attempt has been made to define
alternative ventilation systems. It is a guide on
structural design to reduce air infiltration and, although
the effects on ventilation are described, there is no
information about the merits or demerits of alternative
ventilation systems. | | | |
| D. Etheridge
(U.K.) | In Sweden, is natural ventilation an option being considered for the future ? | | | |
| A. Elmroth
(Sweden) | There is no restriction on the use of natural ventilation
in Sweden but almost all new houses have mechanical
ventilation. | | | |
| M. Liddament
(U.K.) | May I ask Arne Elmroth whether, in Sweden, there are problems with noise generated by mechanical ventilation systems, especially in bedrooms ? | | | |
| A. Elmroth
(Sweden) | There have been some instances of excessive noise levels
but the modern ventilation systems are not normally
noisy and so present no problems. | | | |
| P. Hartmann
(Switzerland) | We have heard about investigations on the benefits of
some types of retrofit measures but none in which there
was a change from a natural ventilation system to a
mechanical one. Is there any work being done on this ? | | | |
| A. Elmroth
(Sweden) | Changing from natural to mechanical ventilation has not been featured in our investigations and so we have no results. | | | |

2nd and 3rd Discussion Sessions

Tuesday afternoon - 22nd September 1981

Unrecorded

4th Discussion Session

Wednesday morning - 23rd September 1981

Chairman Peter Hartmann (Switzerland)

- M. Liddament A question to David Harrje. You have shown the results (U.K.) of air infiltration rates for many dwellings. Were these based on one or two spot measurements made at each site ?
- D. Harrje In the survey, there were several hundred houses and (U.S.A.) measurements which in total numbered more than a thousand. The houses were re-visited a number of times during the heating season. The significance of the resulting data lies in the number of houses that are shown to require retrofit treatment. There were only a small identifiable number in which further tightening may have caused a problem.
- P. Burberry May I ask Mr Harrje about multiple tracer gas measurement (U.K.) I did not notice any reference in his paper to this important principle.
- D. Harrje (U.S.A.) You are right. I should have cited, for example, the work (U.S.A.) being done by Rodney Gale and David Etheridge who are using a second tracer gas to determine the movement of air between a dwelling at the attic space.
- R. Gale The value of multiple tracer gas techniques depends on the (U.K.) aim of the testing. In most of our work we have been concerned about the amount of fresh air moving into houses and so a single tracer gas technique was inadequate. When the concern is the movement of air within the building then the multiple tracer gas technique is needed with a different gas released in each room.
- P. Hartmann While visiting the National Research Council in Canada (Swtizerland) recently, I noted that an investigation was being conducted into alternative methods of determining interflows between rooms. It is possible that progress on this work may be reported next year.
- P. Geisbrecht I would like to put a question to David Harrje. How do (Canada) you account for such large variations in the leakage of houses ? I noticed that an airchange rate of 196 times per hour was reported for a house in New Orleans.
- D. Harrje (U.S.A.) The degree of variation is largely due to the sensitivity (U.S.A.) of the occupants and is related to the outdoor climate. A leakage of air into a room when the outdoor temperature is -30°C is much more noticeable than in mild winter climates as experienced, for example, in New Orleans where the outdoor temperature may drop to 0°C for only one hour during the heating season. In the colder climates, in North Dakota for instance, occupants having suffered discomfort from air leakage had already undertaken remedial action whereas in warmer climates in places like New Orleans or Charleston, no efforts to reduce infiltration had been made.

A. Elmroth (Sweden) May I draw attention to the variations in the methods of conducting pressurization tests in different countries. In the USA for example, the ventilation openings are not blocked, in Sweden they are. In comparing results, it is necessary to take these differences into account. The various test methods are summarized in the draft Handbook.

P. Hartmann (Switzerland) May I also draw attention to the various sources of information on instrumentation. Firstly, there are the papers of 1st AIC Conference; secondly, a search in AIC's database *AIRBASE* will reveal many papers on measurement techniques; thirdly, this summary paper presented by Mr David Harrje will be included in the proceedings of this conference. There will be information also in the AIC Handbook and AIC Technical Note 4 "Instrumentation for the measurement of air infiltration - an annotated bibliography", which will be regularly updated, is a further source of relevant information.

