INTERNATIONAL ENERGY AGENCY
energy conservation in buildings and
community systems programme

4th AIC Conference

Air infiltration reduction in existing buildings

Proceedings

Air Infiltration Centre

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Annex V Air Infiltration Centre

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PREFACE

International Energy Agency

In order to strengthen cooperation in the vital area of energy policy, an Agreement on an International Energy 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 (Building and Community Systems) has highlighted areas where the level of knowledge is unsatisfactory and there was unanimous agreement that infiltration was the area about which least was known. An infiltration group was formed drawing experts from most progressive countries, their long term aim to encourage joint international research and 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 groundwork 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 Belgium, Canada, Denmark, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the United States.

AIR INFILTRATION REDUCTION IN EXISTING BUILDINGS

4th AIC Conference, September 26-28 1983, Elm, Switzerland

PAPER 1 - KEYNOTE ADDRESS

POTENTIAL AND LIMITS OF ENERGY SAVINGS IN THE SWISS BUILDING STOCK

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1. Potential of Energy Savings

Based on extensive surveys in the Swiss building stock between 1977 and 1983 (Lit. 1) we have a fairly good knowledge of the specific energy consumption (final energy in MJ/a per gross heated floor area in m2) of different building categories in Switzerland (see table 1).

Tab. 1: Specific energy consumption of different building categories

[MJ/m2·a]	Mean		
	E_H	E_E	E_T
One family			
- Combined heating + hot water	850	100	950
- Separate heating + hot water	750	150	900
Multi-family			
- Combined heating + hot water	750	125	875
- Separate heating + hot water	650	175	825
School			
- Kindergarden	800	50	850
- Primary + Middle School	700	50	750
- High School	700	200	900
Office	700	150	850
Nursery home	850	175	1,025
Hospital	1,100	225	1,325
Hotel	900	450	1,350

E_H: Heating + hot water E_E: Electricity E_T: TOTAL

The majority of these surveys are based on housing (individual and multi-family) and schools. In these private and public building categories we have detailed energy data of gross and net energy consumption, use, building geometry, cost of energy, etc. based on several thousand buildings. The data derive from national and regional data gathering campaigns, where usually the owner or his representative is providing the information. No detailled measurements and field tests were made in this context. Additional building categories like office buildings, hospitals, hotels, etc., were surveyed also, but less comprehensive data are so far available. In the context of Swiss building energy consumption statistics, systematic improvement and regular publication of the findings is planned (Lit. 2) in order to provide solid evidence of "good" or "bad" energy performance in buildings and to improve knowledge on standards for new construction.

With a method called "Energy Balance Model" (EBM, Lit. 3) a systematic analysis of the respective share of the different sources of heat loss and gain was made with some 50 buildings (Lit. 4).It shows for the above mentioned categories of buildings (see table 2) a share of 21 - 36 % of the net heat loss being attributed to infiltration both from building leaks and occupant's ventilation with open windows and doors. Artifical ventilation systems are relatively rare within the surveyed categories and may cover only some 10 % of the building stock. These findings are based on gross energy consumption data and building simulations without detailed measurements and are therefore to be checked with measurment projects. In detailed analyses we refer to two buildings in Switzerland that have been measured by EMPA, namely: Maugwil (a single family house, Lit. 5) and Limmatstrasse (multi-family housing, Lit. 6).

Tab. 2: Energy balance: infiltration share of net heat loss

Heat loss (%)	Infiltration
Housing	24
Elderly housing	36
Offices	21 - 28
Schools	
- Primary + Middle school	24
- School with swimming pool	22
Mean	26

Based on the EBM a typical minimum consumption of each building category can be calculated with improved insulation standards (k ∿ 0,3 W/m2·K), tight window an door joints a < 0,2 m3/h·m·Pa$^{2/3}$, optimum indoor temperature controls and furnace values in order to define the respective energy savings potential. These values also lead to a new SIA* Standard 380/1 "Energy in Buildings" (Lit. 7). This standard prescribes levels to be achieved with new and retrofit construction some time after 1984 (see table 3).

* Swiss Engineer's and Architect's Association

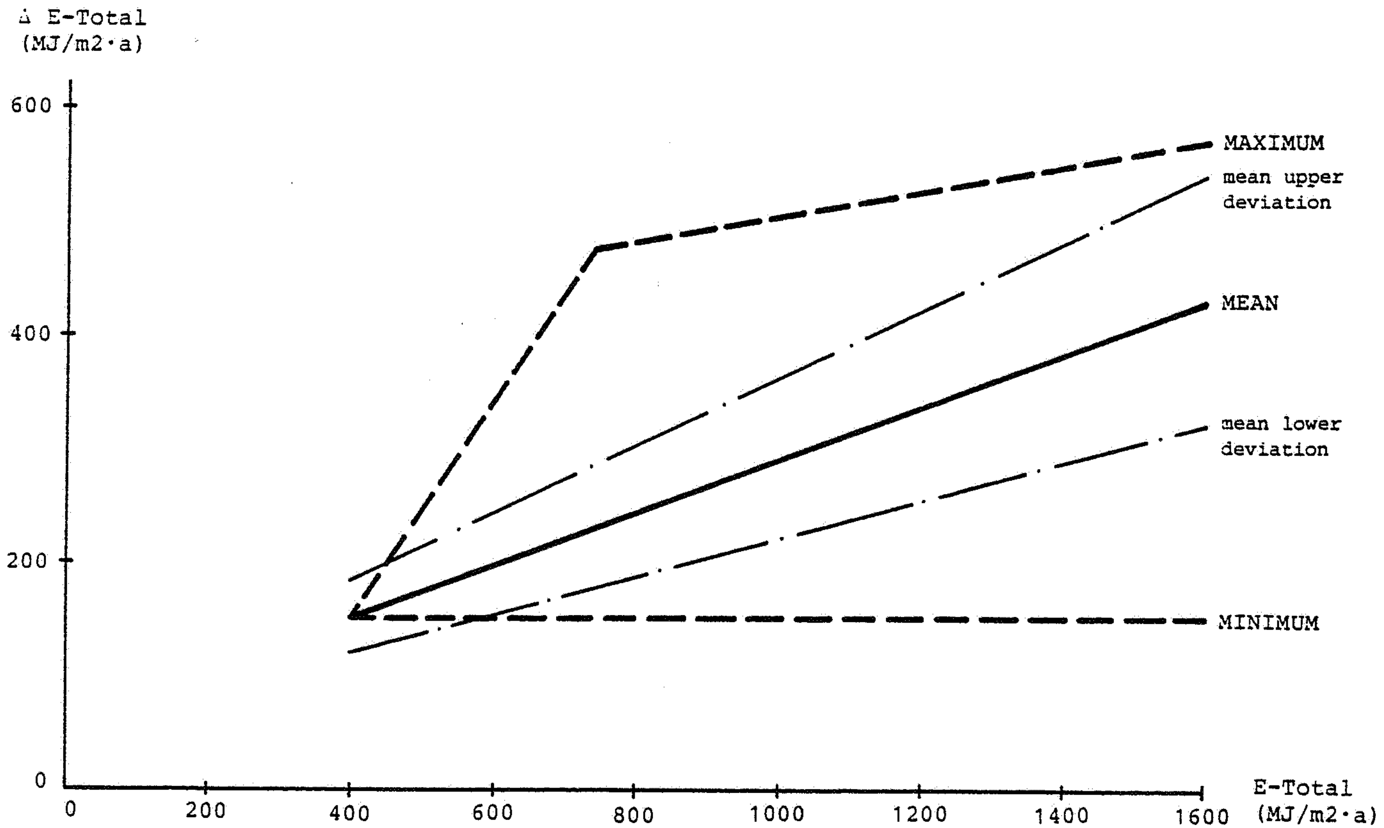
Tab. 3: New energy performance standards (Switzerland SIA 380/1, draft 1982)

Net heat demand [MJ/m2·a] Smaller than:	Minimum requirement Space heating
One family Multi-family Office	330 300 270

Coefficient of performance COP [-] Bigger than:	Minimum requirement
Space heating	
to 60 kW	0,75
61 to 300 kW	0,80
301 kW and more	0,85
Hot water	0,70

The savings potential of existing buildings can be estimated in relation to initial consumption levels according to graph 4. "Savings" are defined as measures that are feasible with present energy prices within the life cycle of a planned measure. The savings usually involve rather basic and conventional retrofit measures like attic and basement insulation, window joints improvement, heating plant replacement, etc.

Graph 4: Energy savings potential of existing buildings



2. Limits of savings

A national program to conserve energy in the whole Swiss building stock is in progress. Investment, in the order of 10 - 20 · 10^9 SFr. are forseen over a 20 year period. Different kinds of limits to energy savings must be respected while planning such a nationwide program (Lit. 8).

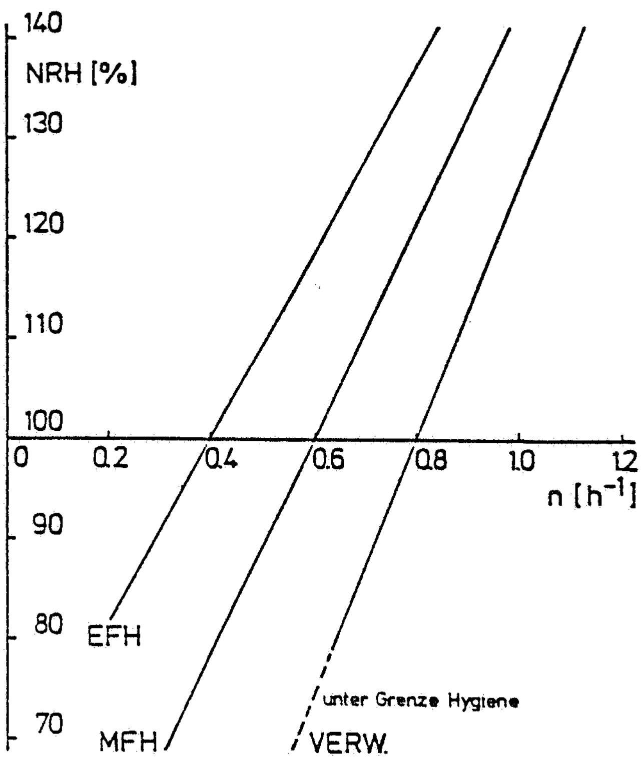
The first limits are cost/benefit-factors. These are usually more relevant for improvements of heating plants than for renovation of the building envelope. Available investment capital or interest rates are in this country (due to the generally low mortage rates, 5 1/2 % at present) no limiting factor. The inertia of the owner-investor, especially in the rent situation, is the severest limitation. Some 70 % of the Swiss population lives in a rented apartment and pays the actual energy cost. Therefore, the owner has no specific incentive in investments for energy conservation.

Another kind of limitation results from existing building standards and old codes. Constraints exist for instance, for minimum window areas, ventilation rates, indoor temperatures and humidity standards. These were all set at a time when energy was plentiful and the belief was common that technology could provide every possible indoor climate at all times. Today a number of these standards are being revised; new testing and research is about to redefine the necessary standards. Neither hygienic nor safety standards of our buildings will be compromised in the new standards. A specif problem in this field is the kitchen with tight windows and a gas range. Lack of outside air may produce dangereous levels of NO_x or CO during extended periods of intense cooking.

Lower k-values (k ∿ 0,3 W/m2·K) have increased the inner surface temperatures in winter to 1 or rarely 2 K below room temperature, so that surface-condensation is no longer a problem. The humidifier business has started to look for new markets because well insulated houses do not need that equipment any more. Excessive humidity has been a problem where low insulation of exterior surface was combined with tight joints in humid spaces like kitchens, showers and bath rooms. Problems also occurred where the occupants did not apply the rule of opening windows twice a day for a ten minute period during cold winter weather.

The largest limitation to realizing the full potential of energy savings both in new and existing buildings is the cooperation of the occupants regarding behaviors affecting energy performance. In graph 5 the effect of air change rate on net energy consumption of three typical building types is shown. These computations (Lit. 9) show window ventilation, together with indoor temperature and hot water consumption as the crucial factors in heat demand due to occupant's influence.

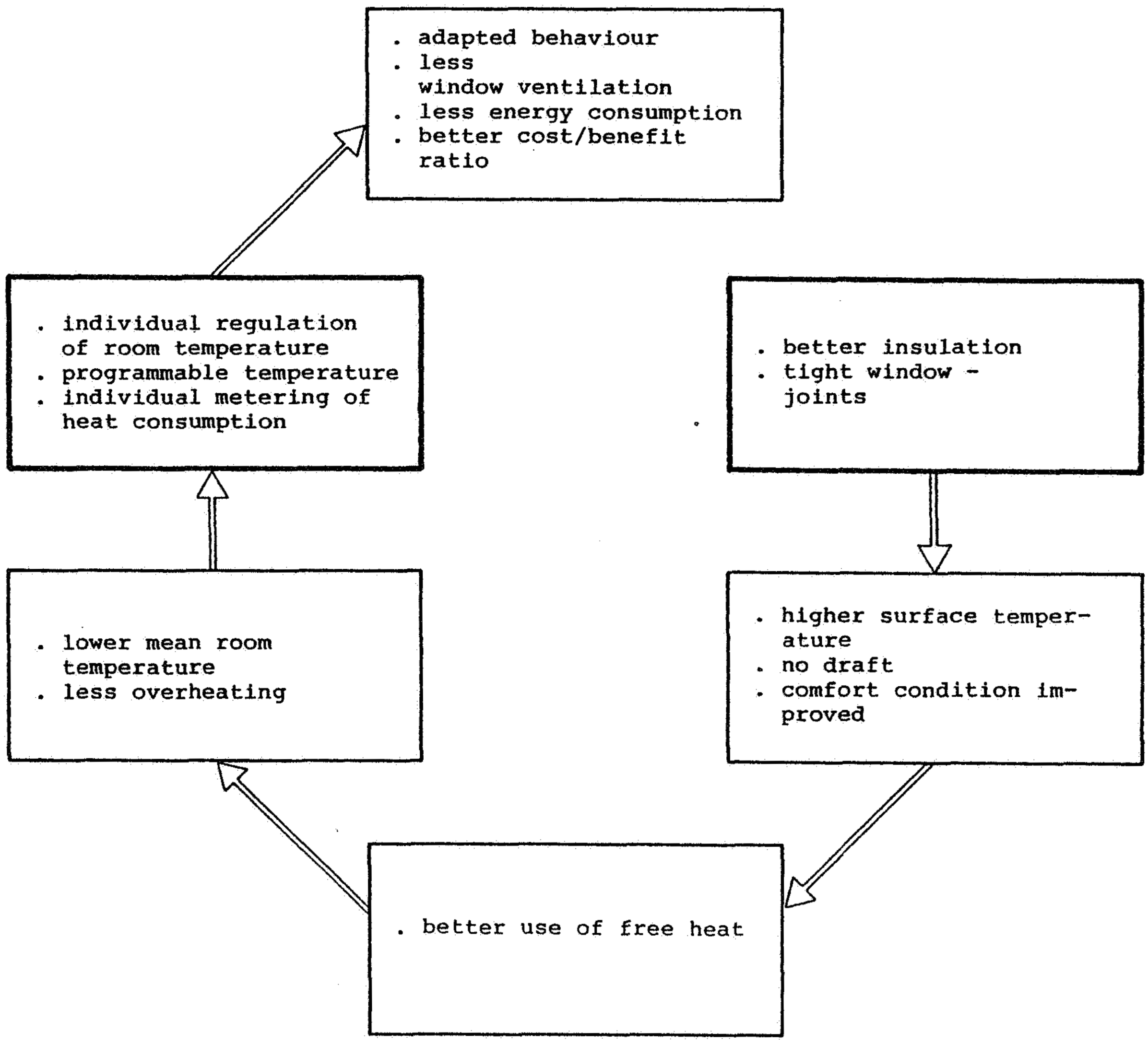
Graph 5: - Air change rate influence on energy consumption



NRH : net heating energy
n : air change rate per hour
EFH : single family
MFH : multi family
Verw.: office

In the retrofit housing project Limmatstrasse in Zurich (Lit. 6) a 10 family building was equipped with programable room temperature controls that were at the same time used as a means to divide heating costs among the tenants. The result of a two year testing period shows a surprisingly positive effect of the combined savings from insulation, regulation and occupant behavior (see graph 6).

Graph 6: Synergetic link between building and user



The synergetic link between better indoor climate (due to better insulation) and improved behavior (due to better controls and cost feedback) is important. It shows a possible path of future development wherein the occupant is voluntarly in harmony with the building. Forced compliance such as occurs with mechanical ventilation is hence not the sole way of limiting excessive infiltration rates commonly attributed to "bad" users. Technical provisions such as insulation, tighter joints and control of temperature are necessary in order to initiate permanent more energy saving behavior. It is not surprising that we discovered significantly fewer open windows during cold weather in the so equipped apartments compared to similar apartments with standard temperature controls (thermostatic valves, see table 7).

Table 7: Limmatstrasse window opening pattern

	Programable indoor temp. control and cost-feedback Type A	Standard manual valves, no cost-feedback Type B
Number of apartments	10	100
Number of windows observed	42	596
Open windows in 4 observations (-4°...+6°C)	3,6 %	6,5 %

3. New energy performance standards

In a research project (Lit. 7) we have established the basis of a new Swiss building standard for energy consumption (see also table 3). We have departed from the old k-value system and estabilished two sets of standards:

- the net annual heat consumption per floor area (N-H in MJ/m2·a)
- the mean annual coefficient of performance (COP) of the total heat production including all losses (see table 3).

The system is based on a standard calculation procedure both for N-H and COP which can be executed both manually or with the aid of small computers.

The idea behind this change from component standards (k-value, a-value, etc.) to gross specific energy consumption performance is based on the understanding that an optimum situation can be achieved by the planning team with a maximum choice of options (see table 8) but with a precisely defined goal. This should also avoid discussions as for instance whether maximum insulation or maximum passive solar gains will lead to optimum energy performance. Both paths are accepted.

This new procedure shows clearly the shift in relative importance of transmission to infiltration losses with raised insulation standards. The average annual air change rate per hour is set at:

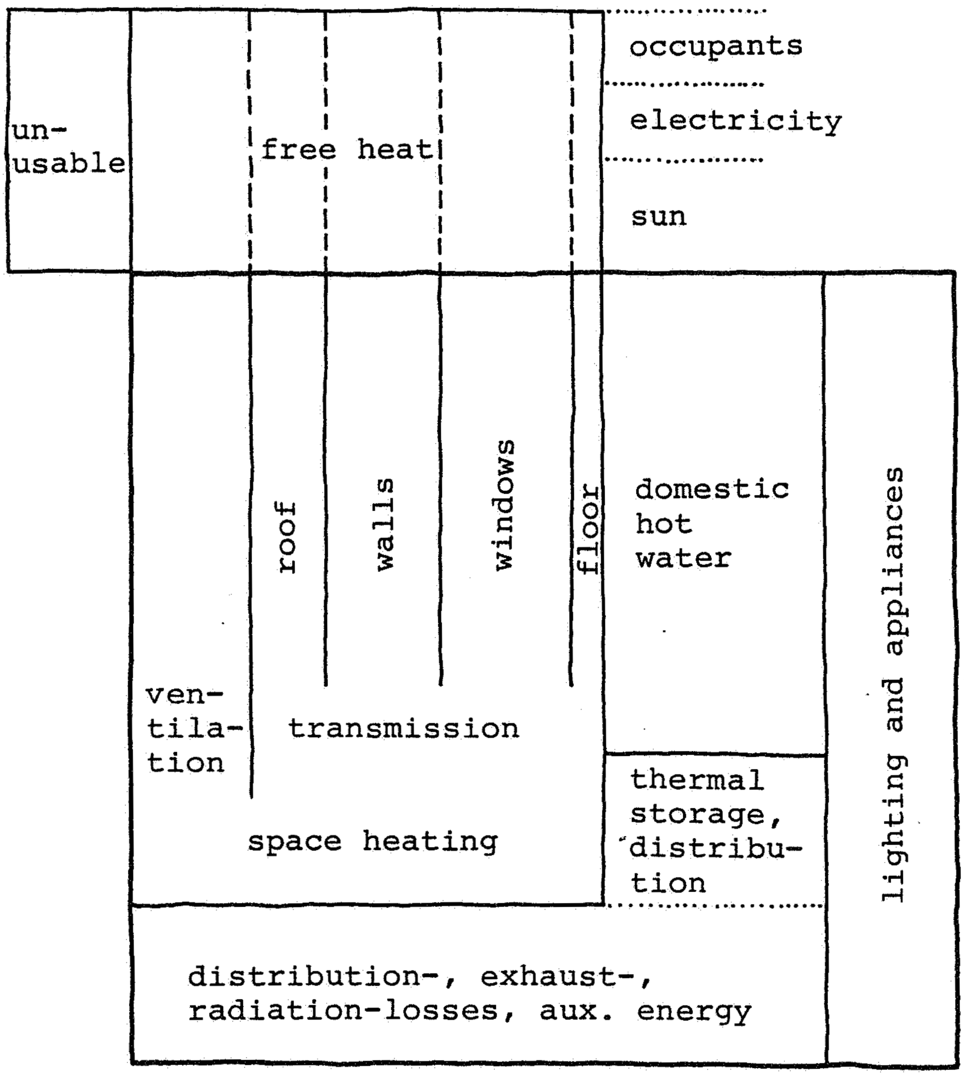
0,4 h^{-1}	for individual houses
0,6	apartments
0,8	offices

Table 8: Provisions for low heat losses due to ventilation and infiltration

- indoor materials with low toxic and odor emissions - temperature zoning according to use (living, bedroom etc.) - buffer zones at entrances (air locks) - zoning according to odor emission (toilet, kitchen) and humidity (bath, shower etc.) with direct ventilation - humidity absorbing wall and ceiling materials (no paint covers) - no windows with provisions for leaving permanently open - crack control after initial shrinking period - individual indoor temperature control, programable - limited heat delivery of radiators: insufficient for permanent window opening in winter - provisions for condensation of excessive humidity (condensation trap) - share of energy cost according to actual heat consumption - tight windows and doors - high internal surface temperatures with good k-values and limited thermal bridges

The user factor is included in the calculation procedures with a standard occupancy, which does vary in practice according to the actual user behaviour. This variation should not inhibit architects and engineers from designing good buildings that allow good living and working conditions and have low energy consumption. Field tests of new buildings will check actual specific consumption levels after two years of occupancy. This period provides a bases to decide whether the standards have been fulfilled. Quality control in building techniques will become a major topic, i.e. avoiding or limiting thermal bridges and cracks due to shrinking material. Detailed analysis of a building is needed where measured consumption is more than 20 % over computed consumption. Every owner should include this form of field test in all contracts and guarantees. An energy-check after two years will become routine practice.

Graph 9: Energy balance of well a insulated house



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AIR INFILTRATION REDUCTION IN EXISTING BUILDINGS

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PAPER 2

RECOMMENDED RETROFIT ACTIONS BASED ON AIR INFILTRATION EVALUATIONS IN A VARIETY OF BUILDINGS

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1. INTRODUCTION

During the past decade we have witnessed an ever increasing interest in determining air infiltration and ventilation rates in buildings. The interest has been spurred by the growing realization that even when the thermal characteristics of building envelope and conditioning system efficiencies are greatly improved, unless the tightness and the associated control over air infiltration takes place, problems of excessive energy use or problems of local comfort remain. Even the life of the building itself may be jeopardized because of undesirable moist air flow paths which cause severe moisture problems in the building envelope. The appropriate retrofit action based upon a knowledge of air infiltration is often key to the achievement of energy, comfort and building integrity goals, while maintaining indoor air quality.

Because of the interest in probing just how much infiltration is present, major advances in the techniques for measuring air infiltration have taken place.[1,2,*] These developments have provided a wide assortment of diagnostic tools ranging from simple smoke guns and acoustic leakage test methods to variable flow rate blower doors, extremely sensitive measurement systems for differential pressure, and tracer gas systems that automatically record infiltration rates over hours or weeks. In the most advanced tracer gas systems, constant concentration levels are maintained in 8-10 zones so that multi-chamber air infiltration effects in more complex buildings can be properly documented.

What have these advancements meant to the small energy consultant company? Can these techniques prove useful in the day-to-day questions that must be addressed by the consultant? This paper, through a series of case studies, will attempt to point out some of the challenges that can be met and the benefits that are available to the client. These benefits are more than establishing the tightness of the buildings and/or documenting air infiltration rates under "design conditions", but also include determining exactly what is the appropriate building envelope retrofit to more closely approach the desired building tightness.

2. CASE ONE - THE LARGE BUILDING

Although the majority of the studies that have been reported in the Air Infiltration Centre literature have concerned houses, often the request to the energy consultant is to quantify the air infiltration associated with the large building. In total dollars the larger building owner has more to gain from this important energy component assessment. Naturally, the request is that the task be performed inexpensively and with reasonable accuracy (plus or minus 10% values are generally suitable).

The question that must be immediately asked when evaluating air infiltration in a building, and especially the large building -- can the building be treated as a single zone or must it be treated as a multi-zone system? The case study is a multi-story building covering much of a city block in Washington, D.C. and is schematically shown in Figure 1. Helping the testing situation considerably was the fact that, like so many U.S. larger buildings, central ventilation systems moved air throughout the building. Actually four separate air handlers were necessary in this basically "H"-shaped building. The air handlers were rather large, using fans more than three meters in diameter to provide the necessary air movement in the 150,000 m^3 volume.

The cross flow between the four building areas was evident early in the testing, which consisted of seeding the air handlers with sulphur hexafluoride tracer gas and measuring gas concentrations on site with a battery-powered SF_6 detector based upon gas chromatography and electron capture principles. The tracer gas was initially measured into approximately two liter plastic bags, one for each air handler. Unless the air handlers were slowly seeded with the proper amount of gas within a few minutes of each other it was not possible to approach single zone conditions. Seeded individually the gas from one zone was seen to build up concentration in the others to a greater or lesser extent depending upon the degree of zone coupling. The additional questions of smoke and odor control directly apply to these interzone events. Simultaneous seeding at the four air handlers was used successfully to reduce interzone effects. The plot of tracer gas concentration versus time for a typical test series is shown in Figure 2 and represents the air change rate for the entire building.

The conclusion from the tests, which took less than one half day to complete was that the air change rate of the building was 2.4 ACH even though the mechanical systems were exhausting at a rate of only 0.9 ACH and design ventilation rate was 1.6 ACH. To further pinpoint the sources of the undesirable 0.8 ACH air infiltration component, use of infrared scanning with pressurization, investigation of critical areas such as the plenum areas above dropped ceilings, and detailed measurements of lower floor leakage associated with entry areas[3] was part of the survey. The conclusion from the additional diagnostics was that leakage problems in the building envelope were present, that the mechanical systems were providing too much air to certain building locations, and that entry areas were causing excessive infiltration. Also of importance was the use of bay windows on the upper floors (see Figure 1). Detailed retrofit actions for each of these problem areas were recommended. In the case of window use and swinging door use (rather than revolving doors), education of the occupants as to proper use was also recommended. Figure 3 breaks down the key leakage and ventilation flow rates with an indication of the method of documentation.