R. Lipscombe (U.K.) A short question for our first speaker. I was surprised at the low figure of heat loss through the walls of 4%. You talked about sealing internal doors, but you made no comments about the sealing of external doors and windows. Do I assume that you have much higher standards in Holland than we do in England ?

R. Gale A couple of points on Willem de Gids' contribution. He (U.K.) concluded that internal doors had no effect but I think he would be aware that that was due to his model. In the model, external leakage connected directly to flues which went straight out of the top of the building, so leakage into the bathroom and kitchen went straight out of the flue ventilation ducts. From our experience of practical measurements we have found that sometimes internal doors can have an effect on ventilation. It depends whether it is wind-dominated or stack-effectdominated and on the configuration of the individual house. I just wanted to make that clear in case people drew that conclusion as a very firm one. Another point relates to what I said earlier about the difference between fresh air entry and air mixing within the house. In the example you presented, variation in wind direction resulted in one bedroom being over-ventilated at one point and under-ventilated at another. That would be true only if you are concerned about fresh air directly entering that room. However, the excess fresh air that entered the room on the windward side will find its way to the leeward side bedroom and satisfy the needs for fresh air in that room. I think that needs to be borne in mind when we are seeking to meet air requirements within a house.

W. de Gids (Holland) I agree with your first point. I did not say that internal doors had no influence at all. In our study, the doors of the bathroom and WC were leaky for ventilation purposes and so the differences between open and closed were minimal. With regard to your second point, in the case I described there was, with a closed door only, a cross flow of only 1.1 litre/s of fresh air so your comments are not totally applicable in this case.

M. Modera (U.S.A.) I have a brief comment on a previous point. I would think that the leakage through the walls appeared to be so low because of the overriding influence of ventilation stacks. If they were not there, then the leakage through the walls would represent a much higher proportion.

5th Session Discussion

Wednesday morning - 23rd September 1981

Chairman Peter Hartmann (Switzerland)

- D. Harrje (U.S.A.) I have a question for David Etheridge and Rodney Gale. Your studies have shown that the pattern of natural ventilation in a house can vary and that to establish the required pattern was sometimes rather complicated. Would not the introduction of a mechanical ventilation system be a more rapid method of achieving the required ventilation ?
- R. Gale There is still a tendency in the U.K. to depend on (U.K.) natural ventilation. We are extremely surprised at the large differences (in some rooms a three-fold increase in ventilation rate) found in tests made at the same time of the year under similar weather conditions. We have not properly digested the implications of these results or of the design requirements of a mechanical ventilation system to cope with changes in the neutral plane within the building. It is too early for us to answer your question.
- P. Hartmann Do you expect to conduct similar experiments on houses (Switzerland) which are less affected by stack effect ?
- R. Gale Yes, but we have no specific plans. This house afforded (U.K.) the opportunity to perform this type of experiment and we intend looking for other opportunities to repeat it.
- A. Elmroth (Sweden) I have two questions to Mark Modera. The first is that, in your test unit you have made arrangements to change the leakage areas in the walls but, as I remember, you have no such arrangement to change the leakage areas through the roof and floor
- M. Modera We can change the leakage area of the floor but not (U.S.A.) the roof.
- A. Elmroth (Sweden) But if you study the results presented by Willem de Gids earlier this morning, you will see that most air leakage takes place through floors and roofs. Would you please comment on this ?
- M. Modera (U.S.A.) It is true in houses in Denmark, for example, but it is not necessarily true in houses all over the USA. Our work shows that the proportion of air leakage through the floor and ceiling varies from 1/3 to 2/3 and was normally about 1/2. In our test unit, the fact that we did not have a leakage through the ceiling would not affect our comparison of the full-scale measured data with that predicted by the model.