The point we are making in this case history is that evidence of excessive infiltration/ventilation was provided by a test of a few hours duration and other diagnostic tests logically followed. Conclusive proof that the problem had been rectified makes use of the same techniques. Since some 40% of the summer air conditiontioning load was related to excessive air supply via mechanical and air infiltration sources, retrofit action represented tens of thousands of dollars in savings potential.

3. CASE TWO - A LARGE SYSTEM

This case study concerns some 700 attached town houses (in groups of eight or ten) operating on a central cooling system. The building complex is representative of several "communities" located in the Middle East and the architectural features are shown in Figure 4. The challenge was to explain why the central system could cool individual houses but could not maintain comfort conditions with 700 houses on line when outside design conditions were present (40°C dry bulb, 29°C wet bulb, wind speed of 7 meters per sec.). Was air infiltration playing an important role? Design specifications are often based upon the 2 1/2% most severe weather conditions experienced over a minimum of five years of weather data (as local as possible). Because of this averaging process, conditions exceeding design may be experienced for short periods and humidities of 70% rather than the 40% RH design may be present, making air infiltration even more important.

Several techniques were available to the energy consultant team: use of the fan pressurization method to check building tightness; and use of tracer gas procedures with on-site measurements and container sampling. These techniques were applied to what are basically mechanically-dominated building ventilation systems, i.e., the air conditioning system is moving air in a "closed ducting system" with mechanical equipment located in a special open room between each pair of houses.

The blower door tests revealed that the building construction was tight, meeting the Swedish standard of less than three ACH.[2] The tracer gas tests with the ventilation system in operation indicated that with this "closed system" air infiltration rates were still sufficient to be the dominant component of the total building energy use. The measured air infiltration values for four building sizes are shown in Figure 5. Plotted in the same figure are the predicted air infiltration values from the blower door testing for the conditions of: stack induced, wind speed of 7 m/s at the house, and wind speed of 7 m/s at the weather station. (The value predicted from "rule-of-thumb" predictions would be only in the 0.15 ACH range (~3/20)). Operation of the mechanical system was found to be a major factor in determining what air infiltration rates actually were present.

The cooling system peak load difficulties were heavily influenced by the amount of outside air that was reaching each living space and on the amount of moisture the air contained. Design conditions depend on the local micro climate and special care must be given to the local relative humidity since these test sites are located near the water causing a departure from the basically desert-like middle east climate. The energy load of this infiltrating air accounted for almost 50% of the total energy load and thus a prime retrofit recommendation was to control the air infiltration by improving such localized building envelope items as kitchen ventilation vents and door leakage. The less desirable alternative for these buildings is the far more expensive option of increasing cooling capacity of the central community cooling system and/or changing individual cooling coils.

The final check of system operation made use of five microcomputer-based data recording systems[4] placed in ten typical buildings each for two weeks duration. Air infiltration rates were checked at or near the peak cooling hours with tracer gas on-site measurements[2] and container samples,[2,5,6] while the critical information on inside temperatures (25.5°C at 50% RH levels were not to be exceeded), relative humidities, cooling system parameters, and local micro climate were measured. In such testing the importance of the role of air infiltration was further documented.

An extreme example of how seriously this infiltration air can impact the space conditioning energy expenditures and indoor comfort levels was shown in a nearby officers quarters. Heavy condensation on interior partitions and water streaming down interior doors took place when outside relative humidity rose to 70% RH levels in the 35°C temperature range. Checking the air infiltration/ventilation rate in this building with tracer gas seeded into separated wings of the officers quarters revealed an air change rate of four ACH. Even when all controllable vents were closed the levels were still greater than two ACH. Air conditioning energy was being devoted, in large part, to wringing out the water from this excessive air flow, intensifying the energy use but never achieving indoor comfort. Again the micro computer-based recording system aided parameter documentation but simple tracer gas methods provided positive proof that the design and operation was deficient.

4. CASE THREE - SPECIAL PURPOSE BUILDINGS

So far the concerns for air infiltration documentation have only centered on energy use and comfort. In the special purpose postal buildings now described, the building houses vehicles as well as the postal personnel. A variety of postal facilities were tested. They varied from the large city branch to the smaller town facility. The same concerns of energy and comfort prevail but in addition one must be concerned with interactions of the vehicle facilities with personnel areas. Using pressurization based upon the facility mechanical system, the interaction between the two zones can be further assessed. To check whether or not garage air was penetrating the personnel area, tracer gas was seeded into the garage at five times the normal concentration level and the areas immediately surrounding the garage were surveyed for tracer gas concentration build-up using the portable SF_6 detector. By injecting the tracer gas as a slug, indications of penetration time into adjacent rooms was also explored. For pinpointing the leakage sites, smoke gun techniques making use of the pressure differences between zones were found to be very useful.

The retrofit strategy had two purposes: first efforts were concentrated on correcting structural leaks (cracks and other building anomalies) that allowed garage air to pass into other work spaces; (an example is shown in Figure 5), the second effort was to rebalance the ventilation system so that the garage area was at a lower pressure than the adjacent building areas causing air flows to always go into the garage.

The measurement of local pressures was greatly aided by the use of a specialized field instrument, a digital output, high sensitivity yet stable pressure gage. The instrument captures a reference pressure on one side of the sensitive differential pressure transducer and then measures the difference between the reference and the local pressure. This device has proven very useful in balancing building ventilation systems by measuring local pressure differences across window and door openings, various rooms, hallways, etc. Used to measure differential presssures across the building envelope, the instrument locates those areas which should receive detailed infrared scans and/or represent areas for retrofit action. By eliminating the need to run pressure lines, and all the complications that it entails, together with the high sensitivity of the instrument (order 1/2 Pa per count), makes the unit a very worthwhile component of the building energy consultants instrumention "kit".

5. CASE 4 - INDOOR AND OUTDOOR POLLUTION

5.1 Indoor Sources

The energy consultant must deal with a variety of often conflicting demands, one of those demands is the maintenance of suitable indoor air quality in new or retrofitted buildings which may conflict with lowest energy use. The recent dramatic increase in sales of unvented fuel-fired space heaters in the United States has raised the question of whether or not the building air infiltration alone is sufficient to maintain appropriate indoor air quality in our homes using such devices. Again the consultant can use two methods to check either the building tightness or the natural air exchange rate through tracer gas techniques.

In the testing of a single-story rancher, the use of fan pressurization indicated an air change rate of slightly more than 10 ACH, at 50 Pascals. This is a very typical leakage rate for U.S. housing of the 1950s. In applying the tracer gas technique, a floor fan was necessary to aid tracer gas mixing because the house was hydronically heated (no ducts to aid room-to-room communication). The measurements took place over a three hour period at midday and indicated air infiltration rates never greater than 0.25 ACH for the 16°C differential temperature inside to outside (typical winter values for the location).

This case is cited for two reasons. First, indoor air quality questions are anticipated to generate increasing interest in exactly what range of minimum air infiltration rates can be anticipated in a wide variety of housing designs that do not rely on mechanical ventilation. Climate factors must be part of that question. Second, is the question of techniques and the ability to predict infiltration rates. When the pressurization data was used with the LBL model[7] (inserting building, terrain and weather factors) an air infiltration rate greater than 0.6 ACH was predicted in contrast to the 0.25 maximum ACH observed using tracer gas. For the consultant to limit testing to only pressurization or single point tracer gas measurements may cause a considerable error in predicting air infiltration conditions, especially minimum conditions, as they actually exist. With pollution questions room-to-room variation is also critical and will require the use of more sophisticated tracer gas testing such as the constant concentration approach, for a broad range of outdoor weather conditions. Perhaps the reason this house behaved so differently for the two testing approaches was that the hydronic heating design resulted in isolation of the living space from the basement[3]. In addition two sets of doors limited stairway coupling to the basement. Further field experience is needed to clarify such points.

5.2 Outdoor Sources

The previous example dealt with indoor pollution where hopefully adequate exchange rates with the outside air provides the needed ventilation. The opposite condition may also exist -- where the toxic substance is outside and extreme tightness of the building shell is the requirement. One example is the nuclear power plant control room where regulations mandate an almost zero leakage condition to prevent toxic fumes from entering the room as a result of a possible upwind toxic accident from influencing the power plant operators.

The newly established ASTM tracer gas standard procedures[8] are used as a stringent guideline for these tests which must be government approved. In making the tests, the consultant must carefully measure out the amount of tracer gas into the enclosed volume since the extremely low exhaust rates preclude venting within a reasonable time should high concentrations be inadvertently introduced. A side benefit from such testing is that an accurate measure of the "active volume" of the control room and attached duct work and circulation blower system can be ascertained from knowing exactly how much tracer gas was added to the volume. The testing process must be extended to at least four hours in order to satisfy the accuracy requirements, because of the small rate of tracer gas concentration decay. Care must be taken not to contaminate the duct system in the premixing procedure, i.e., tracer gas must be slowly introduced with all systems operating (circulation fans operating throughout the period with all vents closed). Otherwise strange events such as increasing concentration over time can take place, even hours after the test has begun. This is due to trapped pockets of tracer gas in low velocity locations in the ducts or room. Such mistakes will result in a costly new appointment with the control room staff who must remain within the room for hours throughout the test period. Automated air infiltration measurement equipment is extremely helpful during this type testing which is often scheduled after midnight.

6. CONCLUSIONS

The examples we have provided in the form of case studies are representative of the kind of challenges that can be met today by the knowledgeable investigator working with the tools and techniques that have been widely publicized by the AIC in the past few years. Often it is the air infiltration measurement that provides the justification to proceed further in the detective work associated with tightening the building envelope. Numerous other diagnostic techniques can be employed at that stage to pinpoint local problems or add to the documentation. Retesting with tracer gas and/or pressurization techniques confirms that proper retrofit measures have been taken. Suitable indoor air quality and occupant comfort go hand-in-hand with the correct application of these air infiltration measurement techniques which point out whether buildings are too leaky as well as being so tight that mechanical ventilation should be used.

In the many applications in the commercial, residential and industrial worlds there is a need to exchange field experiences because often test anomalies are only indications that unanticipated events are taking place. These events, when placed in proper perspective, will help all of us to understand our buildings better. The tools and techniques to perform such tests are now available. It is up to us to make full use of them.

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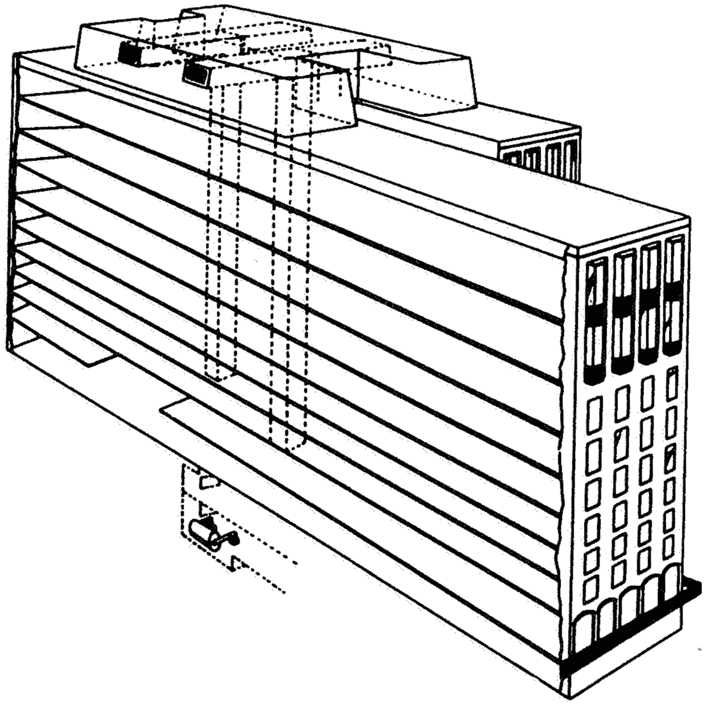

Figure 1 - Nine-story office building showing rooftop set of four air handlers used to distribute SF_6 tracer gas uniformly throughout the volume.

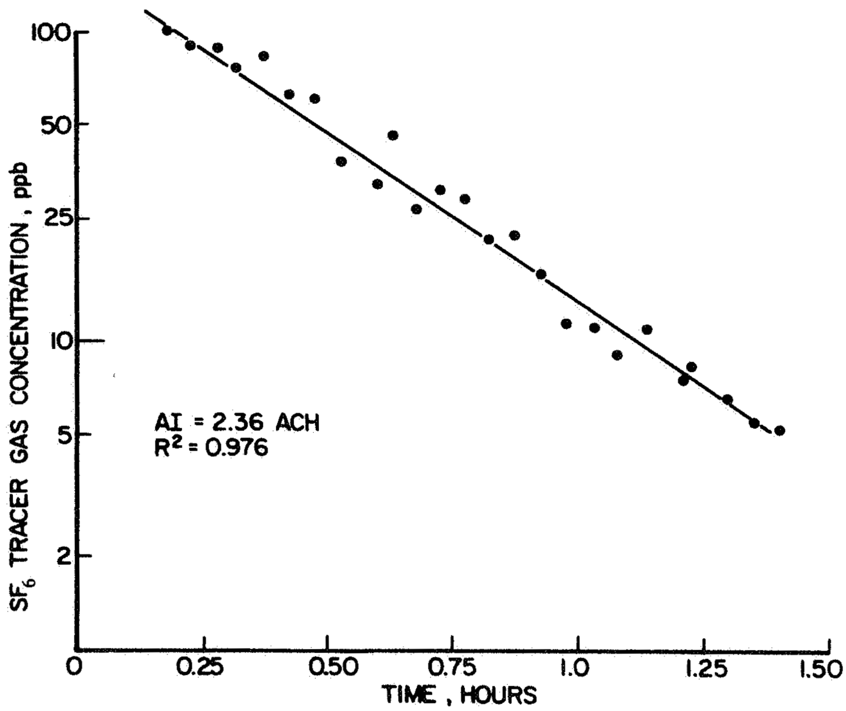

Figure 2 - Tracer gas concentration versus time for the building in Figure 1 as monitored with portable SF_6 detection equipment at the air handlers.

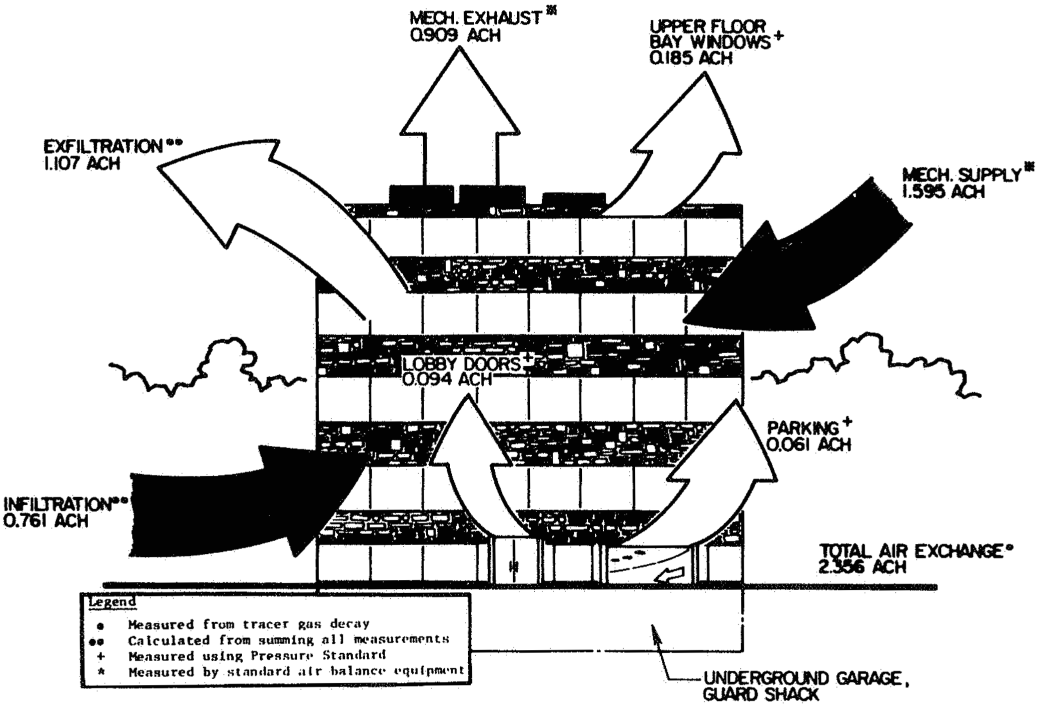

Figure 3 - The breakdown of air flow in the nine-story building using tracer gas techniques, supply and exhaust flow measurement and individual critical component leakage measurements.

Figure 4 - The horizontal spread is illustrated for this single-story housing located in the Middle East. Cooling is supplied by a central chiller plant. Gooseneck kitchen exhausts are one point of air infiltration.

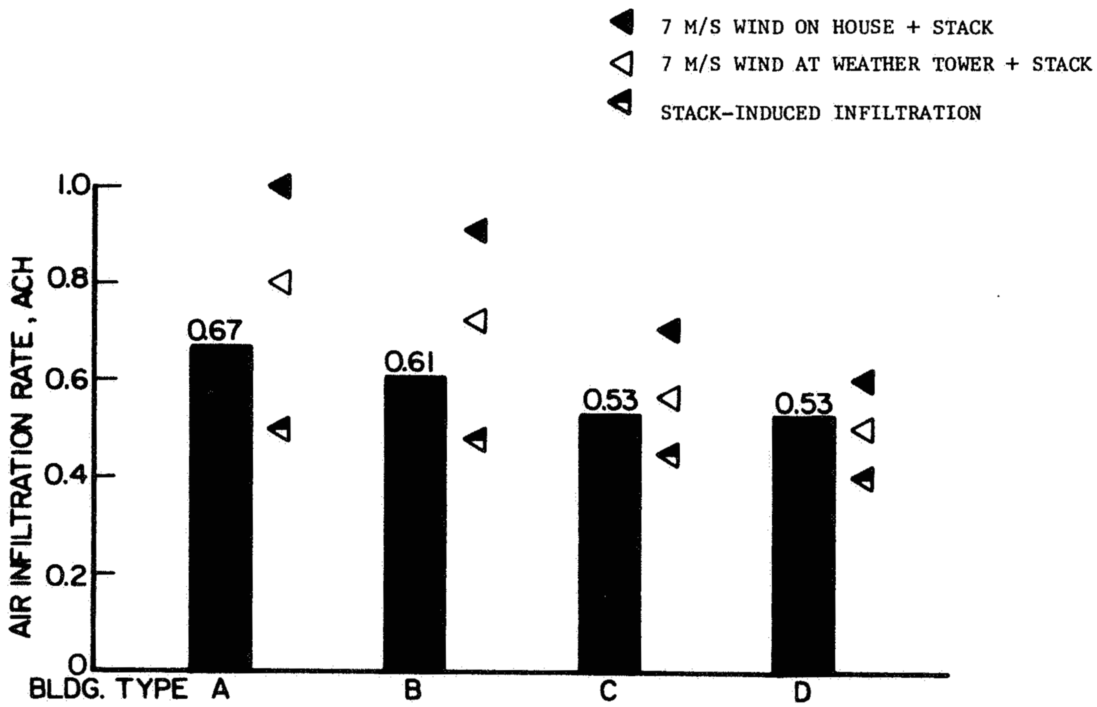

Figure 5 - Comparisons of air infiltration rates by tracer gas and pressurization techniques are shown to cover a range of values depending upon model inputs for the four types of houses.

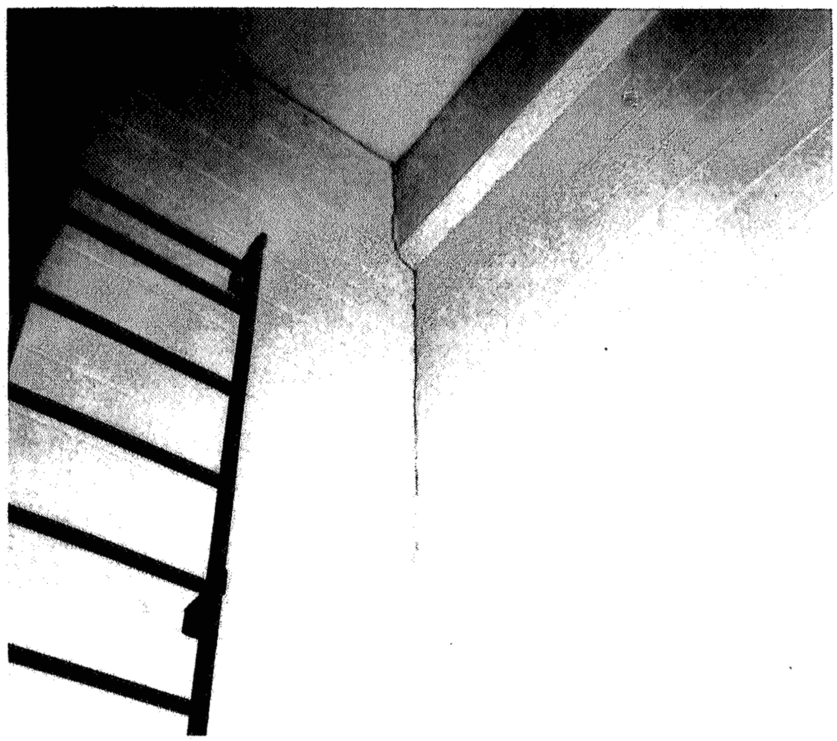

Figure 6 - A structural crack separating vehicle areas from personnel areas was proven to be a source of indoor pollution using tracer gas and smoke flow techniques.

AIR INFILTRATION REDUCTION IN EXISTING BUILDINGS

4th AIC Conference, September 26-28 1983, Elm, Switzerland

PAPER 3

AIR INFILTRATION CONTROL IN HOUSING - A GUIDE TO INTERNATIONAL PRACTICE

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ENERGY for heating and ventilating buildings constitutes a significant proportion of the total energy consumption in many countries. Traditionally, a building's energy status has been characterised primarily by the k-values - coefficients of thermal transmittance - of the various sections of the building. For this reason, there is a considerable amount known about thermal transmittance and detailed regulations exist in various countries as to how k-values should be calculated. Energy consumption resulting from transmission through the building envelope is therefore well-defined by the k-values of the structural components and the indoor-outdoor temperature difference.

In contrast to thermal transmission far more limited knowledge is available on the subjects of ventilation and airtightness. Standards and regulations are lacking. However, in recent research, efforts have been made to consider air leakage and ventilation in more detail. In many respects, the development of methods to save energy have led to a completely new construction technology. The aim of this construction technology is to make the building envelope so airtight that undesirable air leakage is minimized, and to do so in a safe manner.

From an energy viewpoint, it is important to limit the ventilation to the amount required for maintaining acceptable indoor air quality because significant quantities of energy may be consumed in heating outdoor air. There is great potential for reducing the total energy consumption for heating and ventilating by making both existing and new buildings sufficiently airtight to minimize undesirable air leakage.

It is becoming more and more important to consider the interaction between building technology and ventilation technology. Calculation methods have been developed which explain the mechanisms that govern the air leakage into a building. The driving forces for air leakage and ventilation are air pressure differences. These are made up of components from temperature and wind effects and, when mechanical ventilation is used, the effects of the fan.

The amount of air leakage is dependent also on the leakage characteristic of the building envelope. This means that a sufficiently 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 to some extent with controlled natural ventilation.

An overview of different ventilation systems for residential buildings is presented in Table 1. This table also contains a summary of advantages and disadvantages for each system.

Several new measurement methods have been developed to check the air-tightness of a building envelope. Some of these methods can be applied to determining air leakage and ventilation during different climatic conditions. Some methods are suitable for production control, othersfor research purposes. A schematic overview and comparison of different methods is given in Table 2.

It has been considered a matter of urgency to consolidate available research results and other experience in the form of a Handbook. This Handbook, "Air Infiltration Control in Housing - A Guide to International Practice", reviews the state-of-the-art with respect to air infiltration and leakage problems associated with housing in the countries which participate in the work of the Air Infiltration Centre.

General principles, motives, standards, assumptions, climate, energy balance in a house and common recurring design solutions for both existing and new buildings are treated in the Handbook's general section, Part A. It also includes a chapter on retrofits in existing buildings.

With regard to airtightness, lightweight types of constructions (wooden constructions, prefabricated lightweight elements, etc.) present many more problems than do massive types of constructions (brick walls, site-mixed concrete, etc.). However, all connections, joints and seams are critical, regardless of the construction style (see Figure 1). It is important to pay attention to the fact that cracks or gaps can develop as a consequence of movement in the structure. Sometimes it is difficult to seal such openings permanently. For this reason, well-fitting joint packings must be used that can fulfil their function even with relatively large movements in the structure.

A structure must be designed in such a way and with such materials that satisfactory thermal insulation and airtightness can be achieved in a durable way. This is especially true in view of present working methods and associated rapid installation rates. It is desirable that well-tried and tested construction techniques should be used to avoid making costly errors.

Examples from the handbook giving different solutions for joints between window or door frames and walls are shown in Figures 2 to 5.

Figure 2 shows two methods of jointing with internal sealing using mastic and mineral wool packing. To facilitate good sealing, it is recommended that the joint dimension is 15 ± 5mm. It is the mastic which provides the seal and, if the correct type is used, it forms an elastic, tight joint. The purpose of the bottoming strip is to provide a limit to the compression of the mastic in the joint.

Figure 3 shows how a polyurethane foam joint should be made. The joint width should not be less than 7mm, bearing in mind the application of the foam. The joint has very good thermal insulation properties compared with frame timber and adjacent wall material. The joint is normally sufficiently diffusion-tight and airtight even when joints are relatively wide.

In Figure 4 the thermal insulation in joints is provided by mineral wool. The actual airtightness (and diffusion seal) is achieved through the plastic film around the mineral wool strip. The thin plastic film adheres well to the frame and the wall. Good airtightness is achieved for joints between 10 and 20mm wide. Point leakage often occurs at window corners and around wedges.

Joint sealing between frame and wall by using profiles of EPDM rubber to provide the actual airtightness in the joint is shown in Figure 5. The gap should be between 10 and 20mm. At least two different moulding sizes are required for installation, bearing in mind different tolerances. To achieve good airtightness, both frame and adjacent wall should be very smooth. The tube should not be stretched too much during installation. Plastic films in timber walls should be joined to the tubular mounding in the joint.

Air leakage in older buildings has often been found to be unnecessarily high. Considerable energy savings are possible in many cases using relatively cheap and simple sealing measures. The main principle for sealing existing buildings must be to ensure that sufficient, but not excessive, ventilation is achieved. The full implications of the retrofit action must be considered. For example, Figure 6 shows the redistribution of air flow resulting from weatherstripping in a house with exhaust ventilation.

The Handbook includes discussion of techniques for retrofit sealing of windows, doors joints, joist connections, penetrations, timber flooring, walls and ceilings.

Part B of the Handbook contains detailed information about the climate in different countries and several design examples showing how building structures can be produced to achieve a reasonable degree of airtightness.

By tradition, building technology differs from country to country and thus the design and degree of airtightness are also different. In some cases, new building technology is necessary to minimize 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.

Figure 7 shows a design example of a Swedish design construction joint between the outer wall and the intermediate joint structure. The figure shows how good airtightness can be achieved by a continuous air/vapour barrier.

The continuity is achieved with a strip of reinforced polyethylene film which extends without a break between the intermediate joist structure even though the external wall in the upper floor is displaced outwards in relation to the external wall on the bottom floor. This strip, fitted when the framework is raised, is held in position between the joists with the aid of a nogging piece.

The joint between a gable external wall of load-bearing concrete and an intermediate joist structure is shown in Figure 8. Airtightness is achieved with mineral wool strips and internal mastic. The mastic must maintain its seal even after small movements in the joists. From an insulation aspect, the full thickness of mineral wool should be opposite the joist structure.

It is essential to improve airtightness at the ceiling/wall junction. Air leakage from the living accommodation to the attic can cause moisture problems in the structure. The example in Figure 9 shows a junction between the timber roof structure and a brick wall faced with plaster-board. The polyethylene vapour barrier above the ceiling is turned down the wall and fixed behind a plaster stop bead. Insulation is retained by a board which maintains a ventilation gap to the roof space and protects the insulation from the ventilation air.

Figure 10 shows a Canadian structural example. A unique double stud wall system has been developed which eases the installation of a vapour barrier. The air/vapour barrier is positioned in the outside of the inner stud wall. with this design the electrical wiring can be run on the inside of the air vapour barrier. Shown on the drawing are how and where joints in the polyethylene film can be made. Joints are not permitted elsewhere.

The examples given above are just a few of the design solutions which are illustrated and described in this 410-page reference book. It will be of great practical value to all those concerned with the design of problem-free dwellings with low energy demands and who recognise that design technology is being affected by new and more stringent requirements for building low-energy, well-insulated, well-sealed houses.

TABLE 1 Properties of ventilation systems for dwellings

Ventilation system	Advantages	Disadvantages
Natural ventilation (N)	Simple, low-cost installations. No moving parts in the system No electricity cost	Ventilation dependent on many factors: – Wind and temperature. Highest ventilation in cold and windy weather – Human behaviour in opening windows or special ventilation provision – Airtightness of the house and leakage distribution. Leaky houses suffer from excess ventilation and draught. In airtight houses there is a risk of insufficient ventilation with eg, condensation and air pollution problems as a result – Length of ducts and height of building Space demanding ducting (wide ducts) especially in multi-storey buildings
Natural controlled ventilation (NC). Automatic control of supply or exhaust air flows due to wind and/or temperature conditions	Low-cost improvement of N-system	The effects of such systems on ventilation and energy consumption are not yet sufficiently documented. Problems could arise in controlling air flows and airchange rates especially when driving forces are small and building not airtight Space-demanding ducting especially in multi-storey buildings
Mechanical exhaust fan ventilation (E)	Ventilation depends mostly on speed of fan Depressurization of building which reduces the risk of moisture convection outwards in the structure Low-cost mechanical ventilation system Air airtight envelope with properly sized and placed air inlets could provide a well distributed and controlled ventilation Easy to fit with heat recovery on the exhaust air (eg heat pump for hot water production)	A risk of insufficient ventilation in parts of building if leakages are unevenly distributed with big leaks close to the exhaust Air inlets must be properly sized and placed to reduce the speed of air into conditioned space (draughts). Discomfort caused especially during cold weather Fan forces are dominating which means that sealing measures are only effective to a certain limit. Ducts must often be cleaned
Mechanical supply and exhaust fan ventilation (SE)	If airtight building excellent control of ventilation in whole dwelling Possibilities to treat supply air with preheating and filtering Supply air could be taken from a place where air pollution is low Easy to fit with heat recovery	Expensive installations, especially in existing buildings Needs a very airtight building to function as intended. Very sensitive to pressure disturbances Noise from fans could be a problem Supply air devices must be placed properly to avoid dirt on surfaces caused by the airstream. Ducts must often be cleaned

TABLE 2 Comparison of methods for air infiltration measurements

	Method	Advantages	Disadvantages	Result
Determination of air changes (ventilation) in whole buildings or part of the buildings (single rooms)	Tracer gas (instantaneous)	Gives information about ventilation rate under running conditions. Needs relatively cheap equipment	Indirect method. Result depends on actual weather conditions. Mixing is difficult. Needs special training	Simultaneous air changes per hour (ac/h), m^3/s or m^3/h at operating conditions
Determination of air changes (ventilation) in whole buildings or part of the buildings (single rooms)	Tracer gas (instantaneous)	Gives information about the ventilation rate over a longer period under different operating conditions	Indirect method. Expensive equipment. Needs specialists. Can only be used in research and development projects	Air changes at operating conditions (ac/h), m^3/h or m^3/s)
Determination of air changes (ventilation) in whole buildings or part of the buildings (single rooms)	Tracer gas (container sampling)	Simple to handle and cheap method	Indirect method. Low control of taking samples	ac/h
Determination of the airtightness of the building envelope	Whole house pressurization	Gives information about the leakiness of the building envelope. At difference in pressure between in- and outside, the method is mostly independent of weather conditions. Cheap equipment. Easy to handle	Gives no information about actual ventilation degree. Gives information about air leakage at other pressure differences than operating conditions	Air leakage at high pressure differences (ac/h, m^3/s or m^3/h)
Determination of the airtightness of the building envelope	Components pressurization	A possibility to quantify airleakage through building components. Simple equipment. Relatively easy to handle	Takes time to adjust the equipment to actual component	Air leakage in m^3/h, m^3/s, or $m^3 m^2 h$ at x Pa
Qualitative detection of air leakage sites	Thermography	Gives information about leakage sites and at the same time defects in the thermal insulation. Can be used as control of workmanship	Expensive equipment. Needs temperature difference of at least 10K between outside and inside. Needs specialist	Identifying leakage sites
Qualitative detection of air leakage sites	Smoke pencil	Gives information about leakage sites and air movements. Very simple and cheap method	Difficult to find leaks especially with internal over pressure	Identifying leakage sites

FIGURE 1 The structural sections which often give rise to complaints about draughts. The ways in which airtightness is achieved at joints between different building elements are seldom shown in building documentation.

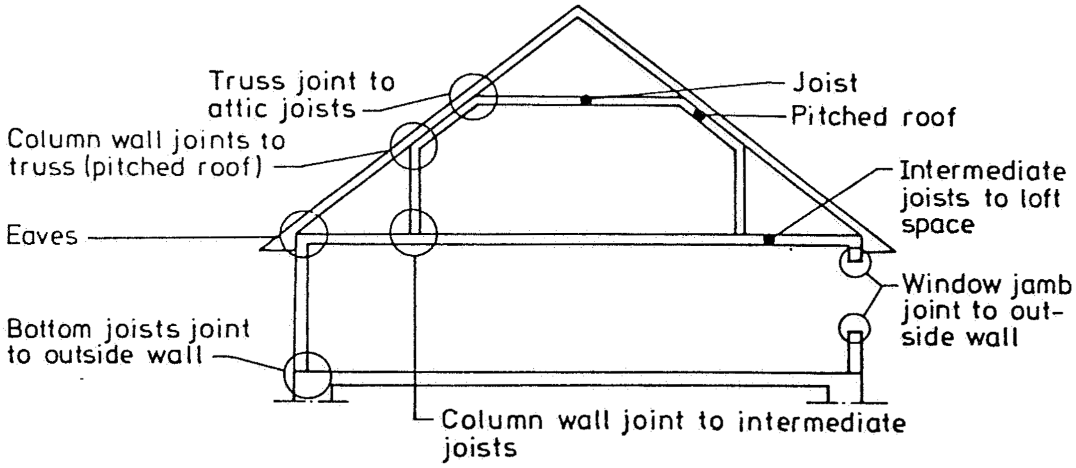
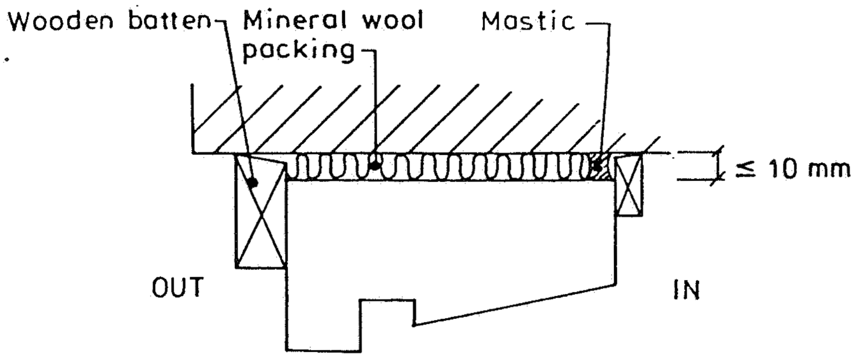


FIGURE 2 Two methods of jointing with mastic



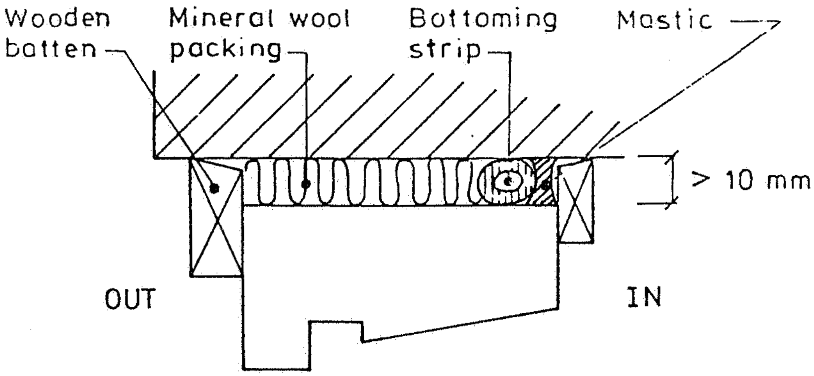


FIGURE 3 How a polyurethane foam joint should be made

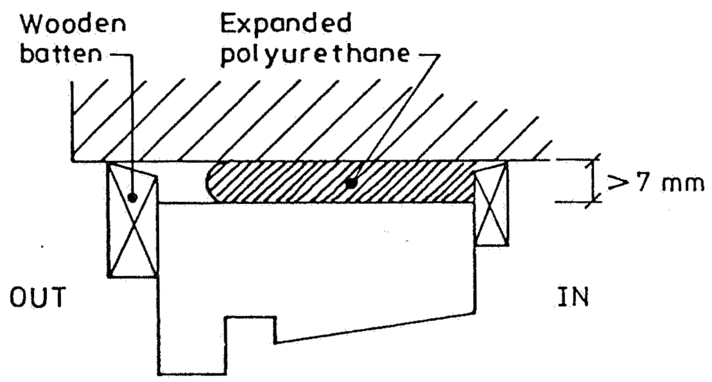


FIGURE 4 Sealing strips and plastic film

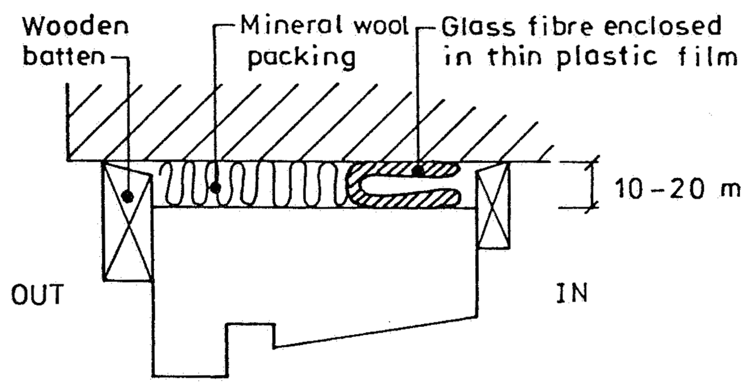


FIGURE 5 Tubular strip

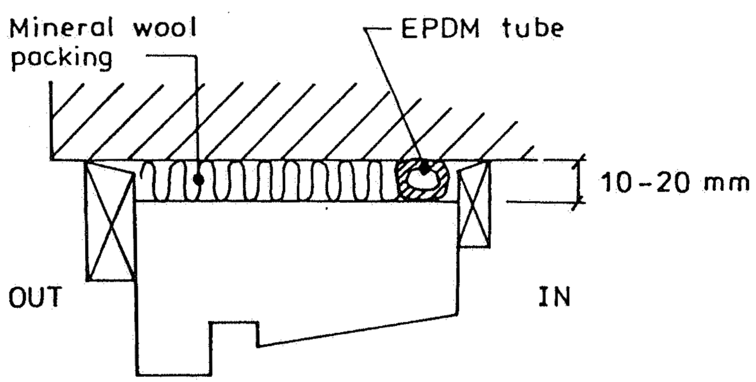


FIGURE 6 Flow change in an exhaust air ventilated house when windows are fitted with new weatherstripping.

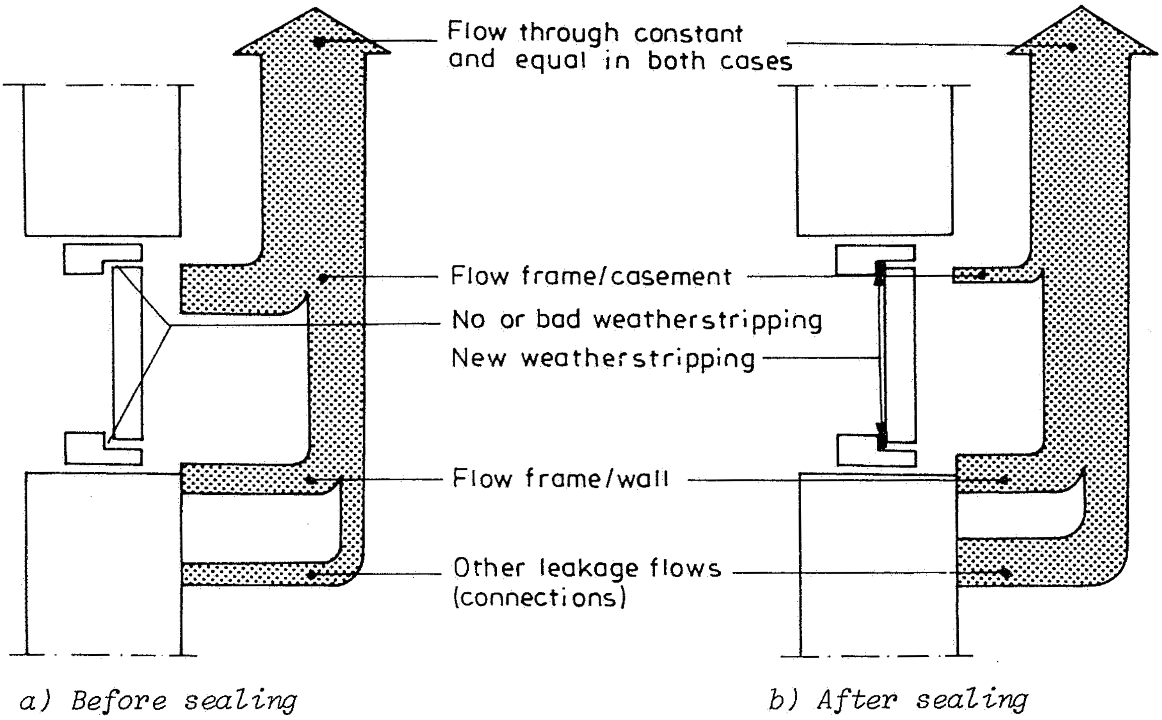


FIGURE 7 Joint between outer wall (facade wall) and intermediate joist structure

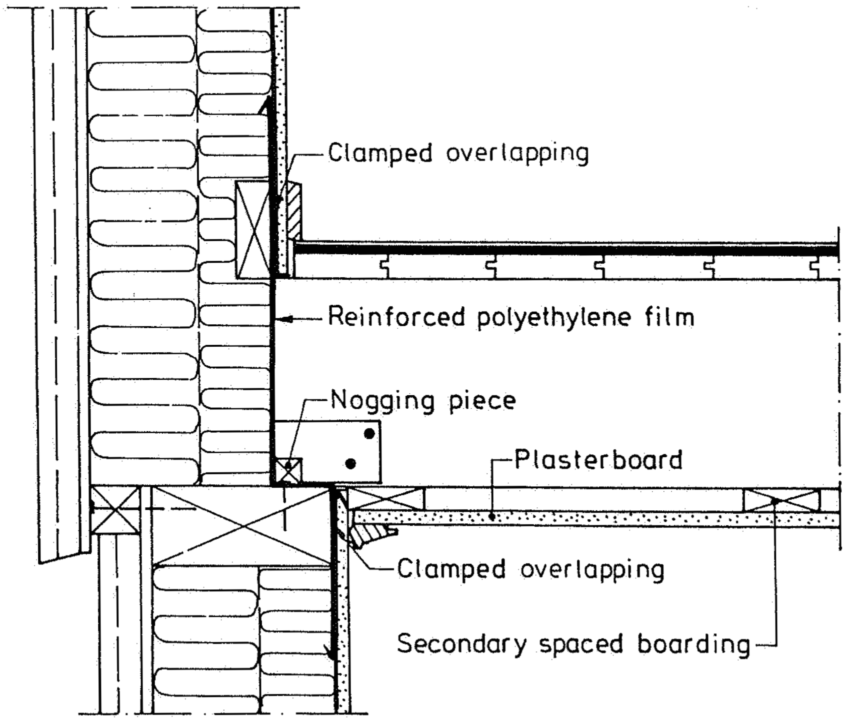


FIGURE 8 Joint between gable external wall of concrete elements and intermediate joist structure

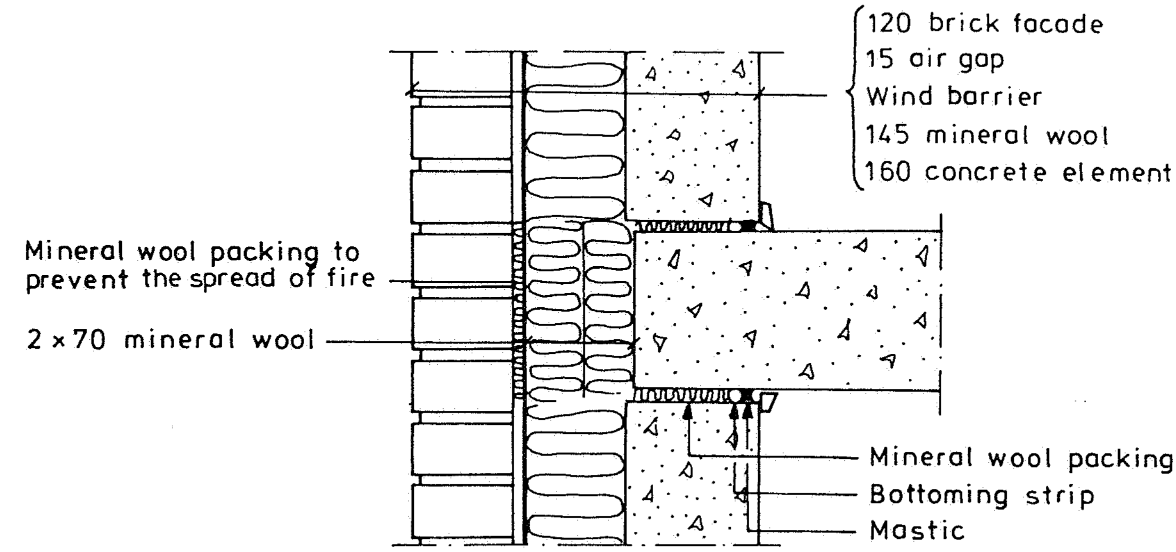


FIGURE 9 Roof junction with external wall (United Kingdom)

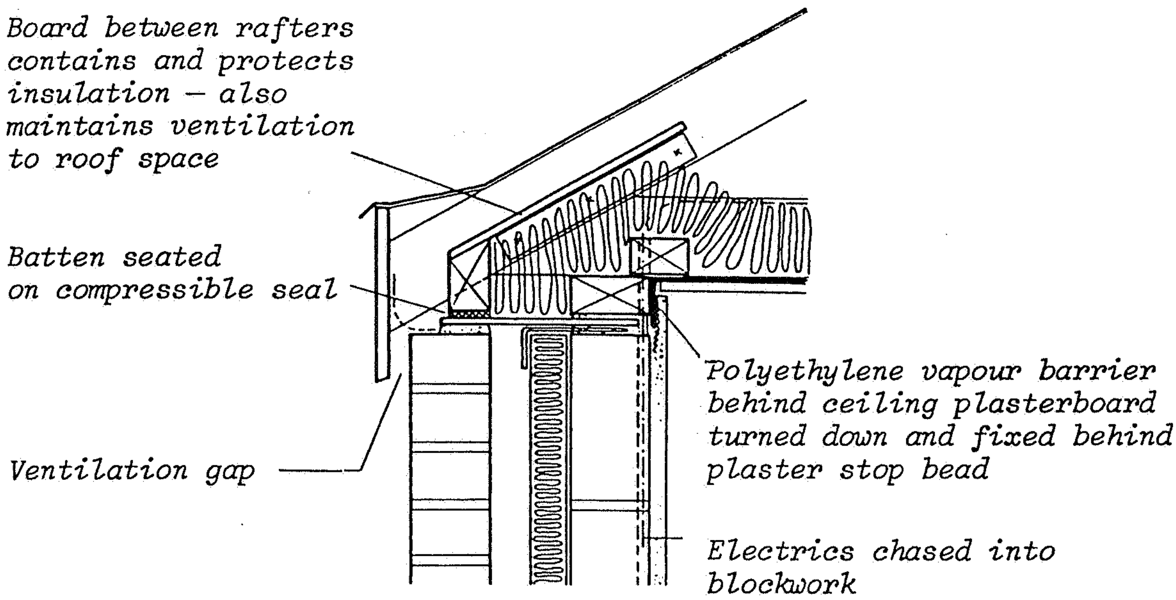
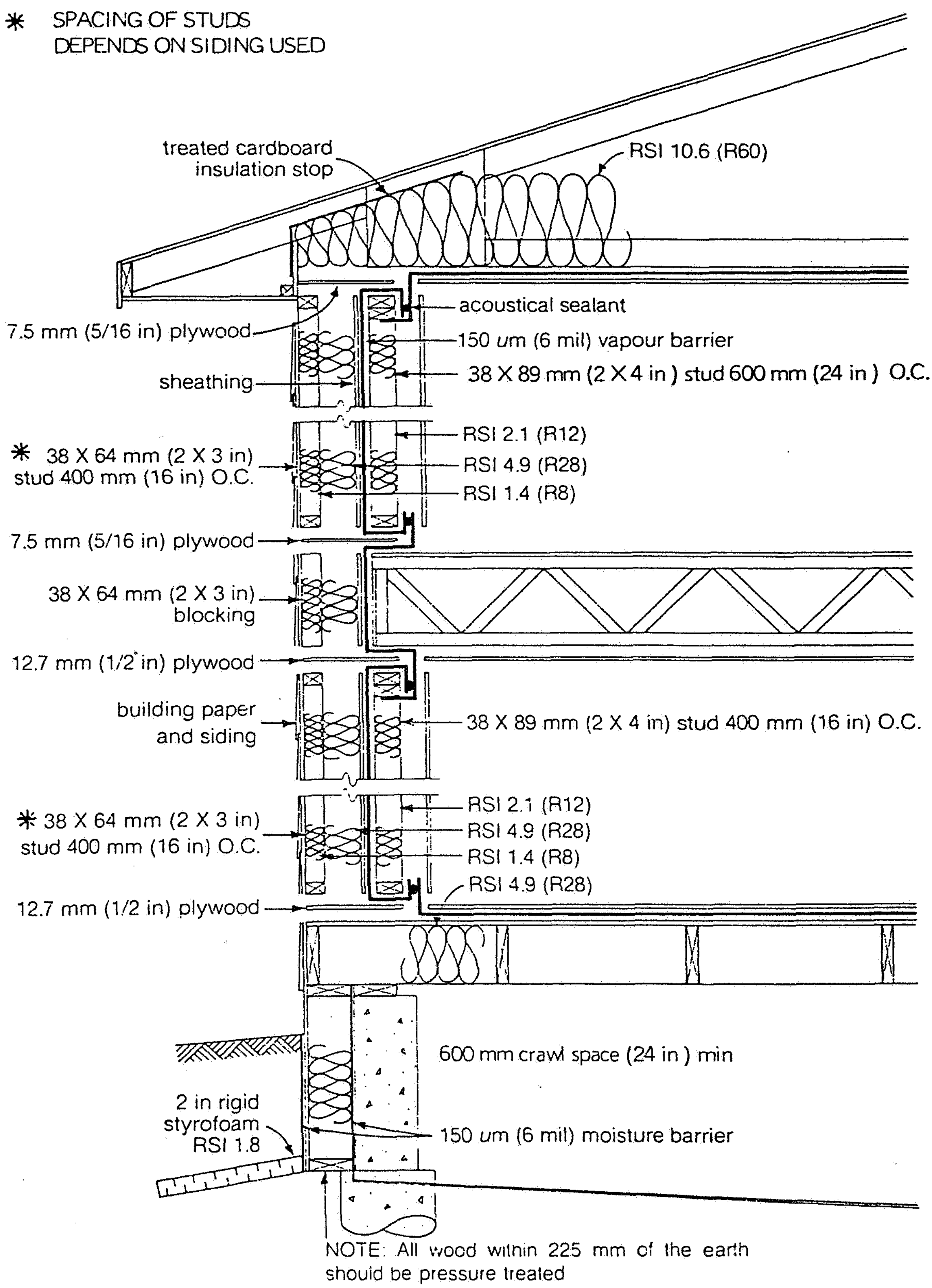


FIGURE 10 Wall section - grade beam and piling foundation



AIR INFILTRATION REDUCTION IN EXISTING BUILDINGS

4th AIC Conference, September 26-28 1983, Elm, Switzerland

PAPER 4

THE MEASUREMENT OF AIR INFILTRATION RATES IN LARGE ENCLOSURES AND BUILDINGS

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CONTENTS

SYNOPSIS

The paper describes work carried out as part of a research contract funded by the U.K. Department of the Environment and the Commission of the European Communities.

The object of the research is to develop a validated method of measuring air infiltration rates in industrial buildings and to use the method to measure ventilation rates in some selected buildings.