A. Elmroth	My second questio	n is as follows.	In your	calculations,
(Sweden)	do you assume tha	t the neutral pla	ne is at	the mid-height
	of the building ?			-

M. Modera (U.S.A.) No. In our calculations we simply use the measured pressure differences across the individual leakage areas. There are no assumptions regarding the neutral plane.

P. Burberry May I refer back to the question of mechanical as opposed to natural ventilation ? What Mr Gale has said is (U.K.) exactly right - there are many reasons for supposing that we shall continue with natural ventilation in the UK. There is one very fundamental factor which influences this and it is economic rather than technical. We in the UK have no requirements for separate ventilation provisions for bathrooms and kitchens. Therefore, mechanical extract is liable to be grossly uneconomic. Whereas, in other countries, it may appear to be only a marginal increase in cost and so be financially attractive. A number of such factors would seem to be very important in addition to the purely technical issues. The economics involved and the particular differences in national regulations obviously have a very great effect and do constrain the technical solutions.

P. Hartmann As has been noted before, I think there will be some more (Switzerland) discussion on these economical aspects and on the benefits of mechanical ventilation next year in the next AIC conference.

W. de Gids A question to Mark Modera. Why did you choose a half-(Holland) hour period ?

M. Modera (U.S.A.) There was no strong reason for choosing the half-hour period. It was chosen because it produces a reasonable amount of data to deal with. If measurements were taken every five minutes there would be too much, and if they were made every hour there would be too little.

W. de Gids A question to Peter Collet. Did you encounter any problems (Holland) in using 50 ppm of nitrous oxide in occupied houses ?

P. Collet No, no problems as all. (Denmark)

P. Hartmann We have also used nitrous oxide for measurements in (Switzerland) rooms that were occupied and we have not experienced any problems either.

W. de Gids (Holland) My third question is to David Etheridge. You briefly mentioned that with your new system you also monitored window opening habits. What type of instrument did you use ?

D. Etheridge Our equipment only monitors whether a window is open or (U.K.) shut.

H. Orr I have a comment regarding the cost of providing (Canada) openable windows compared to that for mechanical ventilation. Our situation in Canada is that we are required to have either an openable window or mechanical ventilation and, generally, contractors are finding that the cost of installing a window is 10 times more than the cost of mechanical ventilation.

P. Hartmann I think that that is a situation specific to your (Switzerland) country.

R. Gale (U.K.)

May I ask a question of Peter Collet and also make a comment for the benefit of other people making measurements using nitrous oxide. First a question for Peter; you showed an example of how your system could respond to an increase in ventilation rate when the window was opened and how the injection rate he needed continually rose and so it was possible to maintain good control. How long does it take your system to get back to equilibrium when the window is closed ? This is a much more difficult situation to deal with as you are essentially out of control at that point because you will be injecting for too long. While he is thinking about that, may I sound a note of caution for anyone using nitrous oxide. Careful consideration must be given to the specification and performance of the analyser, because some analysers are rather sensitive to water vapour. This is quite an important point for anyone who is trying to do measurements using nitrous oxide in occupied houses where water vapour levels can change quite considerably.

P. Collet Our sampling occurs every five minutes and so for the (Denmark) concentration of tracer gas to double between samples there would need to be a reduction of more than 12 air changes per hour. Let us consider a room which, at the commencement of a 5 minute period, has 12 air changes per hour but that just after the start of the injection of nitrous oxide equivalent to that ventilation rate, the window is closed. There will be nearly five minutes when the high rate of injection will occur and this could raise the concentration from 50 ppm to 100 ppm. The injection of tracer gas would then be shut off and the time taken for the reduction of the concentration back to the control level will depend on the infiltration rate in the window closed condition. It is not likely in any reasonably normal circumstances to generate a concentration level as high as 100 ppm, and if it occurs the gas injection shuts off anyway.

P. Hartmann (Switzerland)

In concluding this conference, may I express on your behalf a sincere word of thanks to the Swedish Council of Building Research and in particular to Arne Elmroth and his helpers Per Levin and to his secretary for their splendid organisation and the preparation of so much documentation. In addition, we thank all of the authors for their contributions and all who partook in the discussions.

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