The following points are discussed:

(a) Poor mixing in industrial buildings.
Implications of poor mixing for choice of measurement method and interpretation of results.

(b) Review of possible measurement methods. Trials of a low cost fuel cell gas analyser designed for measuring ethanol vapour.

(c) A computer-controlled multi-point tracer gas concentration measurement system using infra-red gas analysers and nitrous oxide as the tracer gas.

(d) Preliminary results obtained with only natural ventilation.

(e) Need to validate method by comparing ventilation rates measured by tracer gas method with mechanical extract or supply rates while depressurising or pressurising a test enclosure. Airtightness testing of two industrial buildings in preparation for validation work.

LIST OF SYMBOLS

Symbol	Definition	Units
C	Tracer gas concentration	Dimensionless (%, parts per million,etc.)
C_z	Tracer gas concentration in zone z	Dimensionless
E	Error in calculated time-integrated ventilation rate	m^3
Q	Air flow rate	m^3/s
Q_{xy}	Air flow rate from zone x to zone y, $> = 0$ Zone 0 is defined as the outside atmosphere.	m^3/s
t	Time	s
V	Volume	m^3
V_z	Volume of zone z	m^3

LIST OF TABLES

LIST OF FIGURES

1. ENERGY CONSERVATION IN LARGE SINGLE CELL BUILDINGS

The floor area of industrial and warehouse buildings in the UK is about 410,000,000 m^2.

If we assume that:

i) the mean storey height is 6m

ii) the inside temperature is maintained at 15.5°C

iii) the ventilation rate is constant at one air change per hour

iv) the number of degree days in the heating season (September - May) is 2200,

then the heat required to heat the air from ambient to inside temperature is 1.6×10^{17} J/year. This represents about 3% of the total UK energy consumption by final users (5.8×10^{18} J/year).

However, industrial and warehouse buildings usually consist of a single large space or a small number of large spaces. There is at present no reliable method of measuring ventilation rates in these spaces. Therefore, there is no way of knowing whether the energy loss and possible savings estimated above are over or under estimated and no certain way of determining the cost effectiveness of any measures taken to reduce unwanted ventilation.

The purpose of this research is to develop a method of measuring ventilation rates in large single cell buildings. This will allow data on ventilation rates to be collected and the effectiveness of measures for reducing ventilation rates to be assessed and thus enable energy conservation efforts to be directed to where they will have most effect.

2. VENTILATION RATE MEASUREMENT USING TRACER GAS

2.1 General Principles

The classical method of measuring ventilation rates is to inject a gas, known as a tracer gas, into the air in the building so as to differentiate it from the outside air. If the tracer gas injection strategy and concentration history are known, then it should in principle be possible to calculate the ventilation rate.

Other methods of measuring ventilation rates are possible. For instance, if the total and conduction heat losses of a building were accurately known, the ventilation rate could be derived from the residual heat loss and the inside and outside temperatures. Such unconventional methods have been rejected for this research as containing too many uncertainties to allow their application at present to large buildings.

2.2 Perfect Mixing

It has been usual, when measuring ventilation rates using tracer gas methods, to assume that the air in the space is well mixed. This has been found to be a reasonable assumption for the small spaces such as dwellings and cellular offices where most previous measurements have been made. If there has been doubt that the air in the space is sufficiently well mixed, fans have been used to provide good mixing artifically.

If the air in a space is well mixed the concentration of tracer gas will be substantially constant throughout and the equations relating the ventilation rate and tracer gas concentration can be easily derived. Kronvall (9) derives the equations for the three common measurement methods, which are the concentration decay, constant concentration and constant emission methods. Tracer gas concentration only needs to be measured at one point in the space.

2.3 Imperfect Mixing

If the air in a space is not well mixed then the rate at which tracer gas is removed from the space will depend on the sum of the air flows out of the space and the tracer gas concentration in each air flow.

A single point concentration measurement will therefore not yield sufficient information to enable the ventilation rate to be calculated (or, in the case of the constant concentration method, to enable the tracer concentration to be controlled).

Ideally, each outward air flow would be identified and the appropriate tracer gas concentration measured. In practice, a multi-point tracer concentration measurement system would be used and the ventilation rate would be estimated from the information available.

2.4 Simulation of Imperfect Mixing

To obtain an idea of what the consequences of imperfect mixing might be for ventilation rate measurements in a large space, a simple numerical model was developed which simulates a ventilation rate measurement by the concentration decay method.

The model has nine inside zones and one outside zone. Each zone is assumed to be fully mixed. The size of each zone, the initial tracer gas concentration in each zone and air flows in each direction between adjacent zones can be individually specified. The tracer gas concentration in the outside zone is always zero.

Considering first the case of a concentration decay measurement in a well mixed space, the equation relating the tracer gas concentration and time is

$$\ln C_{t2} = \ln C_{t1} - \frac{Q}{V}(t2 - t1)$$

where C_{t1} = tracer gas concentration at time t1

C_{t2} = tracer gas concentration at time t2

This is the equation of a straight line with gradient $-\frac{Q}{V}$ on a graph of lnC against t. The results produced by the the model were therefore plotted as a graph of lnC against t.

Exploratory calculations using this model produced the following results:

i) All lines parallel, slope shallower than $-\frac{Q}{V}$.

ii) Not all lines parallel, some slopes steeper and some shallower than $-\frac{Q}{V}$

iii) Not all lines parallel, all steeper than $-\frac{Q}{V}$.

Examples of these are shown in Figures 1 - 3. The air flows assumed to produce these results are shown in Figures 4 - 6. Concentrations for zones 3,6 and 9 are not shown as they are the same as concentrations in zones 1, 4 and 7 respectively.

It will be noticed that the slope of the mean concentration line is in general not equal to the slope of the perfect mixing line, so any measurement method which simply relied on average tracer gas concentrations could be seriously in error if used in an imperfectly mixed space.

The range of tracer gas concentration needed to obtain straight concentration decay lines is sometimes very large, several decades. This is larger than the range of most practical instruments. If mixing in practice is as poor as has been assumed for these simulations, this problem will have to be dealt with by using a very large initial tracer gas concentration so as to observe the straight parts of the concentration decay curves as they pass through the instrument's measuring range, or by using an analysis technique which does not depend on exponential decay of tracer gas concentrations. Such a method is described in section 2.5.

The other possible results have not yet been produced, but there does not seem to be any reason why air movement patterns which will produce them should not be found. They are:

i) all lines parallel, slope steeper than $-\frac{Q}{V}$

ii) all lines parallel, slope equal to $-\frac{Q}{V}$

iii) not all lines parallel, all slopes shallower than $-\frac{Q}{V}$

The model can be extended to a very large number of zones. The number used is limited mainly by the labour involved in developing the program and specifying the input data.

2.5 Analysis Method for Imperfect Mixing

This method is adapted from that described by Penman and Rashid (8). Figure 7 shows a generalised multi-zone model of ventilation of a space and air movement within it. It is assumed that the space can be divided into a number of well-mixed zones of known shape and size.

The general equation governing the tracer gas concentrations within the space is:

Rate of supply of gas - Rate of removal of gas
= Rate of change of quantity of gas in space

The easiest ventilation rate measurement method to use is the concentration decay method, in which:

Rate of supply of gas = 0

The rate of removal of gas from the space is simply the sum of the air flow rates from each zone to the outside, each multiplied by its appropriate tracer gas concentration:

$$Q_{10} C_1 + Q_{20} C_2 + \dots\dots\dots\dots + Q_{Z0} C_Z$$

$$= \sum_{z=1}^{Z} Q_{zo} C_z$$

The rate of change of the quantity of tracer gas in the space is the sum of the volumes of the zones each multiplied by the appropriate rate of change of tracer gas concentration:

$$V_1 \frac{dC_1}{dt} + V_2 \frac{dC_2}{dt} + \dots\dots\dots\dots V_Z \frac{dC_Z}{dt}$$

$$= \sum_{z=1}^{Z} V_z \frac{dC_z}{dt}$$

Thus

$$0 - \sum_{z=1}^{Z} Q_{zo} C_z = \sum_{z=1}^{Z} V_z \frac{dC_z}{dt}$$

During a concentration decay measurement the values of C_z and $\frac{dC_z}{dt}$ will vary with time, so by integrating from time t0 to time t1 the following is derived:

$$- \sum_{z=1}^{Z} \left(Q_{zo} \int_{to}^{t1} C_z \, dt\right) = \sum_{z=1}^{Z} \left(V_z \left(C_{z,t1} - C_{z,t0}\right)\right)$$

In this equation Q_{zo} are unknown (assumed constant), C_z are measured and V_z are estimated.

By integrating over T time intervals the following set of simultaneous equations is obtained:

$$- \sum_{z=1}^{Z} \left(Q_{zo} \int_{to}^{t1} C_z \, dt\right) = \sum_{z=1}^{Z} \left(V_z \left(C_{z,t1} - C_{z,to}\right)\right)$$

$$- \sum_{z=1}^{Z} \left(Q_{zo} \int_{t1}^{t2} C_z dt\right) = \sum_{z=1}^{Z} \left(V_z \left(C_{z,t2} - C_{z,t1}\right)\right)$$

etc.

$$- \sum_{z=1}^{Z} \left(Q_{zo} \int_{t(T-1)}^{tT} C_z \, dt\right) = \sum_{z=1}^{Z} \left(V_z \left(C_{z,tT} - C_{z,t(T-1)}\right)\right)$$

If T, the number of equations, equals Z, the number of zones within the space, then a unique solution for the Q_{zo} terms exists provided that all the equations are independent. However, experimental errors in measuring C_z and in estimating V_z make an alternative approach more interesting.

This alternative approach is to insert estimated values of Q_{zo} in the equations and rewrite them as:

$$\sum_{z=1}^{Z} V_z(C_{z,t1} - C_{z,to}) + Q_{zo} \int_{to}^{t1} C_z dt) = E_1$$

$$\sum_{z=1}^{Z} V_z(C_{z,t2} - C_{z,t1}) + Q_{zo} \int_{t1}^{t2} C_z dt) = E_2$$

etc.

$$\sum_{z=1}^{Z} V_z(C_{z,tT} - C_{z,t(T-1)}) + Q_{zo} \int_{t(T-1)}^{tT} C_z dt) = E_T$$

Here the magnitude of each E represents the magnitude of the discrepancy between the observed values of C_z and the assumed values of Q_{zo}.

Provided that T > Z and that the equations are sufficiently independent, it should be possible to use iterative techniques to find the values of the Q_{zo} terms which minimise an error function:

$$f(E_1, E_2, \ldots E_T)$$

subject to the constraint that

$$Q_{zo} >= 0$$

for all z.

The assumption that the space can be divided into a number of well-mixed zones of known shape and size is a very great simplification of the true situation.

Section 7 outlines a programme of work intended to provide data on the accuracy of the method.

3. MIXING IN LARGE SINGLE CELL BUILDINGS

3.1 Probability of Imperfect Mixing

A preliminary analysis suggests that imperfect mixing is likely in large single cell buildings. These are typically factories or warehouses. They often contain large quantities of goods or machinery which present barriers to air circulation between different parts of the space. They are often heated by heaters mounted at high level, which can create stable layers of warm air at the top of the building and cool air below with little mixing between them. This suggests that imperfect mixing is likely to be a problem.

A search has been carried out to obtain information on air movement in naturally ventilated large buildings, but very little published work has been found. Imperfect mixing, however, seems to be common (1, 2, 7).

Air movement in buildings with mechanical supply ventilation or forced warm air heating is largely determined by the mechanical systems when these are in operation. The effectiveness of mechanical systems in mixing tracer gas within a room is currently being studied by other researchers (3, 4,5, 6).

3.2 Objections to Artificial Mixing

There are both theoretical and practical objections to using fans to obtain good mixing in an imperfectly mixed large space.

The theoretical objection to the use of mixing fans is that they may change the infiltration rate by, for instance, destroying temperature gradients within the building.

The practical objections are that:

i) in a large building, large and expensive mixing fans are likely to be required.

ii) in an occupied building, the installation of mixing fans will probably be time consuming for the research team and inconvenient for the occupants.

The programme of research is therefore based on the premises that imperfect mixing is likely and that the ventilation rate measurement method should take account of this. This means that a multi-point tracer gas concentration measurement system will be required.

4. POSSIBLE NOVEL INSTRUMENTS

4.1 Disadvantages of Conventional Instruments

Conventional instruments for measuring tracer gas concentrations, such as infra-red gas analysers or electron capture detectors, suffer from certain disadvantages when a large number of measurement points are required. The instruments tend to be rather bulky and heavy, which is a disadvantage when working away from the laboratory. Also, a balance has to be struck between using many analysers, which is expensive, and using a smaller number of analysers each serving a larger number of measurement points, which results in each measurement point being served less frequently.

A survey of available instruments was therefore made in order to discover whether recent advances in technology had resulted in possible new methods of tracer gas measurement.

4.2 Novel Instruments

The following tracer concentration measurement methods were found to be of interest:

(a) absorption of infra-red laser beam

(b) collection of tracer(s) in thermal desorption tubes

(c) detection of ethanol by use of fuel cells.

4.2.1 Absorption of Infra-red Laser Beam

This method is based on the absorption of an infra-red laser beam as it passes through the test space. The beam is tuned to an absorption frequency of the tracer gas, and the decrease in the intensity of the beam from the transmitter to the receiver indicates the quantity of tracer gas along the path of the beam.

This method can be applied in various ways. The transmitter and receiver can be separate, or they can be adjacent and the beam can be reflected from a room surface so as to fall on the receiver. The measurement beam can be used alone, or together with a reference beam at a slightly different frequency, which will provide a continuous indication of the effects of absorption due to other causes than the tracer gas. The essentials of the method are shown in figure 8.

The disadvantages of this method are the high cost of the equipment (£40 - 50,000) and that it is essentially an averaging method. It can cover a great deal of space from a single point, but yields insufficient information about the distribution of tracer gas in the space. It was therefore rejected as unsuitable.

4.2.2 Collection of Tracer(s) in Thermal Desorption Tubes

The basic measurement equipment consists of a small, relatively inexpensive adsorption tube of similar dimensions to a ball point pen. The tube is packed with a suitable adsorption media eg "chromosorb" which is used to adsorb samples either by direct diffusion, or alternatively a controlled air flow may be induced by the use of a pump. After exposure, a storage cap is placed over the tube for transportation to the laboratory for analysis.

Analysis of the sample tubes may be carried out remotely from the test site, using an automatic gas analyser. The complete sampling tube is heated to 250°C in a flow of carrier gas and the vapours transported directly to the gas chromatograph column. This procedure both injects the sample, and cleans the adsorption tube, which may then be capped and stored for re-use.

A practical ventilation rate measurement system (shown in figure 9) consists of a large number of adsorption tubes divided into groups, one group for each measurement point. A small sampling tube runs from each measurement point to each group of adsorption tubes, where it divides to form a manifold connected to their inlets. The outlets of the adsorption tubes are connected to a common vacuum pump. Valves control which adsorption tube in each group is in use.

Such a system has the advantage that it could be used with multiple tracers to obtain detailed information about air movements. It has the following disadvantages:

(a) no information is available to the experimenters while performing the measurements

(b) as a consequence of (a), the system is unable to be used for constant concentration measurements

(c) the number of adsorption tubes and valves and the size of the racks required to contain them increases in proportion to the number of times a concentration is required for each measurement point.

The system was therefore rejected as unsuitable.

4.2.3 Detection of Ethanol by use of Fuel Cells

4.2.3.1 General

The possibility of using fuel cells as a primary source of energy by converting chemical energy directly into electrical energy has been the subject of extensive research, particularly in the field of space exploration. However, under certain conditions, the electrical power from a fuel cell is dependent on the gaseous fuel it receives, so that the use of such devices as analytical gas sensors is possible. This subject has been extensively researched in the UK, to the point where analytical fuel cell detectors for ethanol and formaldehyde are now on the market, and an adaptation of such device was proposed as a suitable detector for air infiltration measurements.

4.2.3.2 Principle of the Fuel Cell Detector

The fuel cell detector, shown in simplified form in Figure 10, is constructed from porous PVC discs (30 mm ø x 1 mm) which have been gold plated on each surface to form the electrodes of the cell. After electroplating, the discs are immersed in phosphoric acid electrolyte. The cell is then mounted in a sealed plastic moulding with the necessary electrical contacts. The plastic moulding provides a small deadspace volume above each electrode, together with the inlet and outlet ports above the anode plate.

The general principle of the anlaytic fuel cell is quite simple although the exact chemical reactions which take place are not clearly understood. At one electrode, the anode, one chemical compound is reduced and at the other, another chemical compound is oxidised. Therefore, the essential requirement for the fuel cell to operate as an analytical sensor is that the chemical to be detected must be either oxidisable or reducible, at the particular electrode surface, the former applying to most situations. The electrical response of the cell to the presence of an oxidisable gas introduced through the sample port is proportional to the quantity of gas which is absorbed onto the face of the electrode, and hence which is present in the gas sample. Since the absolute quantity of the oxidisable gas is small, the oxygen requirement to complete the reaction at the cathode is correspondingly small, so that diffusion from the air in the deadspace is sufficient. The fuel cell may be used to measure ethanol vapour in the parts per million concentration range, when the following reactions are thought to occur.

At the anode (working electrode)

$$CH_3CH_2OH \quad - \quad CH_3CHOH + H^+ + e$$

$$CH_3CHOH \quad - \quad CH_3CHO + H^+ + e$$

At the cathode (reference electrode)

$$H_2O + \tfrac{1}{2}O_2 + 2e \quad - \quad 2OH^-$$

Electrons generated by the oxidation process cause the working electrode to become polarised with respect to the reference electrode. In all applications, the working electrode is therefore depolarised by connecting a small external resistance across the cell electrodes. The small potential difference, in the order of millivolts, generated across this resistor by the electron flow is an indication of the quantity of gas at the working electrode.

A typical response curve is shown in Figure 11. The external resistance gives rise to an exponential discharge curve, and the combination of this with the charge curve due to the ethanol oxidisation results in the overall response curve characterised by the rapid increase in output to a peak followed by an exponential decay. The level of the peak voltage is directly related to the concentration of fuel in the cell.

4.2.3.3 Advantages of the Fuel Cell Transducer

The main advantages of the fuel cell transducer in its basic form are:

(a) small size, 80 x 60 x 30 mm.

(b) low weight, 100 gm.

(c) no power requirement

(d) low threshold value of detection, a few parts per million

(e) low cost, about £100.

As a result of these advantages it was decided to purchase two fuel cell units for laboratory trials using ethanol as the tracer gas.

4.2.3.4 Detailed Investigation of Fuel Cell

The following conclusions were reached as a result of the detailed investigation of the fuel cell:

(a) its output is strongly temperature dependent. When sampling air at 21°C containing ethanol at 190 ppm, the fuel cell produced peak outputs of 5.0mV at 21° (Figure 11) and 6.6mV at 61°C (Figure 12). To maintain the fuel cell at a temperature of approximately 60°C the manufacturers produce an electrically heated pad which is placed around the fuel cell. A proportional temperature controller was constructed to control the heating power of the pad and thereby hold the temperature of the fuel cell within 0.3°C of the set temperature.

(b) the time required for it to reach its peak output is dependent on temperature, and possibly on tracer concentration.

(c) the time required for the output to decay to a low level that will not interfere with the next measurement is dependent on temperature, on the external resistance of the measuring circuit and possibly on tracer concentration.

(d) the cell produces a spurious output if ethanol is present in the ambient air.

(e) each fuel cell must be individually calibrated.

5. FUEL CELL AND INFRA RED GAS ANALYSER MEASUREMENT SYSTEMS

5.1 Preliminary Design for System using Fuel Cell Analysers

5.1.1 General

Figure 13 shows a preliminary desgin for a multi-point tracer gas concentration measurement system using fuel cell gas analysers. 30 measurement points for concentration and temperature were assumed.

Each fuel cell analyser unit as shown in Figure 13 consists of the fuel cell itself, an electrically heated jacket with thermostatic control, a solenoid actuated diaphragm sampling pump and a thermocouple for measurement of ambient temperature.

The microcomputer controls the scanners, multimeter, printer and disc drive so as to:

(a) select individual fuel cells, thermocouples and other instruments for connection to the multimeter by the scanners and measurement of their output by the multimeter,

(b) receive the measurements from the multimeter,

(c) translate measured outputs into physical quantities using calibration data,

(d) record tracer gas concentrations, temperatures and other data on disc,

(e) print out selected data and operating information,

(f) command the fuel cell analysers to take samples and to reset after completing each measurement.

5.1.2 Technical Problems

A number of technical problems were expected with this system. These are discussed below.

A considerable amount of work was required to establish whether the fuel cell analyser could achieve sufficient speed and accuracy, and to repackage it in a suitable form (incorporating an ambient temperature measurement, an electrically heated enclosure with thermostatic control and remote control of the analyser itself).

The output of the fuel cell analyser rises to a peak and then falls after a sample has been taken, the peak output indicating the tracer gas concentration. The microcomputers which would be suitable for this application on the basis of price, input/output capability and ease of programming tend to be rather slow and thus the computer might be unable to scan serveral fuel cells simultaneously and calculate the peak outputs of each in addition to tis other tasks. The alternative of operating and monitoring one fuel cell at a time could be too slow, as the fuel cell takes about 30 seconds to reach its peak output. Allowing some time for other tasks and some variation of the speed of the fuel cell, 30 cells could each be served by the computer at approximately 30 minute intervals. A higher sampling frequency than this was expected to be required.

The long signal lines from the fuel cell analysers back to the computer and its peripherals would be liable to interference which could lead to inaccuracies or even inability to perform measurements.

The fuel cell analysers are designed to measure the concentration of ethanol vapour in the air. High vapour concentrations near the ethanol source would be probable and would create a considerable fire hazard.

The calibration of thirty or more fuel cells would be very costly and time consuming.

5.1.3 Estimated cost

The cost of the system shown in figure 13 was estimated to be about £23000, not including equipment required for fuel cell calibration, erection on site, etc.

5.2 Preliminary Design for System using Infra-red Gas Analysers

5.2.1 General

Figure 14 shows a preliminary design for a multi-point tracer gas concentration measurement system using infra-red gas analysers.

The gas analysers measure the concentrations of nitrous oxide tracer gas in the samples. Each gas analyser is connected to ten sampling tubes by valves, one of which would be open at a time. Air continues to be drawn through the sampling tubes not connected to the analysers, so that the analysers always recieve fresh samples. The gas analysers have automatic calibration and two ranges with automatic range selection.

The microcomputer controls the scanners, multimeter, printer and disc drive so as to:

(a) command the sampling valves to connect individual sampling tubes to the gas analysers,

(b) select individual gas analysers, thermocouples and other instruments for connection to the multimeter by the scanners and measurement of their output by the multimeter,

(c) receive the measurements from the multimeter,

(d) translate measured outputs into physical quantities using calibration data,

(e) record tracer gas concentrations, temperatures and other data on disc,

(f) print out selected data and operating information,

(g) command the gas analysers to carry out automatic self-calibration and recieve status information from them.

5.2.2 Technical Problems

The technical problems of the infra-red gas analyser system were expected to be much less severe than those of the fuel cell analyser system. All the main components are proven commercial products, and the main problems were expected to be those of interference with signals by voltage transients from relays, solenoid valves, etc and those of suitable buffering and translation on the signal lines between the various instruments.

The infra-red gas analysers take about 20 seconds to reach a steady reading after a change in tracer concentration in the air being sampled. Unlike the fuel cell analysers, they produce a steady output indicating the tracer gas concentration, thus it is only necessary to measure their output after it has stabilised. Three anlaysers could each be served on a 30 second cycle, allowing 20 seconds for each analyser to stabilise and 10 seconds for the measurement. Thus 30 sample points could be served on a 300 second cycle.

5.2.3 Estimated Cost

The cost of the system shown in figure 14 was estimated to be about £31000, not including calibration gases, equipment for erection on site, etc.

5.3 Choice of Measurement System

The cost advantage of the fuel cell system was insufficient to outweigh the performance and convenience advantages of the infra-red system. The infra-red system was therefore selected.

6. PRELIMINARY VENTILATION RATE MEASUREMENTS

6.1 Measurements in a Medium-sized Enclosure

6.1.1 Enclosure and Instrumentation

Figures 15 to 17 show the general arrangement of the test enclosure and the positions of the measurement points. The building has brick cavity walls and a roof of asbestos sheets covered in roofing felt. The line of the roof is broken by monitors with glazed sides and some opening lights. The test space is separated from the main laboratory by a timber-framed partition. Offices within the test space are separated from it by brick walls and a timber floor above. The test space is heated by a radiator and two fan convectors at low level and by heating pipes which run around the monitors at high level. Fans have been installed to permit the mixing of the air within the space to be improved.

The arrangement of the instrumentation used to carry out the measurements was generally as shown in Figure 14, but only 10 measurement points were used. The measurements of wind velocity and direction were omitted.

6.1.2 Measurement method

The measurement method used was to inject tracer gas into the air in the space and then observe the decay of the gas concentration with time.

If perfect mixing were obtained, the ventilation rate could be obtained from the following equation:

$$\ln C_{t2} = C_{t1} - \frac{Q}{V} (t2 - t1)$$

where C_{t1} = tracer gas concentration at time t1

C_{t2} = tracer gas concentration at time t2

This is the equation of a straight line with gradient $-\frac{Q}{V}$ on a graph of lnC against t.

It has already been described (Section 2.4) how if perfect mixing were not obtained, the tracer gas concentrations would be different at different points in the space. The lines on the graph of lnC against t may have different gradients, and would in general not have the gradient $-\frac{Q}{V}$.

6.1.3 Results of Measurements

Figures 18 and 19 show the tracer gas concentration decays obtained in two tests.

In test 4 (Figure 18) good mixing was obtained by natural air movement in the space, and the points showing the tracer gas concentrations lie for all practical purposes on the same line. The ventilation rate obtained from this line is 0.40 air changes per hour.

In test 2 (Figure 19) good mixing was obtained initially, but after about 50 minutes the air movement pattern changed and mixing became noticeably imperfect. The slope of the first 50 minutes of the curve indicates a ventilation rate of 0.41 air changes per hour. The slope of the upper group of points from 80 minutes onwards indicates an apparent local ventilation rate of 0.28 air changes per hour, while that of the lower group indicates an apparent local ventilation rate of 0.49 air changes per hour.

Positions C and H, which have the lower tracer gas concentrations, are located in the monitors at the top of the test space. The remaining positions are located in the main volume of the enclosure. Tracer gas concentrations from positions I & J are not shown on figures 18 and 19 due to limitations of the computer program for graph plotting, but they do not affect the pattern of the results.

6.1.4 Analysis of Results

The results shown in Figure 19 were analysed manually by a simplified version of the method described in Section 2.5. The total ventilation rate of the space was calculated to be 0.3 air changes per hour. Since the ventilation rate during the first part of the test was about 0.4 air changes per hour, this result seems reasonable. It is not yet possible to set margins of error for the calculation of ventilation rates when mixing is imperfect.

6.2 Measurements in a Large Enclosure

6.2.1 Enclosure and Instrumentation

Figures 20 and 21 show the general arrangement of the test enclosure and the positions of the measurement points. The constructional features of the test enclosure are described in Table 1 (building A).

The arrangement of the instrumentation used to carry out the measurements was generally as shown in Figure 14, but only 9 measurement points were used. The measurements of wind velocity and direction were omitted.

6.2.2 Measurement Method

This was the concentration decay method as described in 6.1.2.

6.2.3 Results of Measurements

Some preliminary measurements were carried out in this building before work on improving its airtightness was begun (see section 7).

Concentration decay curves from a typical test are shown in Figure 22. Fairly good mixing was obtained about 4 hours after the start of the test. The slope of the concentration decay curves after this time indicates a ventilation rate of about 0.25 air changes per hour. This test was conducted with all doors, windows and ventilators closed and the building unoccupied. The temperature difference between inside and outside was between 0 and 3^{o}C. The wind velocity was estimated to be less that 1 m/s.

As the conditions under which the test was performed were rather unusual, the infiltration rate in this building would normally be considerably higher than that measured in this instance. If the speed of mixing does not increase in proportion to the infiltration rate, then under normal conditions good mixing may not be attained before the tracer gas concentrations have become too low to be measured accurately.

7. VALIDATION OF MEASUREMENT METHOD

7.1 Need for Validation

It has been established that imperfect mixing is likely in large enclosures such as factories and warehouses, and the fundamentals of a tracer gas method for measuring ventilation rates in such spaces have been outlined.

Before using the tracer gas method in practice, it is necessary to confirm that the ventilation rate measured by it is similar to the true ventilation rate of the space. This is because the calculation method for interpreting the results involves assuming that the space is divided into well-mixed zones of known shape and size. This assumption will be generally untrue, but it is necessary to discover how large an error is introduced by it.

7.2 Method of Validation

To validate the ventilation rate measurement method, measurements will be carried out in a large enclosure with a controlled ventilation rate and, if possible, various patterns of imperfect internal mixing.

To obtain a controlled ventilation rate, a moderately air-tight enclosure is required. When air is supplied to or extracted from the enclosure by a fan (see figure 23), the air leakage through the envelope will create a pressure difference between inside and outside. A suitable combination of envelope airtightness and forced ventilation rate will create a pressure difference that is larger than the pressures due to wind or temperature differences. Thus the pressure difference and therefore the air flow will have the same direction over the entire envelope, and the flow rate through the fan will be the true ventilation rate of the enclosure. The flow rate through the fan can be measured by mechanical methods and compared with the ventilation rate measured using tracer gas.

7.1.3 Airtightness Testing of Two Industrial Buildings

A number of industrial buildings were examined with a view to finding one with a suitable standard of airtightness for the validation work.

Two buildings (referred to here as building A and building B) were pressure tested.

Drawings of building A are shown in figures 20 and 21 and of building B in figures 24 and 25. The essentials of the airtightness test method are shown in figure 26. The main constructional features of the buildings and the results of the airtightness tests are summarised in Tables 1 and 2 respectively.

The striking features of the results in Table 2 are the generally high leakiness of the buildings and in particular the high leakiness of the roller shutter door of building B.

Neither of the buildings were sufficiently airtight for the validation work. Although building A was leakier, it appeared that it would be easier to improve its standard of airtightness. It was therefore selected for the tests and work was begun on sealing the air leakage paths.

TABLE 1

Constructional Features of 2 Industrial Buildings

Feature	Building A	Building B
Floor	Concrete slab on ground	Concrete slab on ground
Roof	Double skin asbestos sheets with glass fibre insulation between skins	Corrugated steel sheets, rigid insulation, roofing felt
Party walls	Brickwork	Brickwork
External walls	Corrugated steel sheets with plasterboard lining and glass fibre insulation between	Brickwork with metal-framed windows above
Goods doors	2 steel roller shutters	1 steel roller shutter

TABLE 2

Summary of Results of Airtightness Tests of 2 Industrial Buildings

	Building A	Building B
Fan airflow rate, m^3/s	4.9	4.9
Forced air change rate, per hour	2.6	3.1
Pressure differences between inside and outside (Pa) with:		
All doors, windows, ventilators and flues sealed	$\simeq 0$	12
All windows, ventilators, flues and personnel doors sealed. Goods door(s) not sealed	$\simeq 0$	2.5

Doors, windows, ventilators and flues were sealed by covering them with polythene sheet taped to the surrounding building structure.

Wind interfered with the testing of building A, making it difficult to obtain accurate results.

FIGURE 1

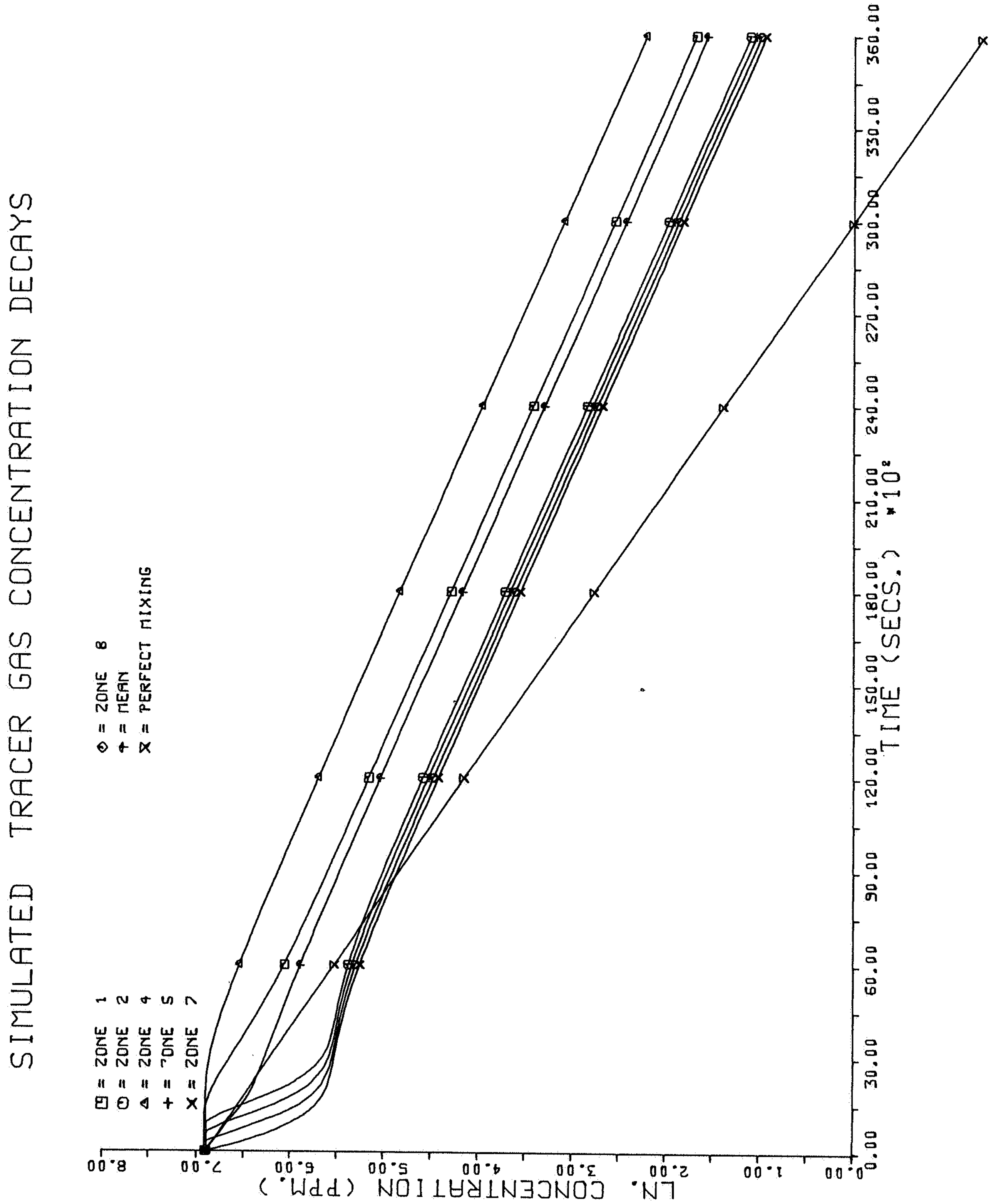
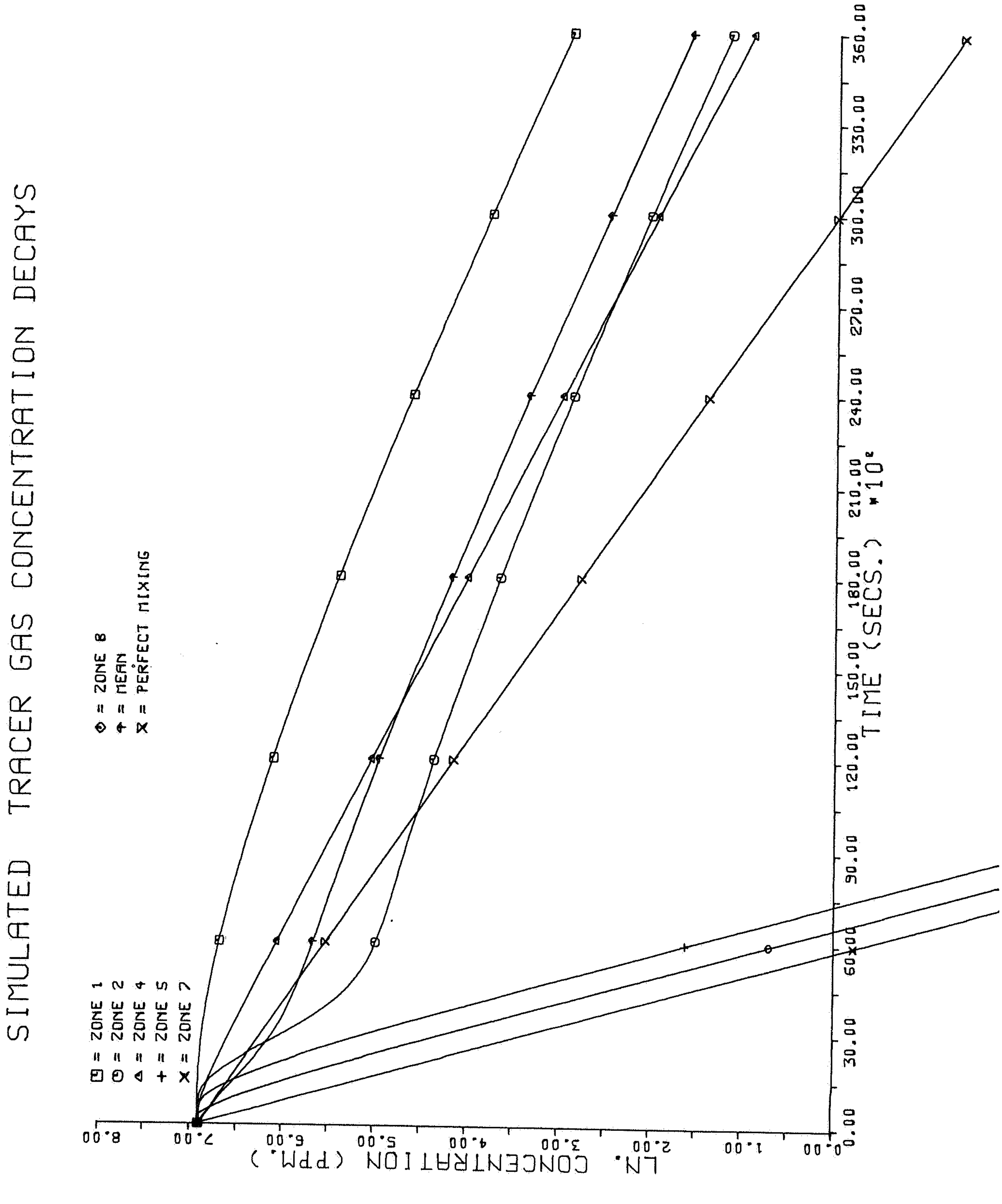

SIMULATED TRACER GAS CONCENTRATION DECAYS
= ZONE 1
= ZONE 2
= ZONE 4
= ZONE 5
= ZONE 7
= ZONE 8
= MEAN
= PERFECT MIXING
LN. CONCENTRATION (PPM.)
TIME (SECS.) *10²
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
30.00
60.00
90.00
120.00
150.00
180.00
210.00
240.00
270.00
300.00
330.00
360.00

FIGURE 2



SIMULATED TRACER GAS CONCENTRATION DECAYS
□ = ZONE 1
⊙ = ZONE 2
△ = ZONE 4
+ = ZONE 5
X = ZONE 7
◇ = ZONE 8
↑ = MEAN
X = PERFECT MIXING
LN. CONCENTRATION (PPM.)
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
TIME (SECS.) *10¹
0.00
30.00
60.00
90.00
120.00
150.00
180.00
210.00
240.00
270.00
300.00
330.00
360.00

SIMULATED TRACER GAS CONCENTRATION DECAYS

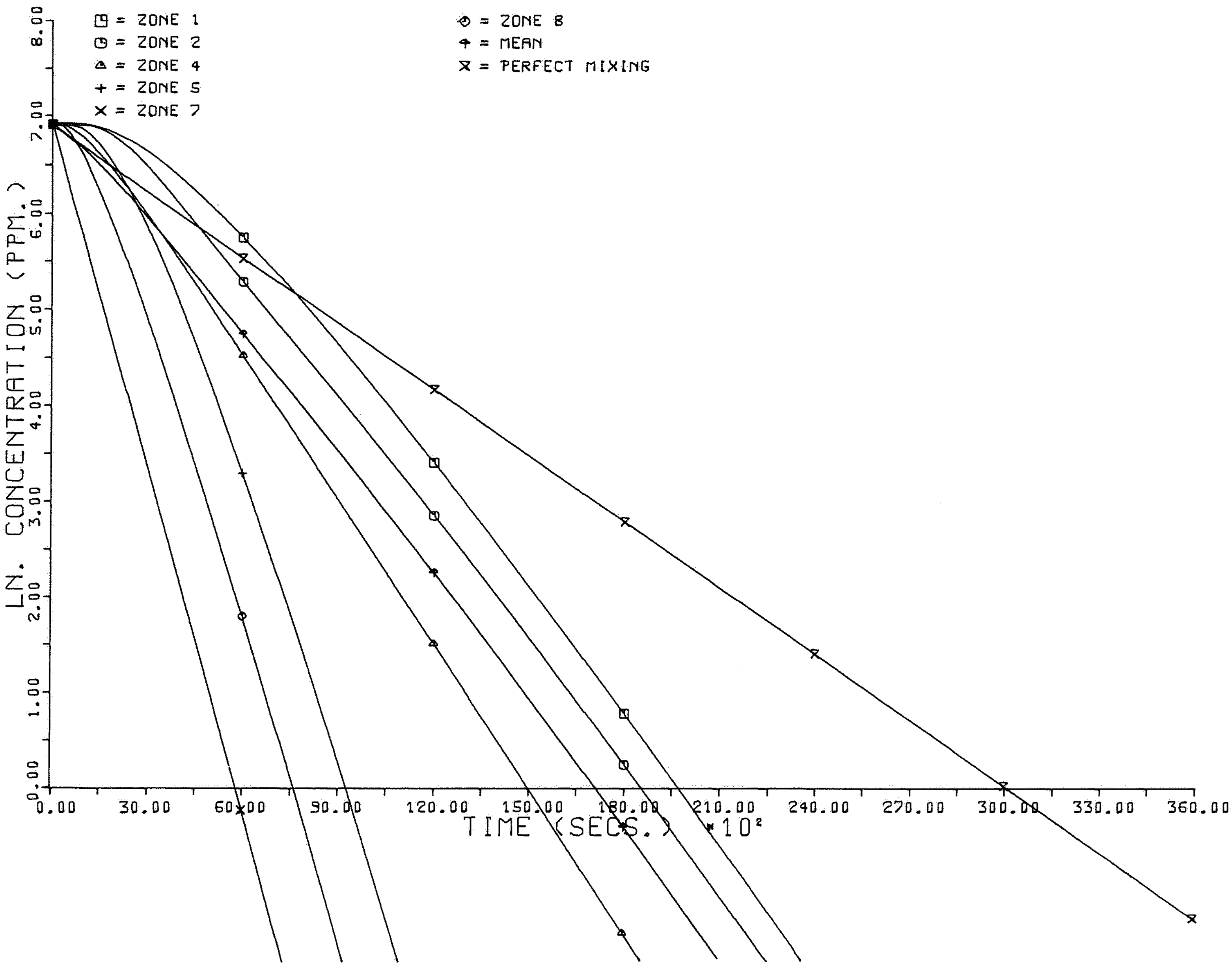
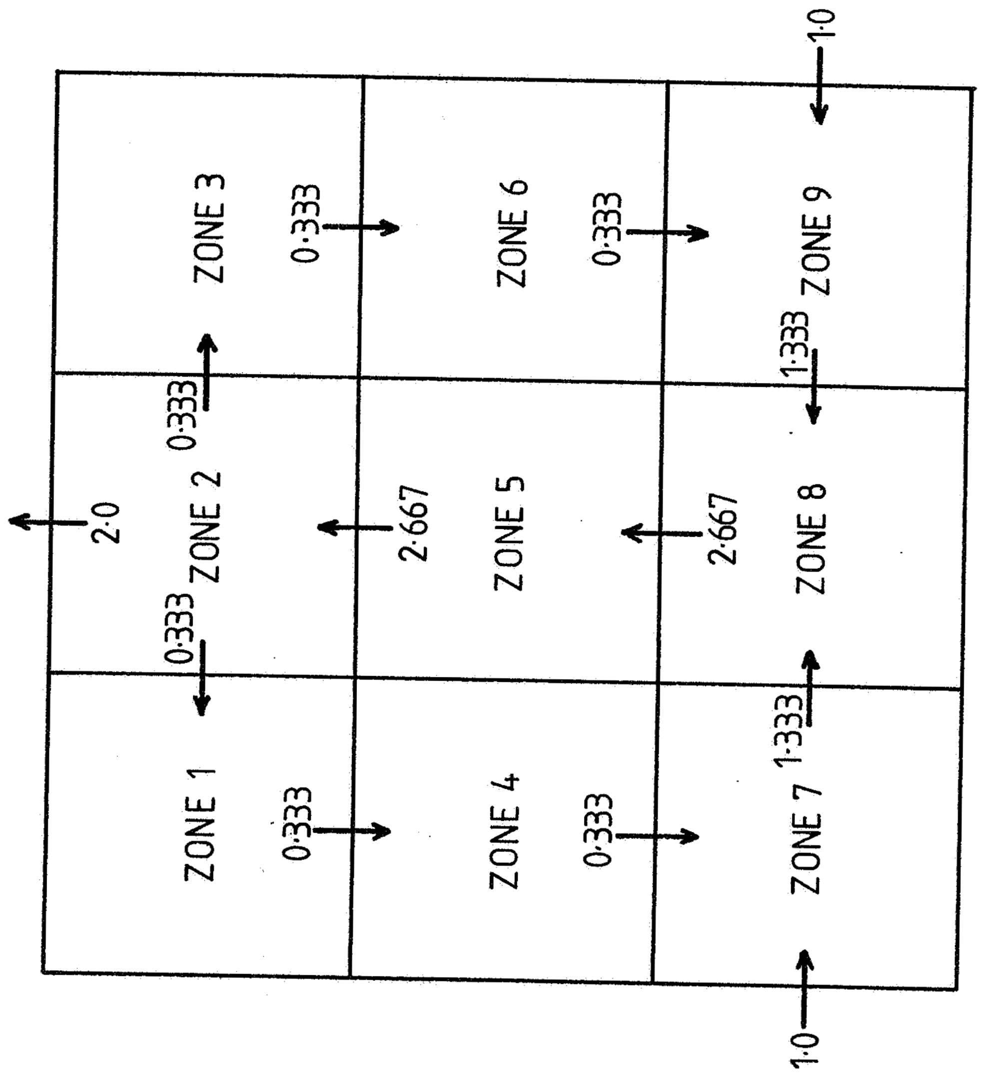


FIGURE 3

FIGURE 4

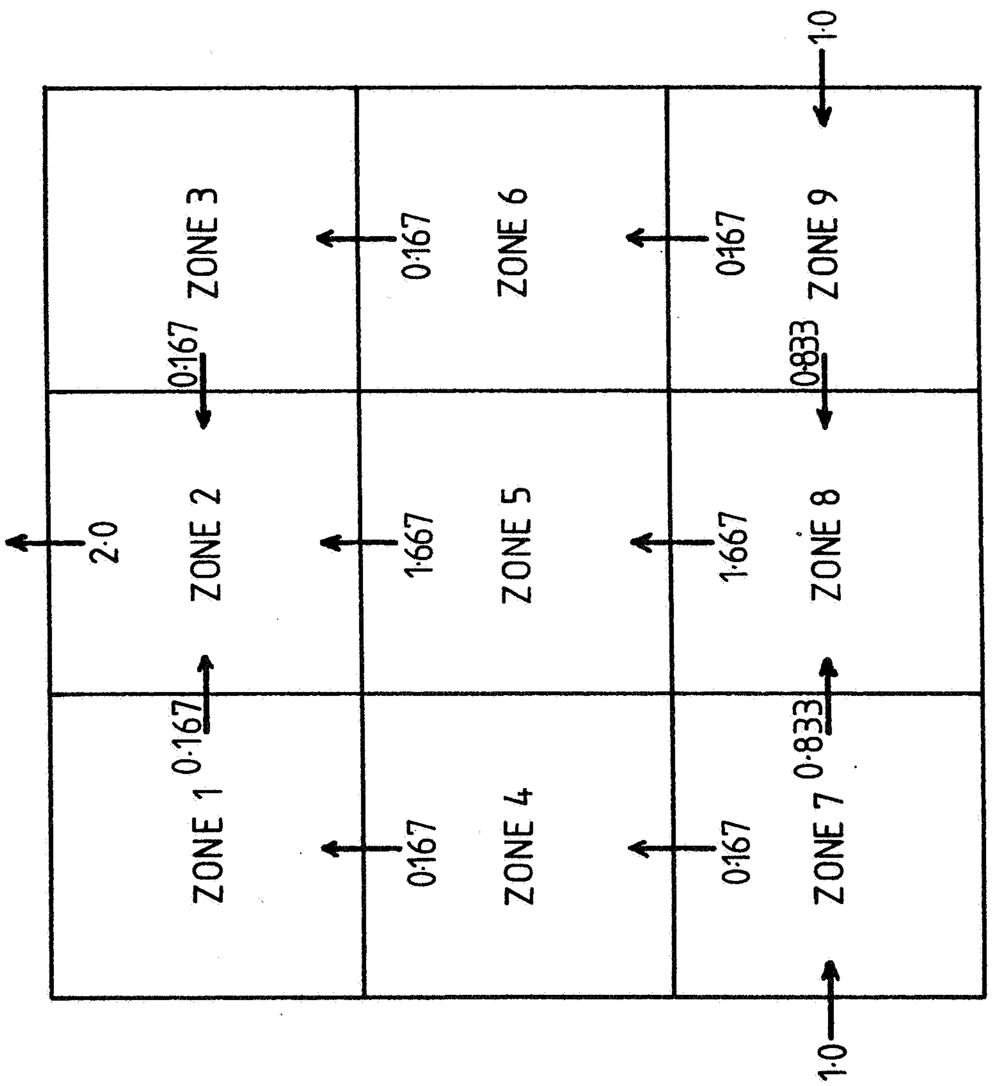
All zones $1000 m^3$.
Air flows in m^3/s.



AIRFLOWS FOR FIGURE 1

FIGURE 5

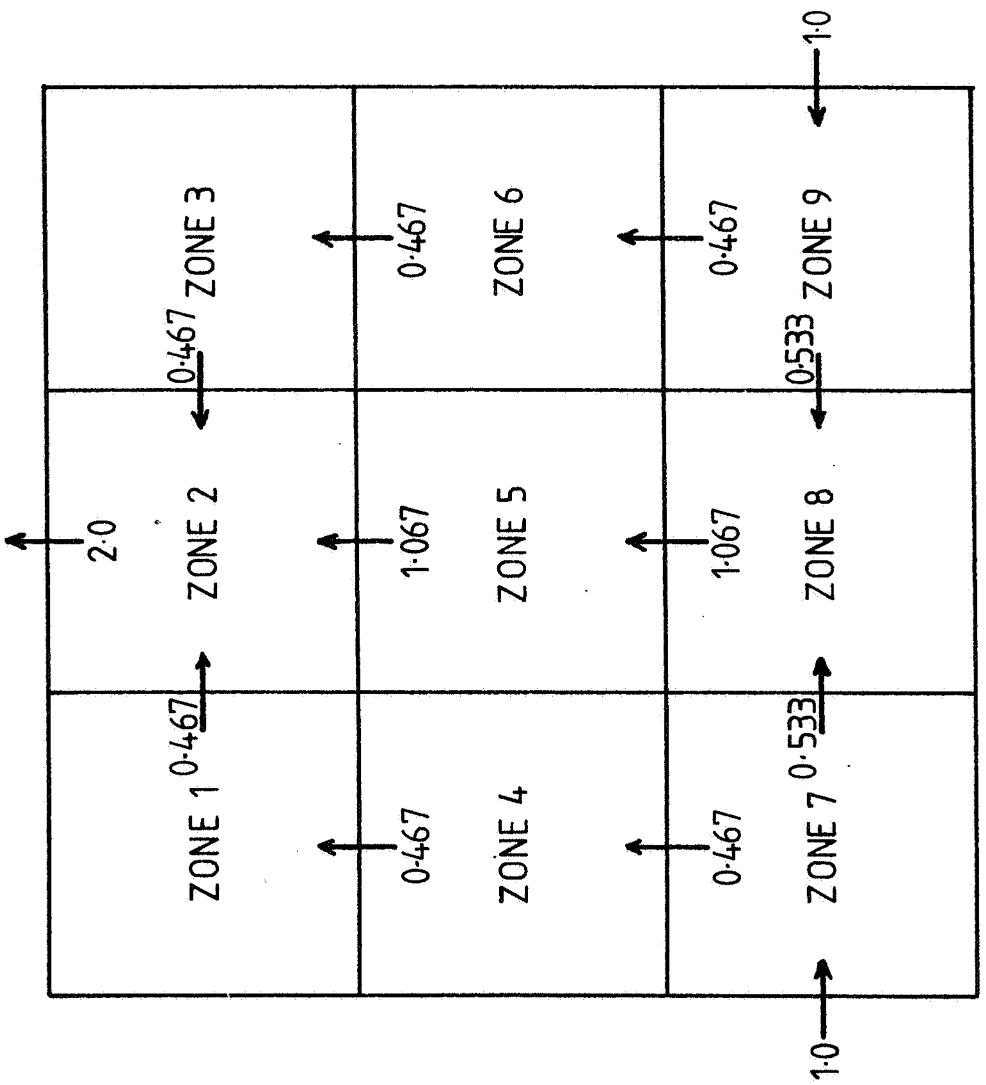
All zones 1000 m^3.
Air flows in m^3/s.



AIRFLOWS FOR FIGURE 2

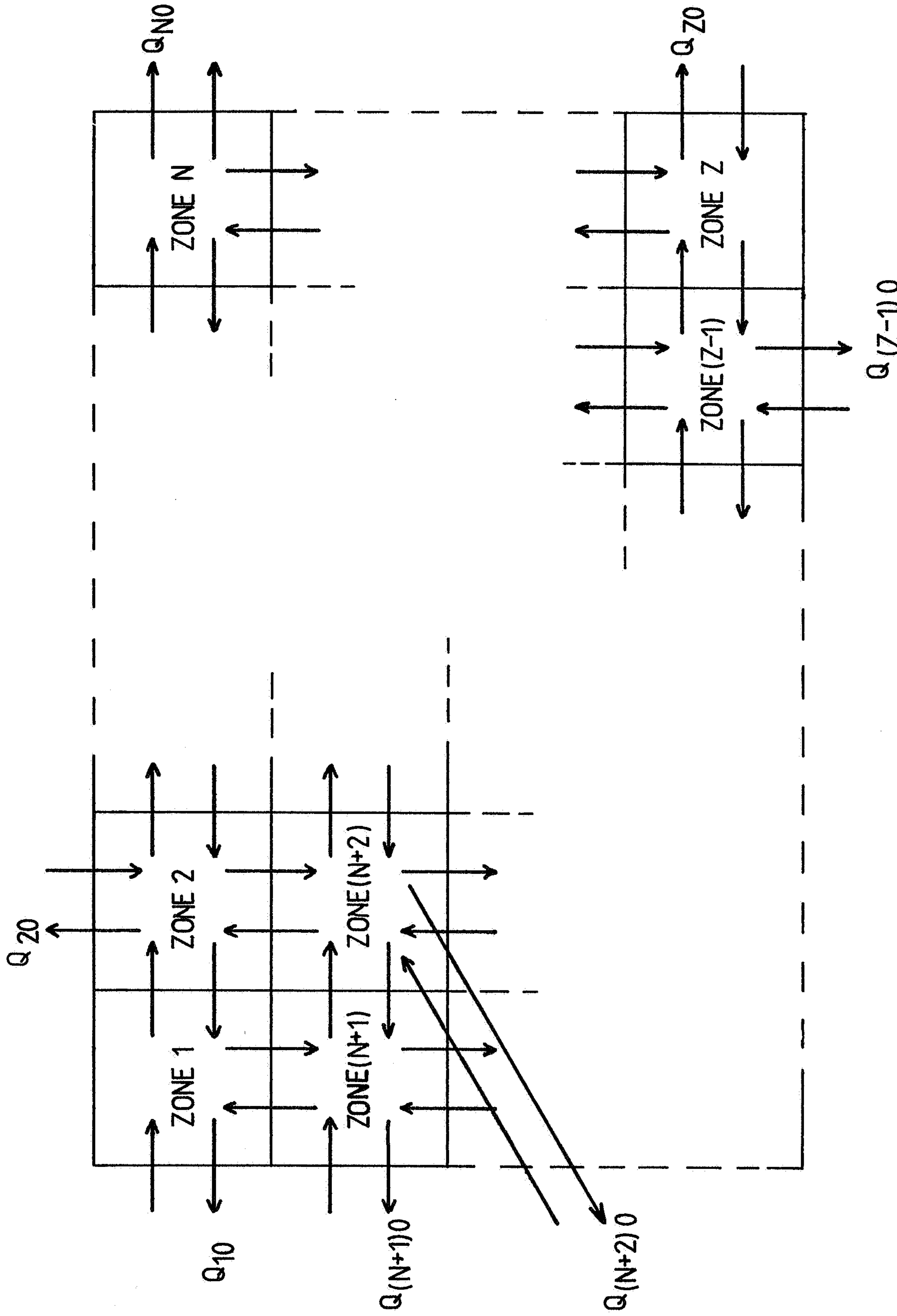
FIGURE 6

All zones 1000 m^3.
Air flows in m^3/s.



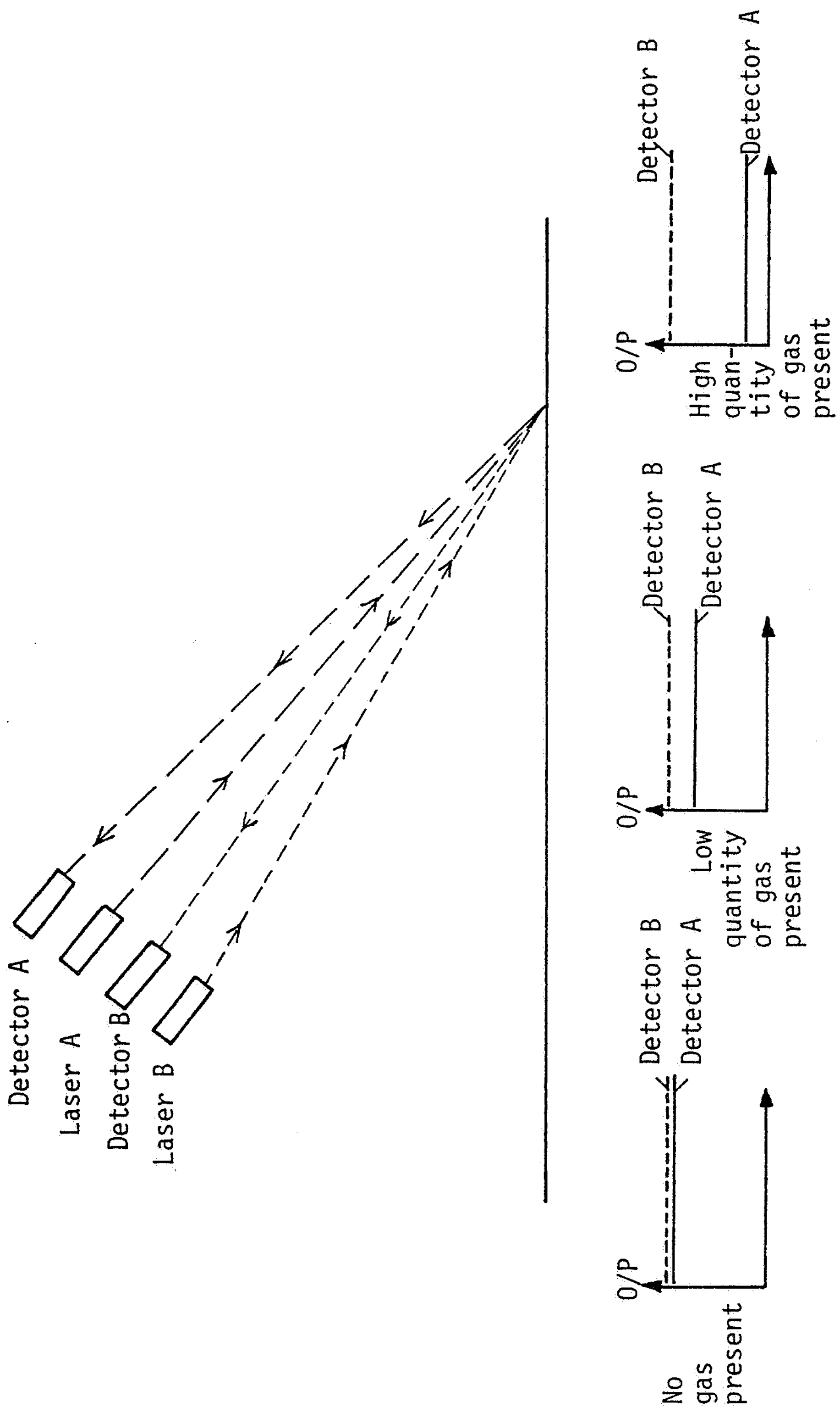
AIRFLOWS FOR FIGURE 3

FIGURE 7



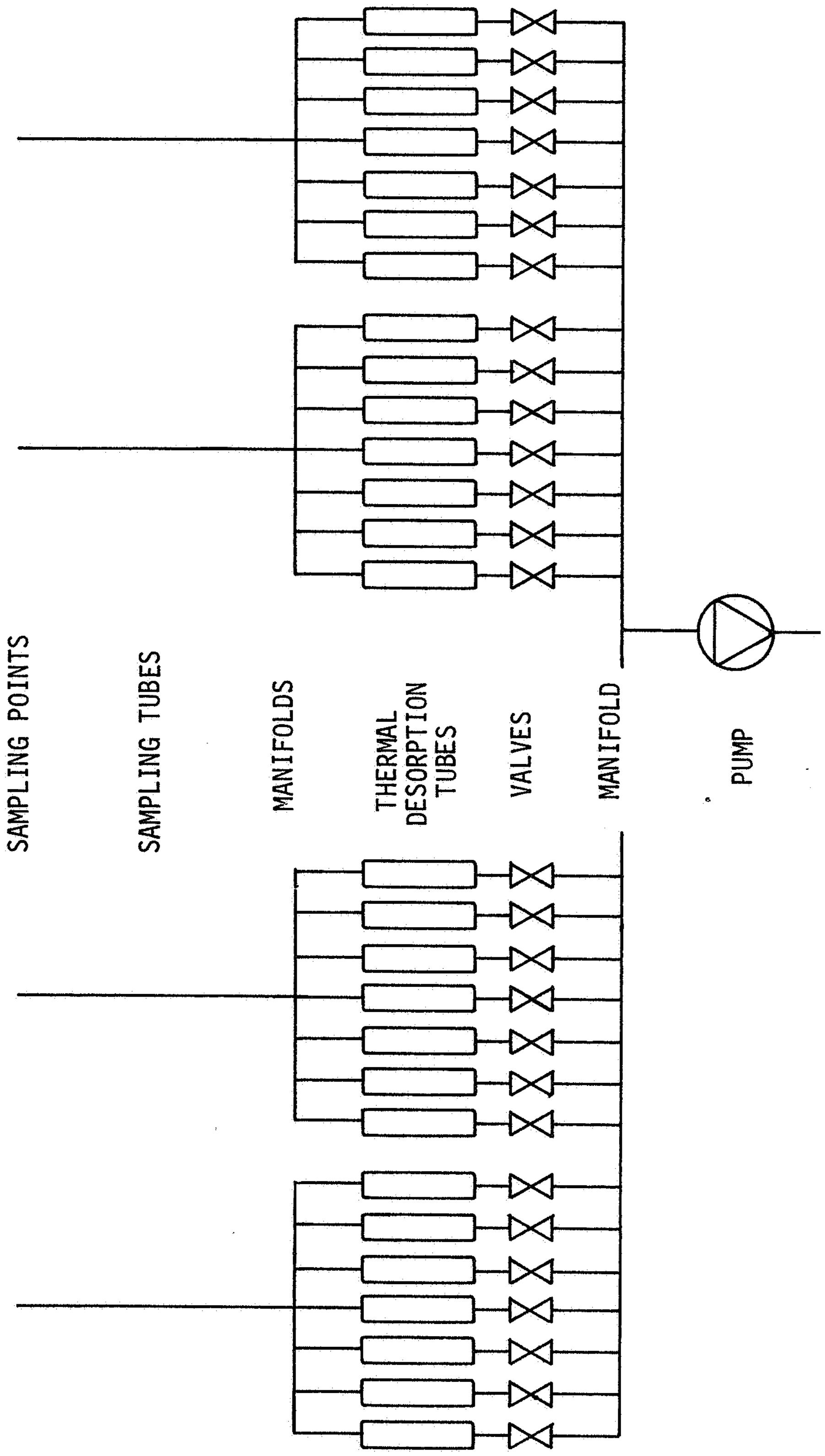
GENERALISED MULTI-ZONE VENTILATION MODEL

FIGURE 8

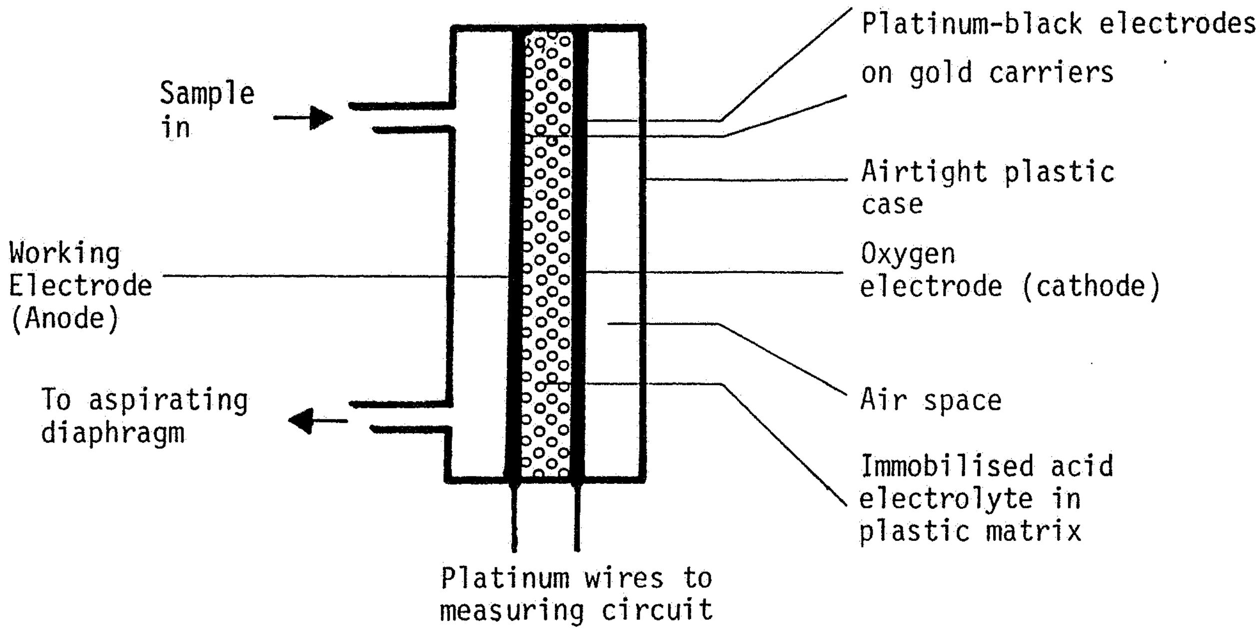


PRINCIPLE OF LASER GAS DETECTION TECHNIQUE

FIGURE 9



MULTI-POINT TRACER GAS CONCENTRATION MEASUREMENT SYSTEM USING THERMAL DESORPTION TUBES



SCHEMATIC OF FUEL CELL SENSOR

FIGURE 10

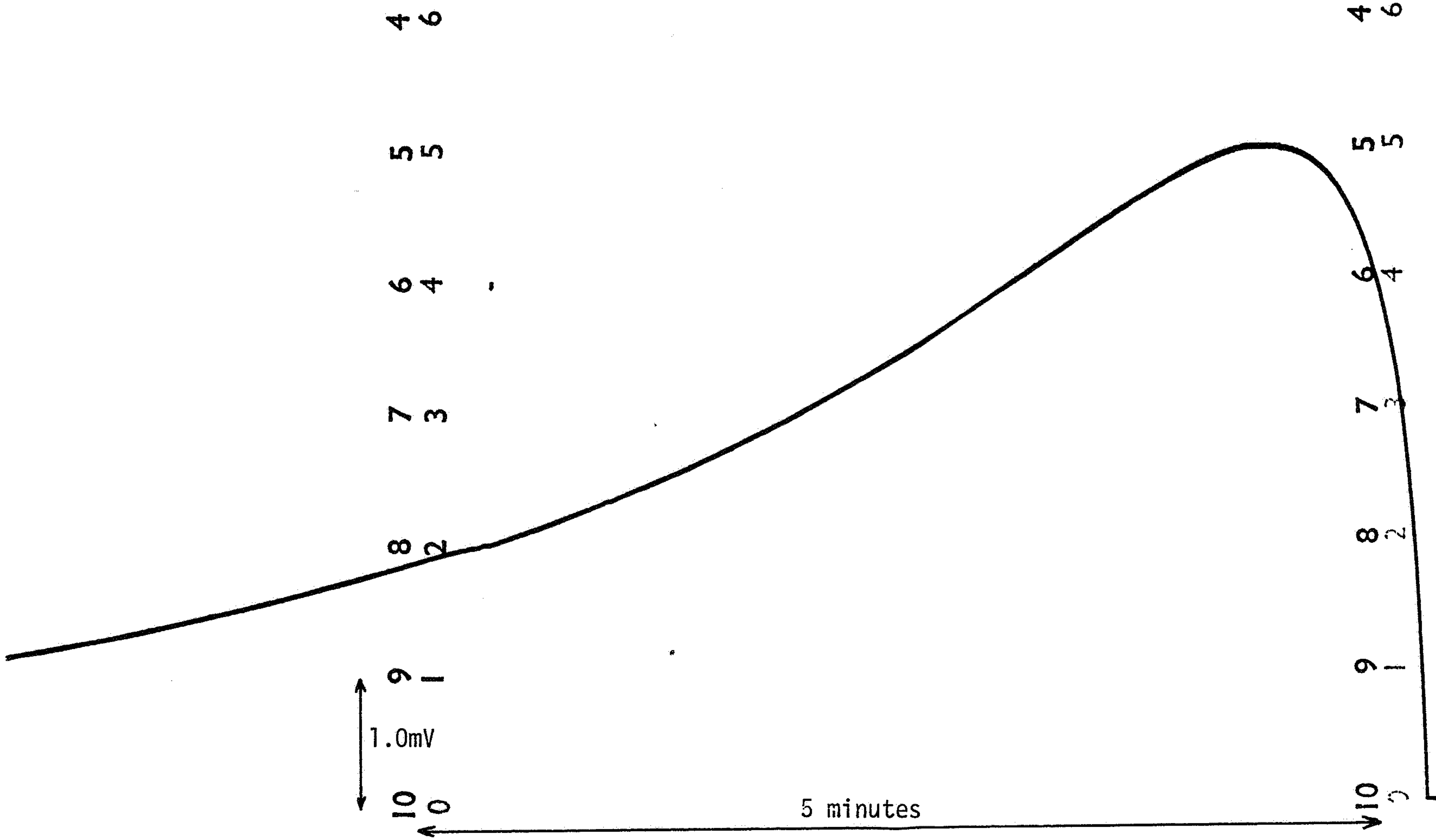
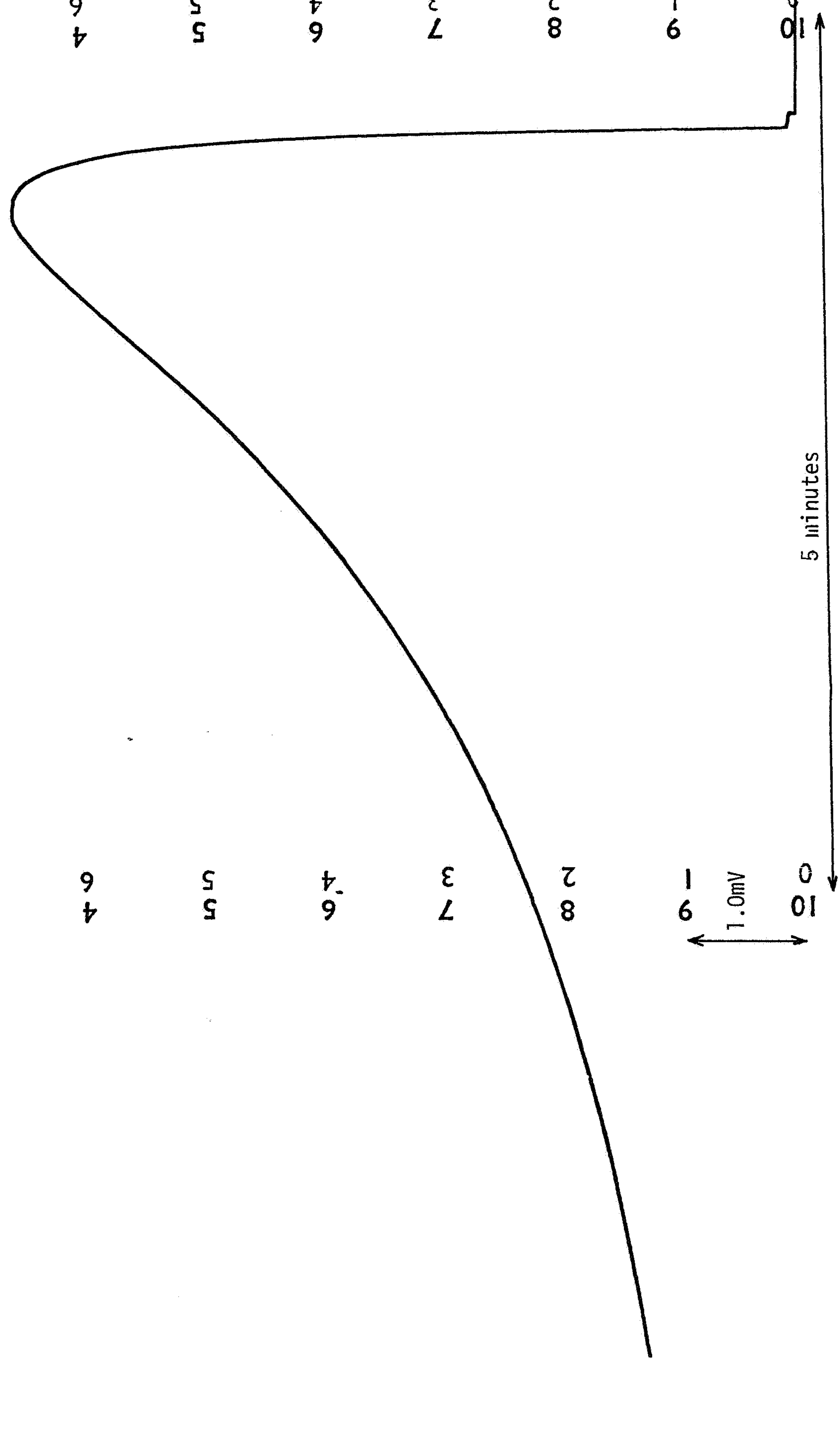


FIGURE 11

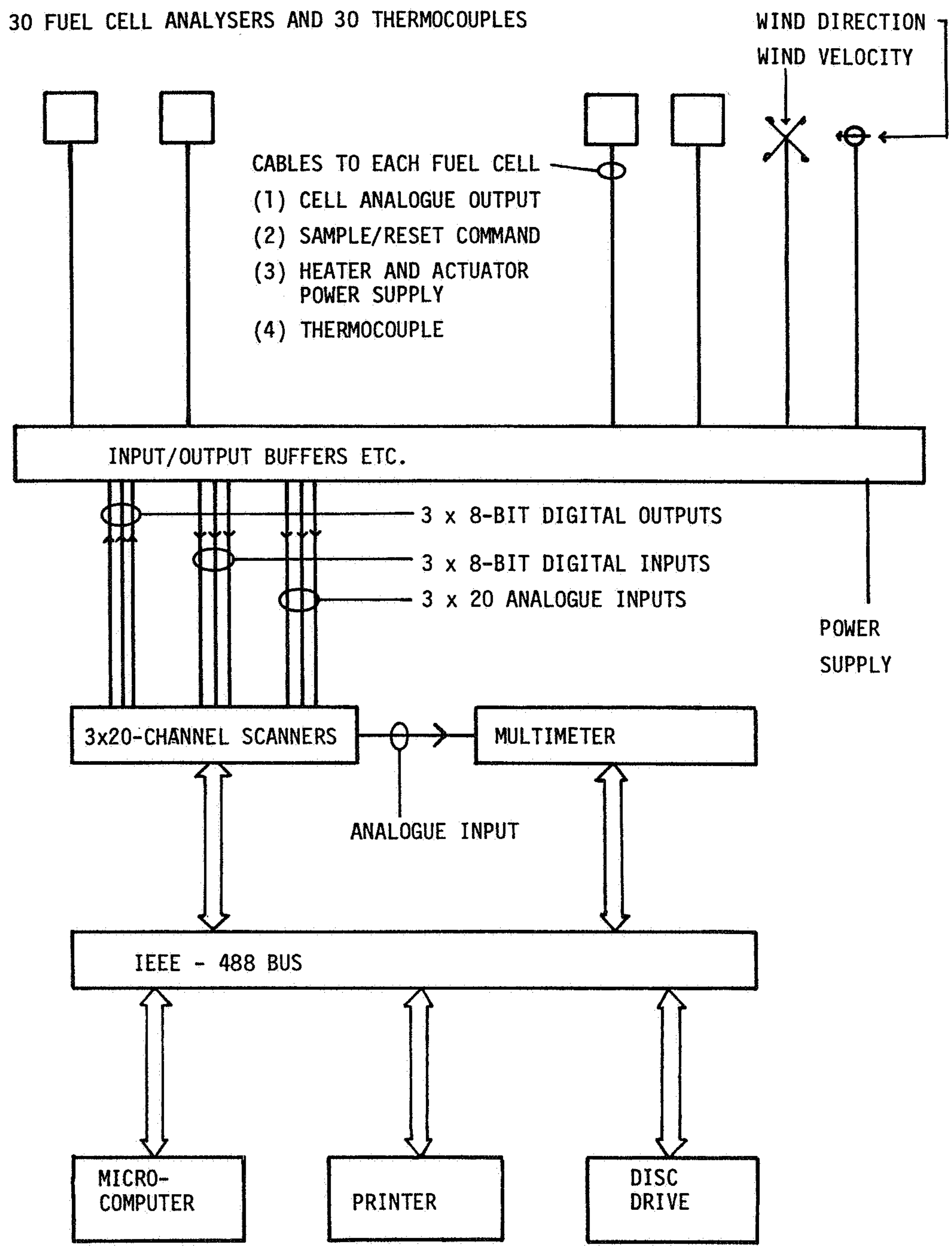
OUTPUT FROM FUEL CELL AT 21^{o}C
SAMPLE 190 ppm AT 21^{o}C

FIGURE 12



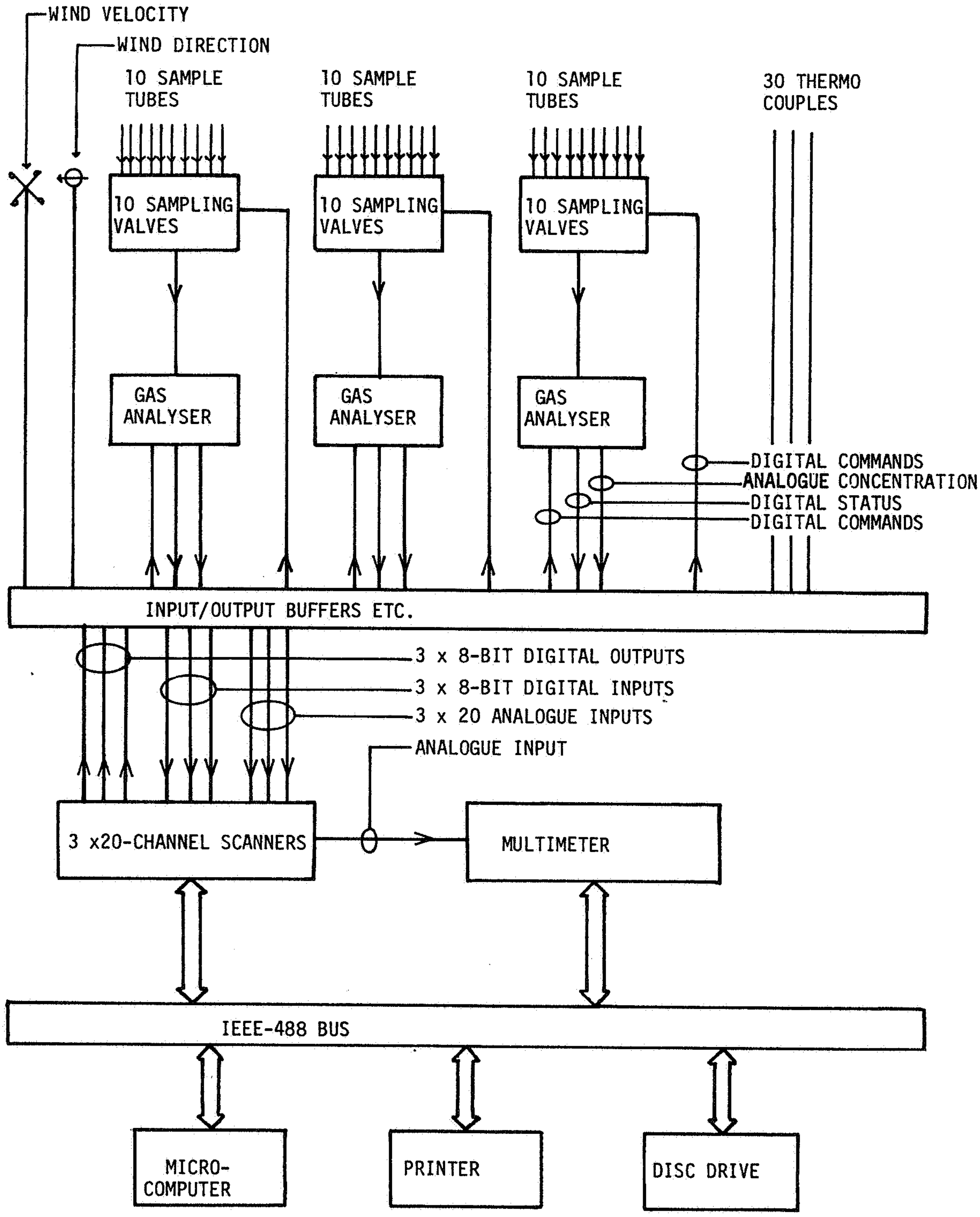
OUTPUT FROM FUEL CELL AT 61°C
SAMPLE 190 ppm AT 21°C

FIGURE 13



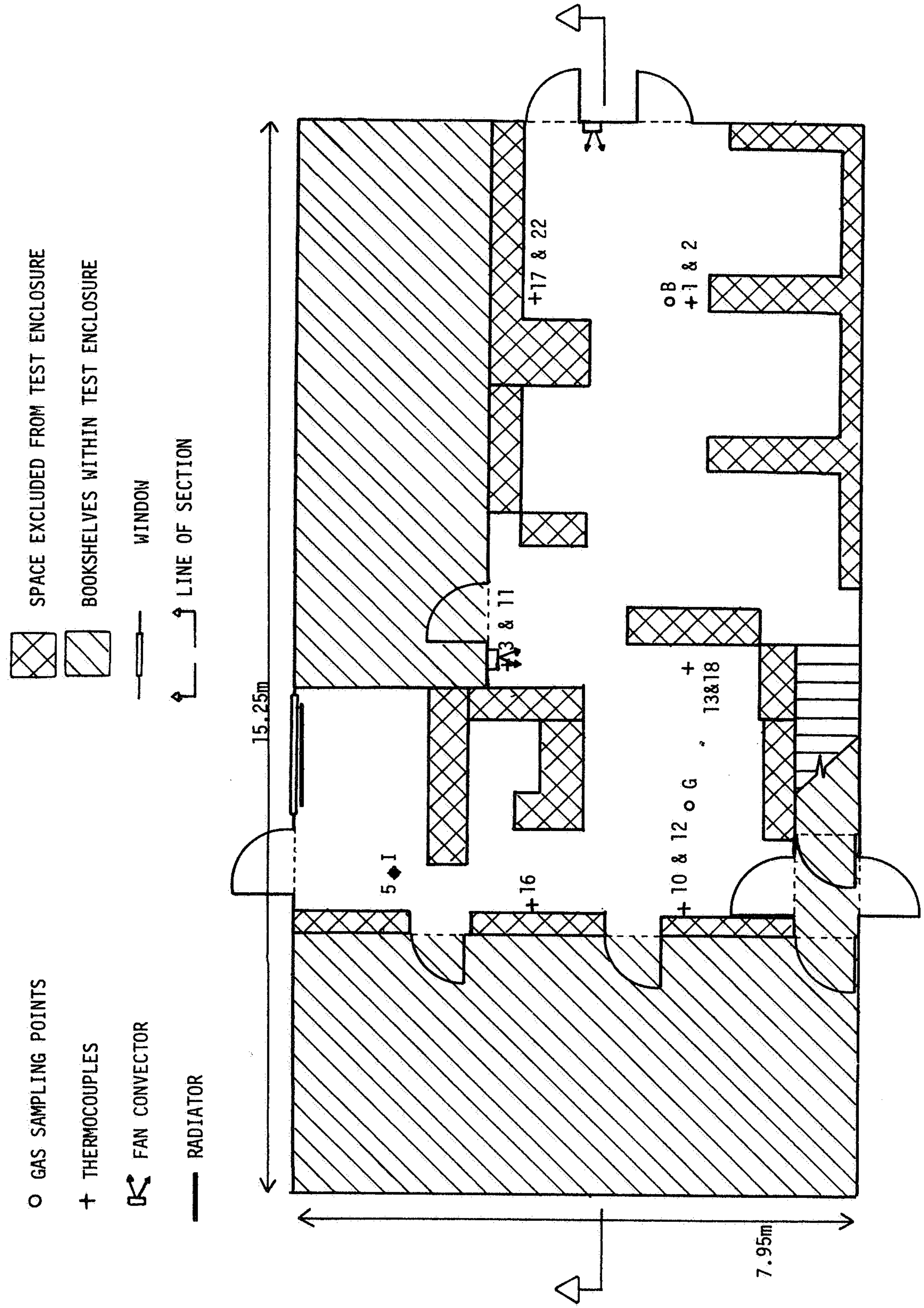
PRELIMINARY DESIGN OF TRACER GAS CONCENTRATION MEASUREMENT SYSTEM USING FUEL CELL GAS ANALYSERS

FIGURE 14

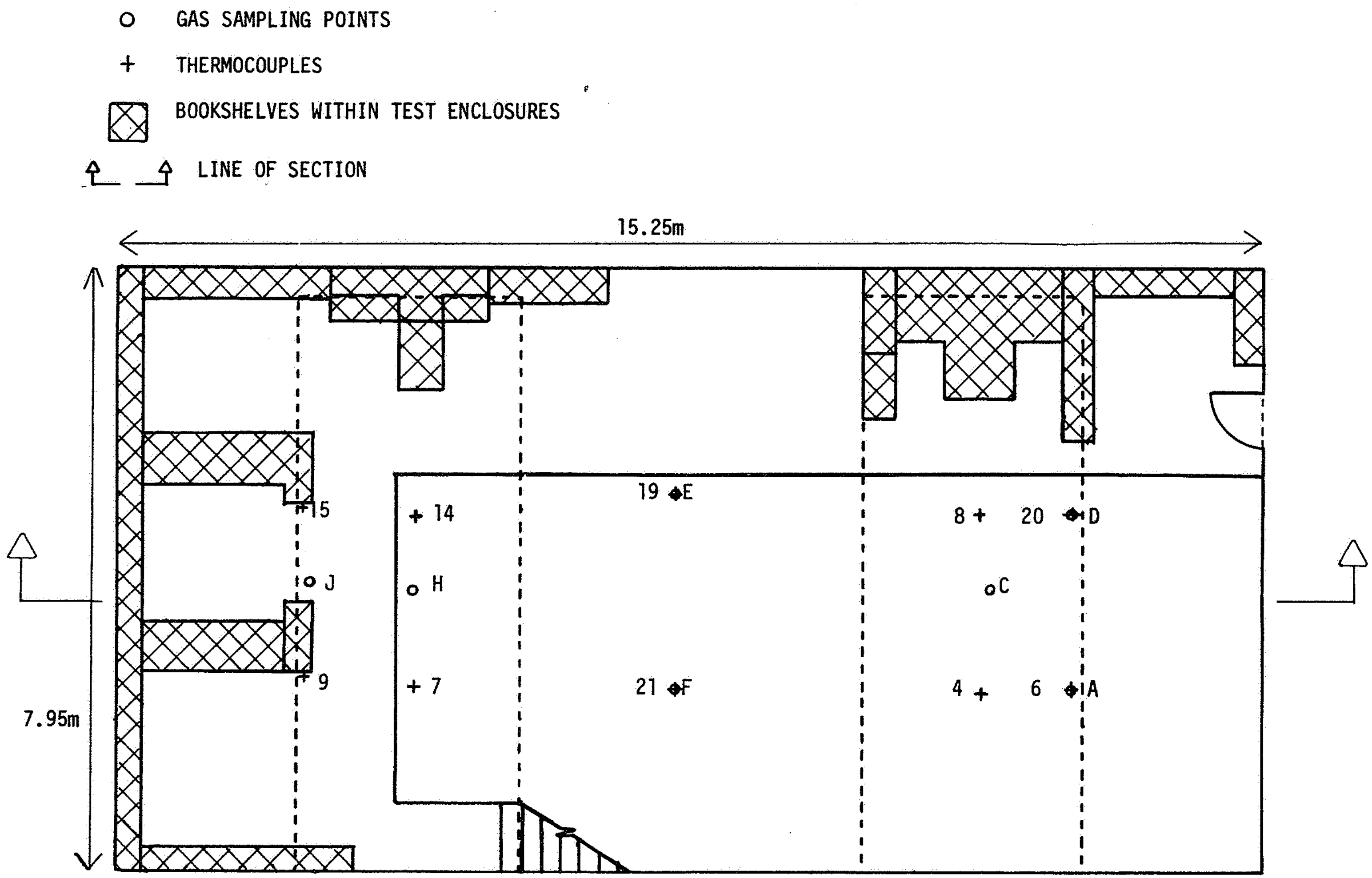


PRELIMINARY DESIGN OF TRACER GAS CONCENTRATION MEASUREMENT SYSTEM USING INFRA-RED GAS ANALYSERS

FIGURE 15



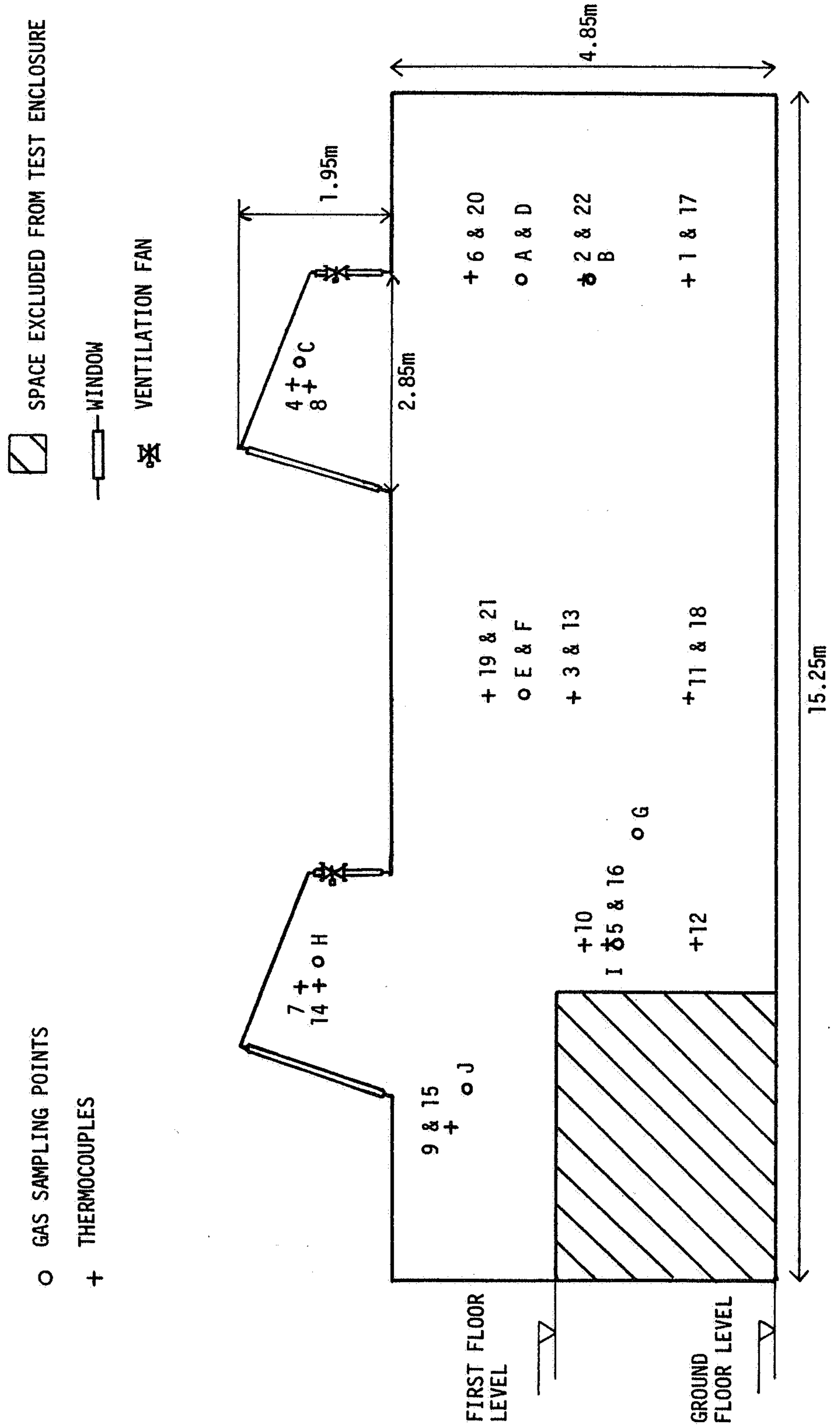
GROUND FLOOR PLAN OF MEDIUM-SIZED ENCLOSURE



FIRST FLOOR PLAN OF MEDIUM SIZED ENCLOSURE

FIGURE 16

FIGURE 17



SECTION THROUGH MEDIUM-SIZED ENCLOSURE

MEASURED TRACER GAS CONCENTRATION DECAYS

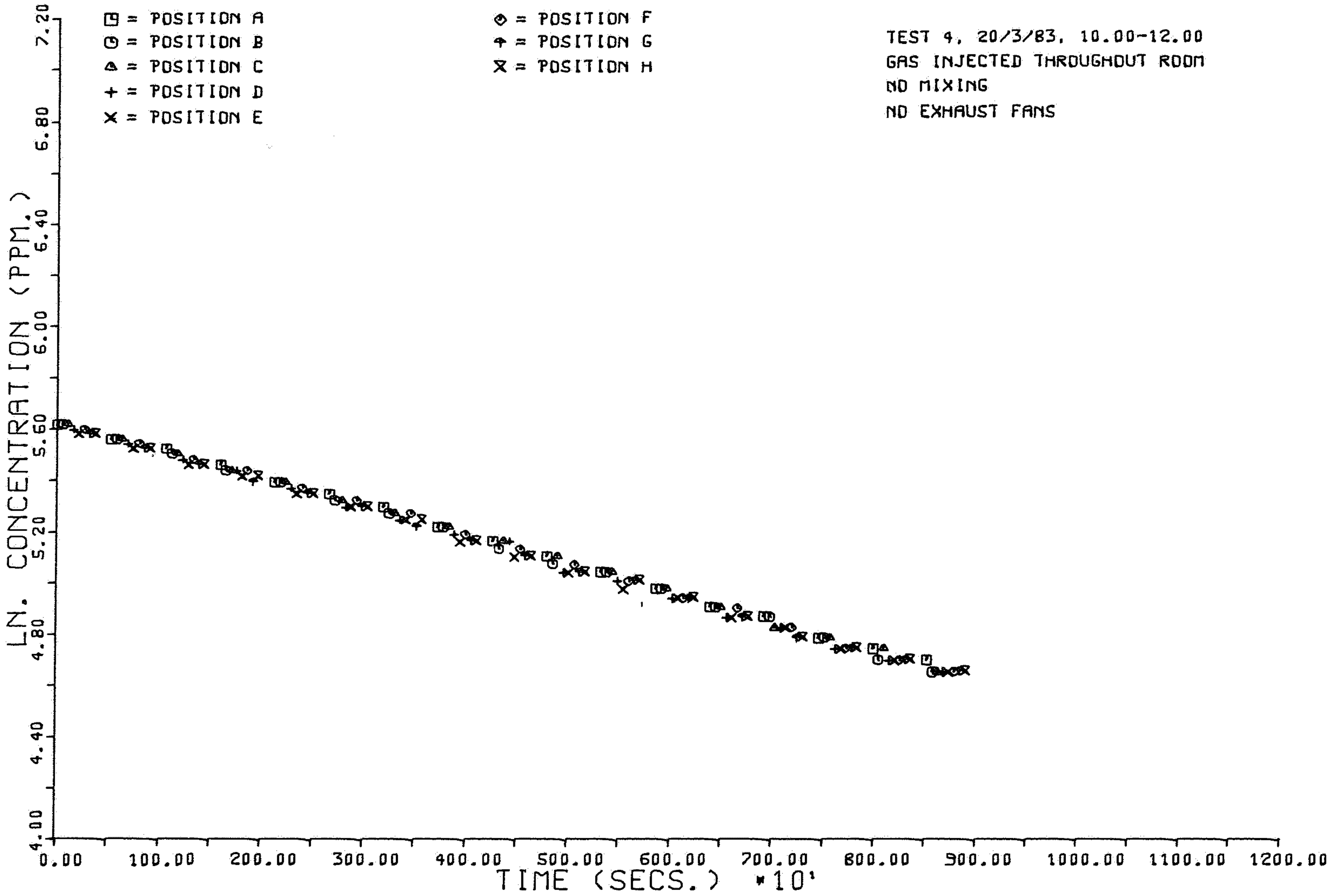
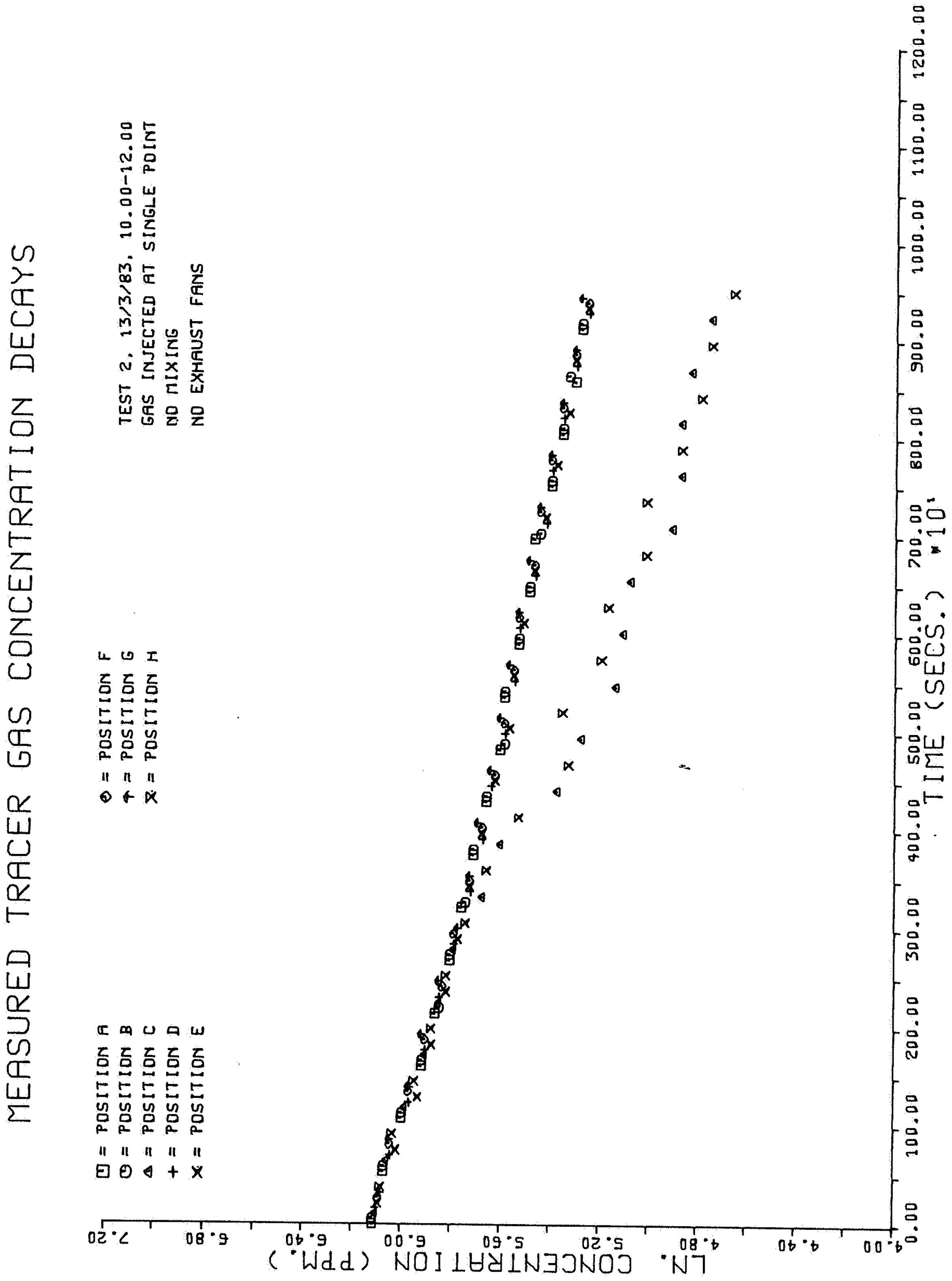


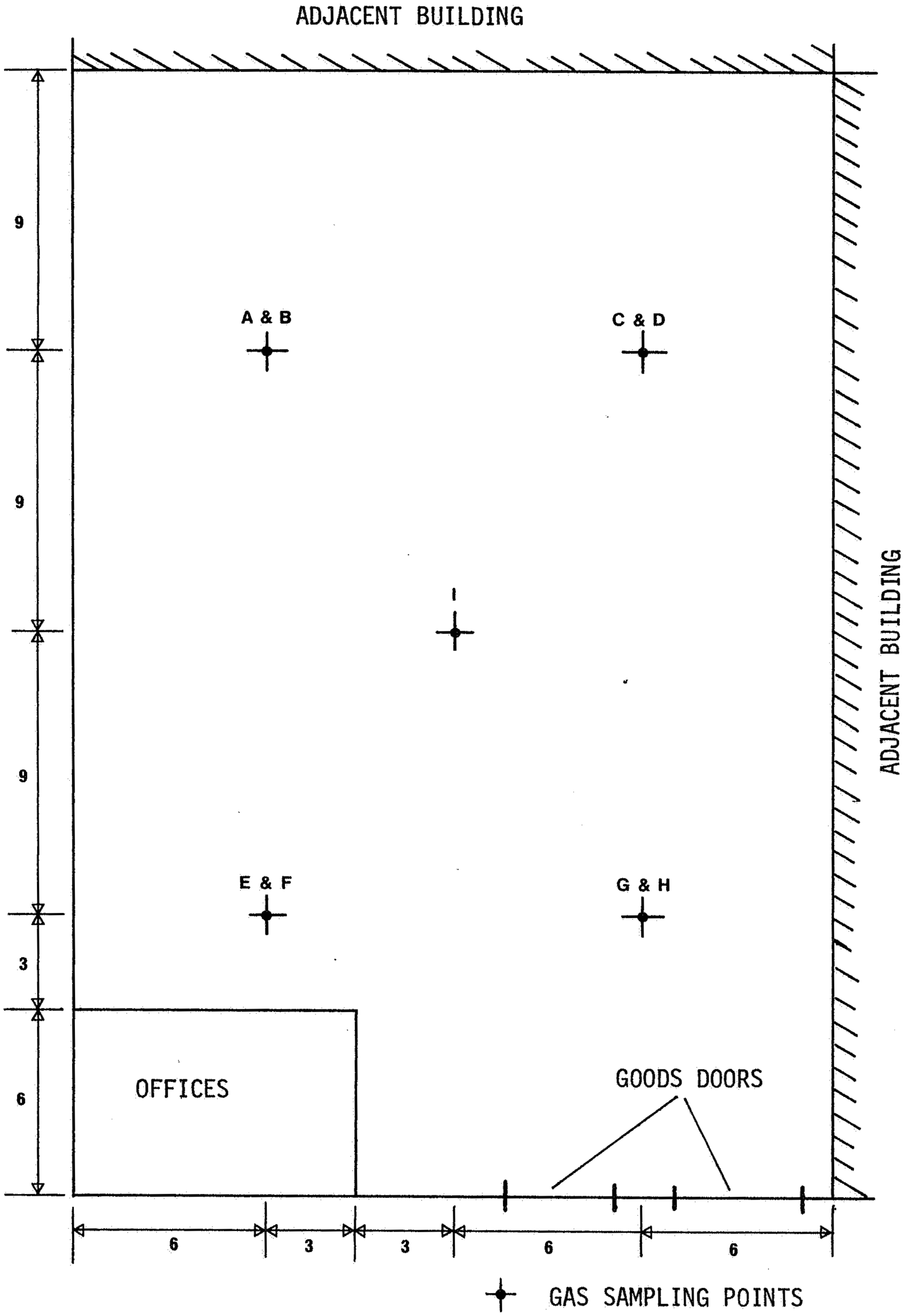
FIGURE 18

FIGURE 19



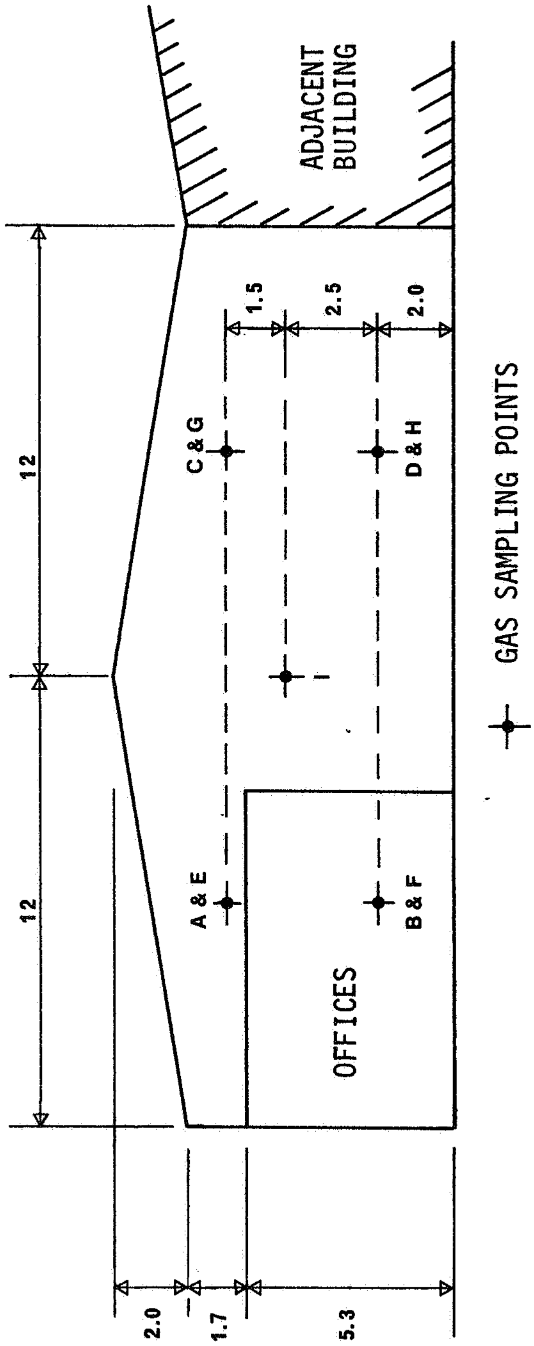
MEASURED TRACER GAS CONCENTRATION DECAYS
⊞ = POSITION A
ʘ = POSITION B
◭ = POSITION C
+ = POSITION D
X = POSITION E
ʘ = POSITION F
✝ = POSITION G
X = POSITION H
TEST 2, 13/3/83, 10.00-12.00
GAS INJECTED AT SINGLE POINT
NO MIXING
NO EXHAUST FANS
LN. CONCENTRATION (PPM.)
TIME (SECS.) *10¹
4.00
4.40
4.80
5.20
5.60
6.00
6.40
6.80
7.20
0.00
100.00
200.00
300.00
400.00
500.00
600.00
700.00
800.00
900.00
1000.00
1100.00
1200.00

FIGURE 20



PLAN OF BUILDING A

FIGURE 21



SECTION THROUGH BUILDING A

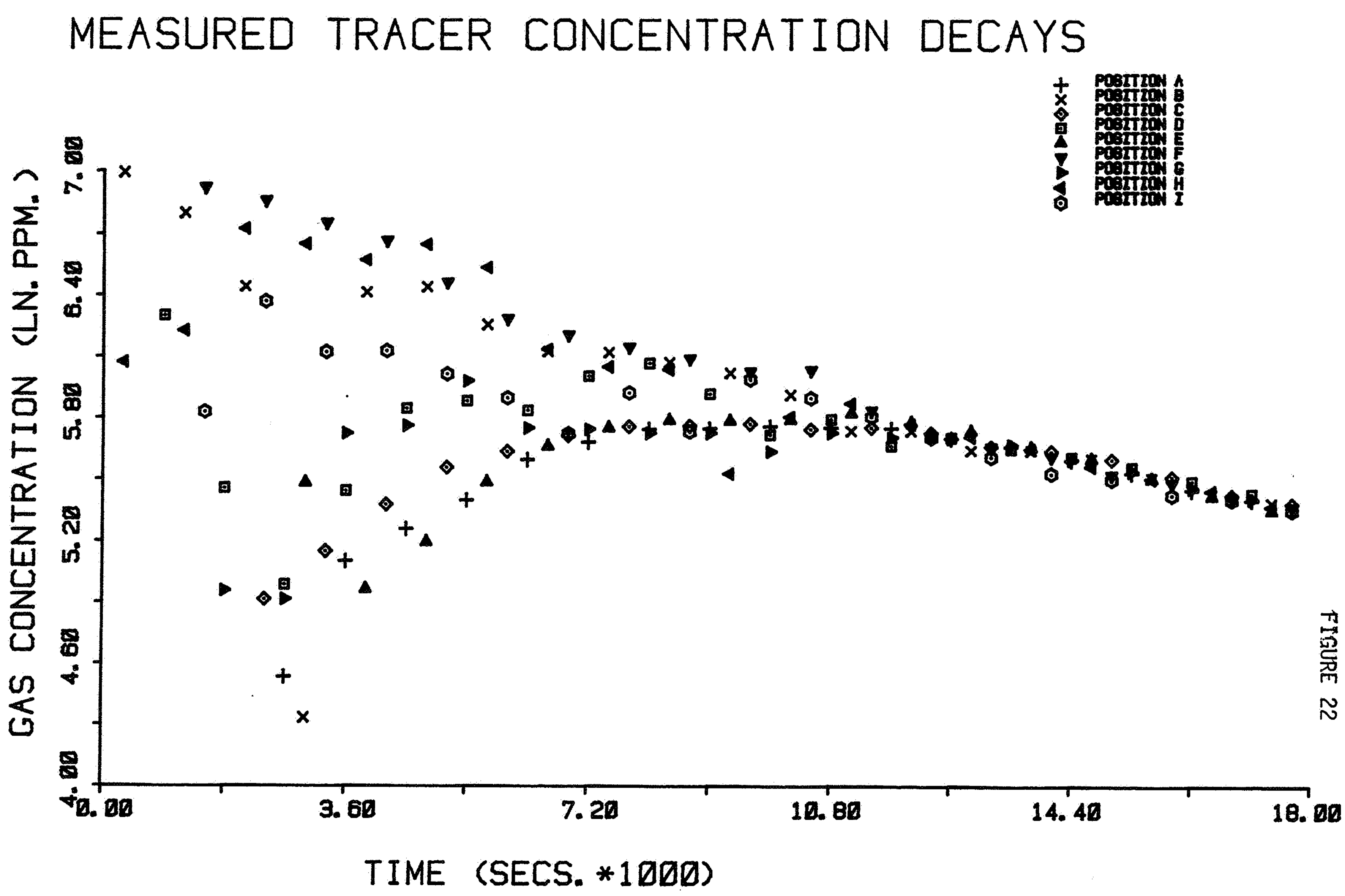
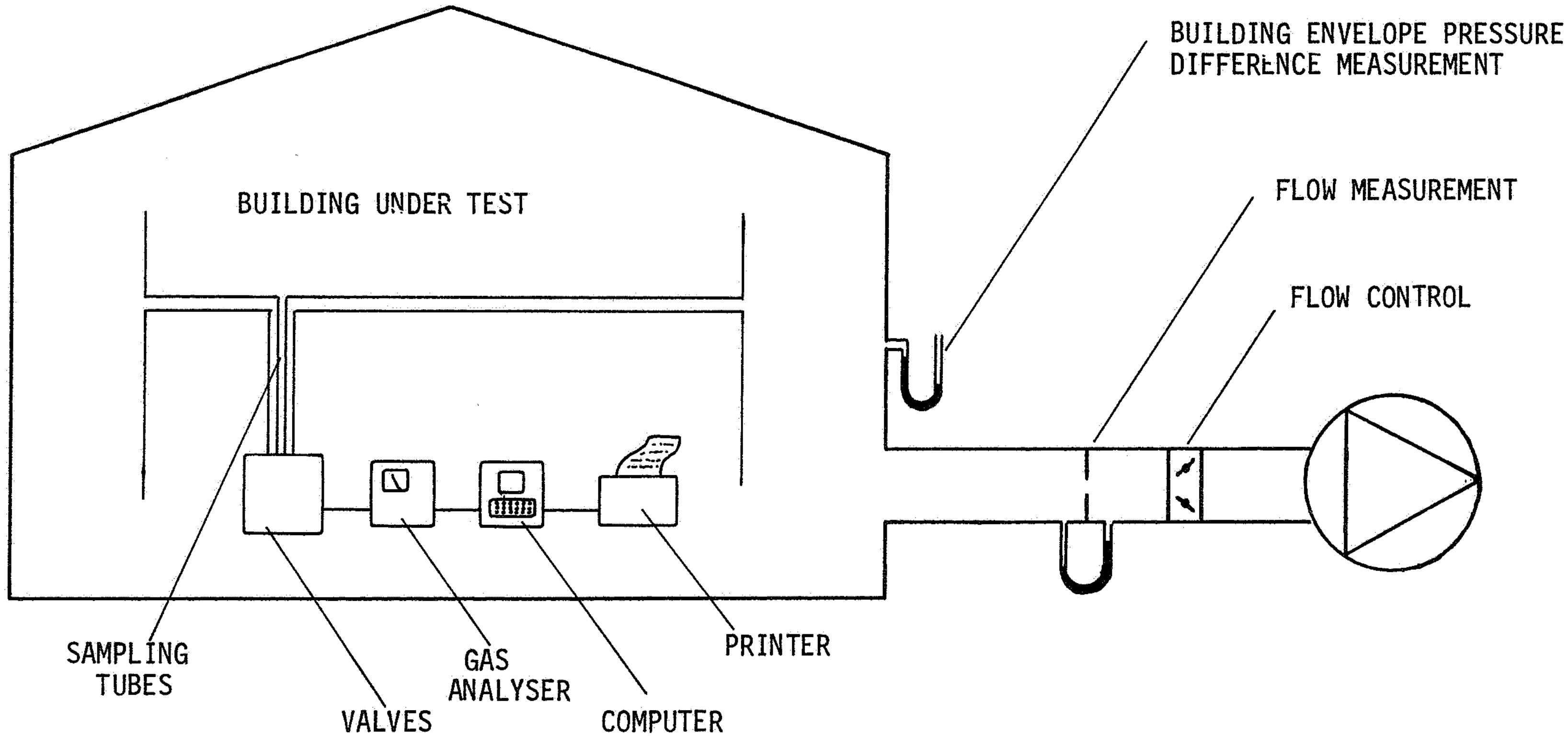
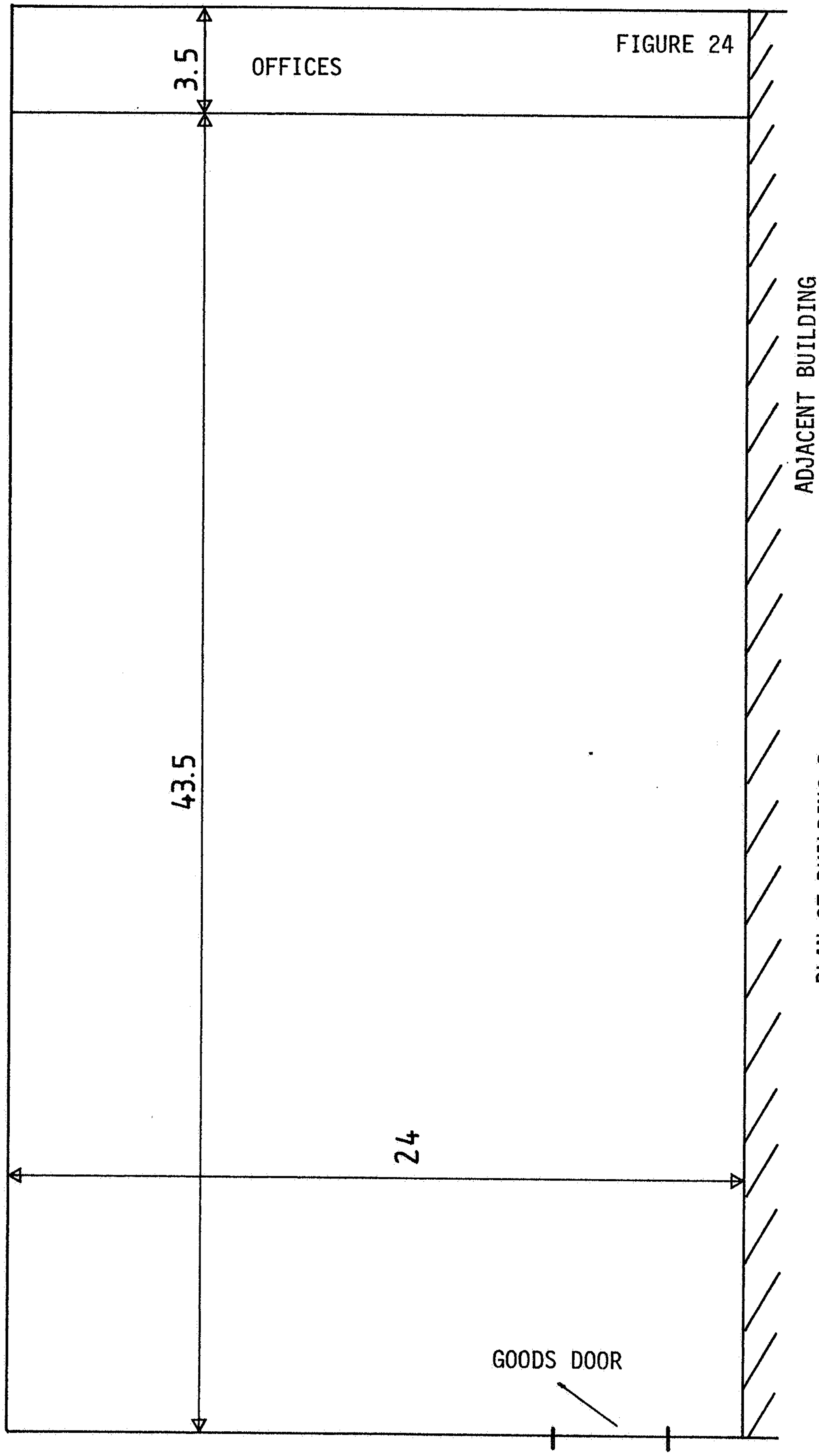

MEASURED TRACER CONCENTRATION DECAYS
POSITION A
POSITION B
POSITION C
POSITION D
POSITION E
POSITION F
POSITION G
POSITION H
POSITION I
GAS CONCENTRATION (LN. PPM.)
7.00
6.40
5.80
5.20
4.60
4.00
0.00
3.60
7.20
10.80
14.40
18.00
TIME (SECS. *1000)

FIGURE 22



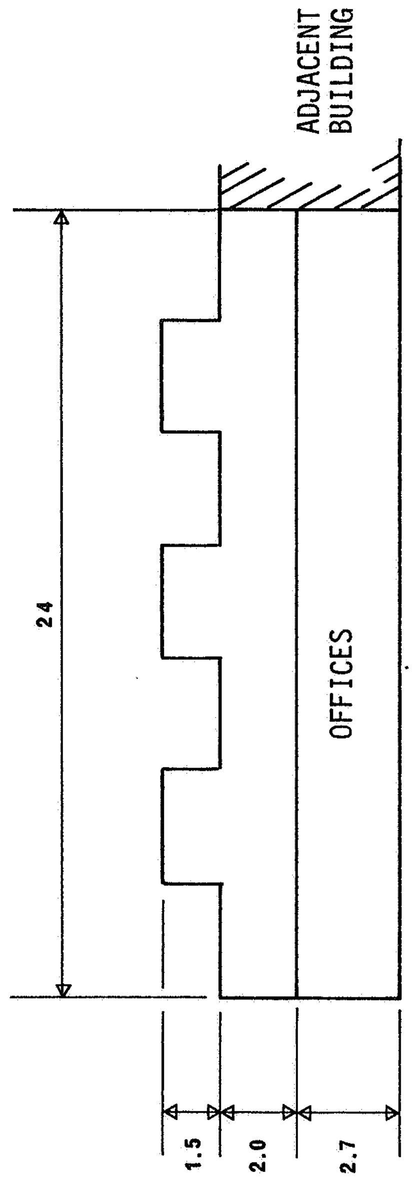
TEST METHOD FOR VALIDATION OF TRACER GAS VENTILATION RATE MEASUREMENT

FIGURE 23



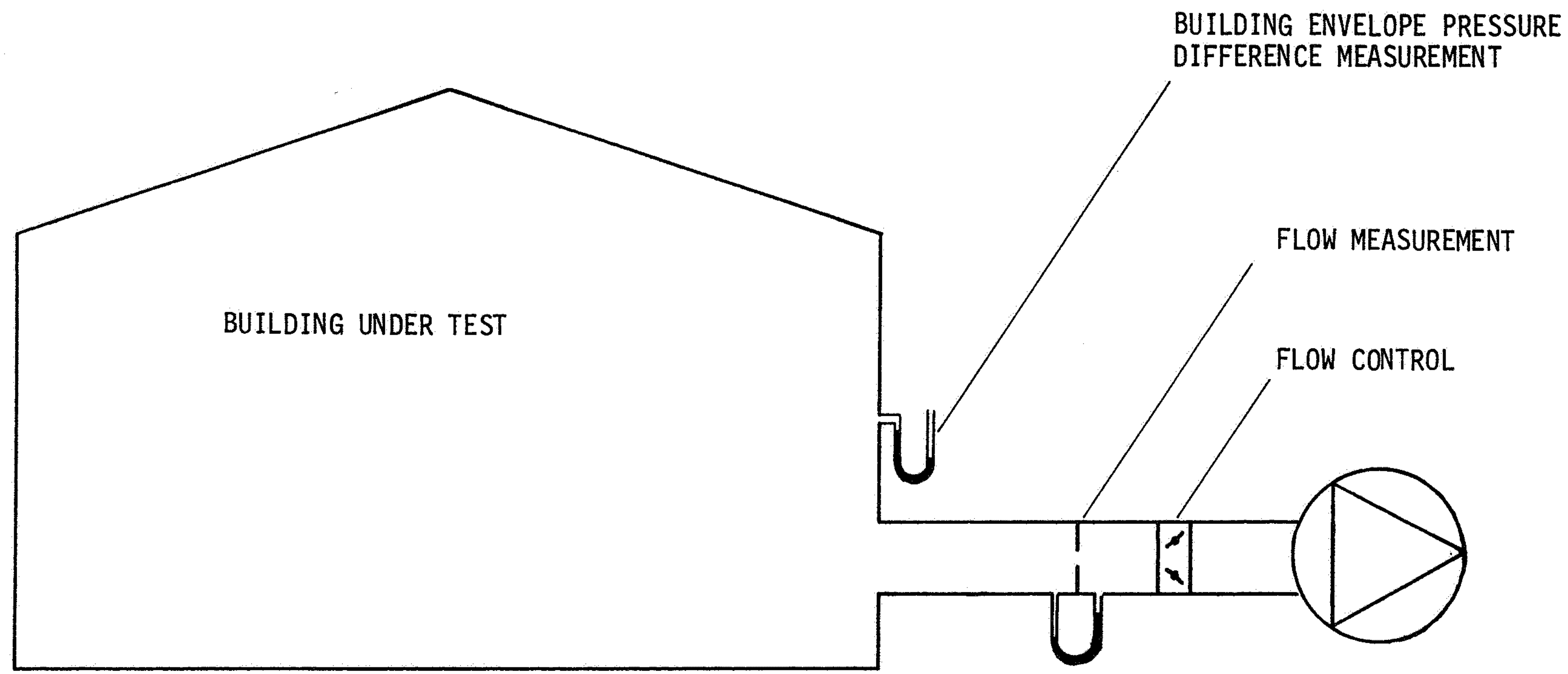
PLAN OF BUILDING B

FIGURE 25



SECTION THROUGH BUILDING B

FIGURE 26



TEST METHOD FOR BUILDING AIRTIGHTNESS

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AIR INFILTRATION REDUCTION IN EXISTING BUILDINGS

4th AIC Conference, September 26-28 1983, Elm, Switzerland

PAPER 5

VENTILATION MEASUREMENTS IN LARGE BUILDINGS

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1. SYNOPSIS

This paper compares and contrasts different methods of ventilation measurement in large buildings. Conventional methods of using tracer gas to measure ventilation rates in large volumes are cumbersome and expensive. These constant concentration and decay ventilation measurements require substantial artificial mixing, complex monitoring equipment, and large installation costs to produce accurate results.

By using discrete injection and sampling units consisting of sealed sample gas bags and peristaltic pumps, long term samples of tracer gas can be collected with the minimum of capital and installation costs. The samples collected represent the mean local equilibrium tracer gas concentrations providing the flow rates of injection and sample pumps remain constant.

The comparison between conventional ventilation measurements and discrete bag sampling is drawn. Hence an assessment of the accuracy of this is obtained when using a constant emmission source of sulphur hexafluoride.

The method was found to be a useful measure of ventilation rate but increasing problems are found with increase of measured volume requiring greater attention to thorough mixing of the atmosphere and injection sample bag positioning.

2. INTRODUCTION

Considerable effort has been focussed on the problems of measuring ventilation in domestic premises (1) and a large degree of success and understanding has been achieved and used by architects and building services engineers to improve the air quality and comfort within dwellings. Ventilation heat losses become a major part of a house's heating load when insulation standards are raised, so it is desirable to keep them to a minimum. However, care must be taken that adequate ventilation is provided for comfortable and hygienic living conditions, and for any combustion appliances requiring fresh air supplies. The problems of ventilation research in large commercial and industrial premises has received much less attention despite early reviews of the subject (2).

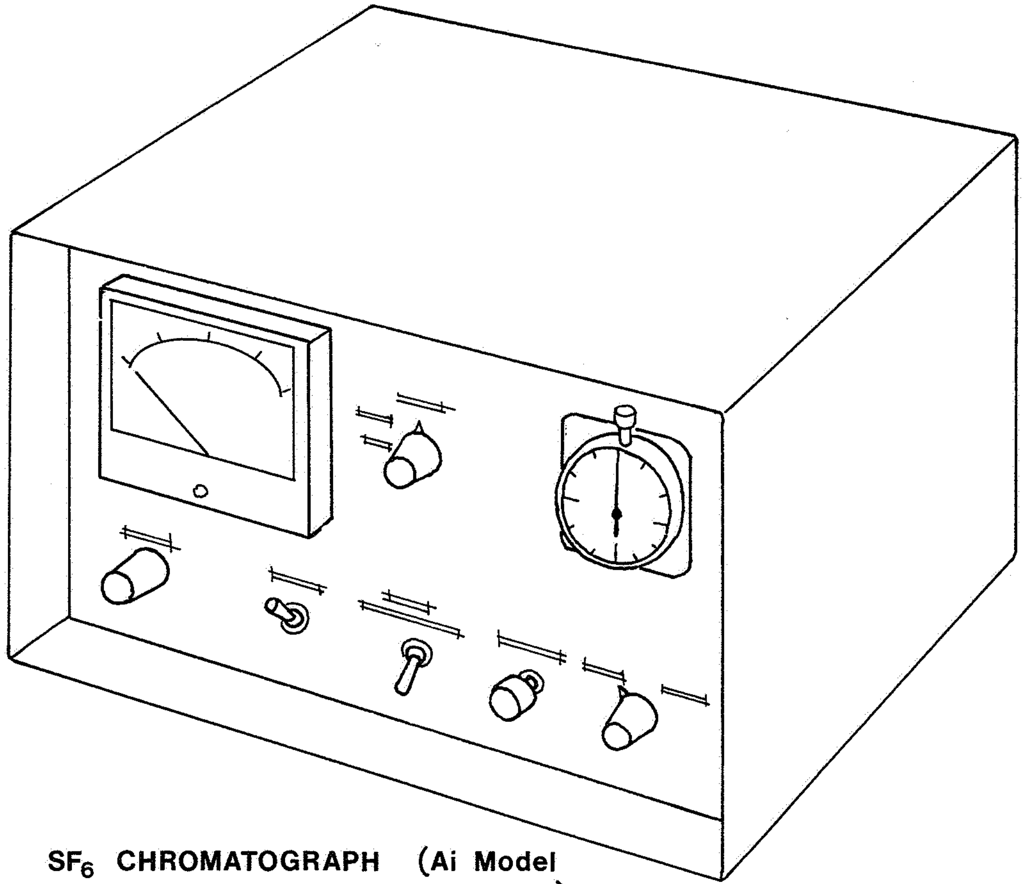
The potential energy savings available from this work are considerable. The large heating bills of factories and commercial complexes may well mean that an individual ventilation survey would be cost effective in terms of subsequent reductions in ventilation heat loss and improvements in air distribution. This is only feasible if simple, inexpensive experimental methods can be devised to provide a suitable level of data capable of indicating where improvements can be made.

In many industrial buildings, undesirable airborne pollutants are released in isolated areas. Knowledge about local ventilation rates and air distribution within the building can help to contain these contaminants and provide for their local extraction, while being able to reduce the overall ventilation rate and still maintain a healthy working environment. This is not unlike the question of air distribution within a dwelling where higher local ventilation rates in kitchens, toilets and bathrooms can lead to both a more healthy environment, and result in energy savings by reducing the necessary ventilation in other parts of the house.

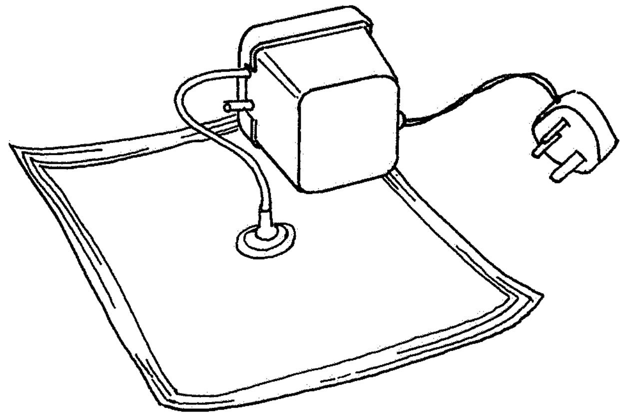
There are two fundamental approaches that can be made to developing ventilation measurements in large buildings. Firstly, the existing experimental equipment developed for domestic ventilation measurements, can be increased in size. It can be adapted to deal with large single cell buildings instead of small, multi-cell buildings. When automated constant concentration techniques are employed, this entails many controlled injection and sample channels, automatically controlled by computer. Mixing must be very carefully performed so that local ventilation rates are measurable without radically altering the airflows in the building. These devices are very expensive to manufacture. Also when a building is measured, many sample and injection lines must be laid requiring much time and labour.

Alternatively, simplified methods of measuring ventilation can be developed which require less capital outlay, and are easy to transport and install. The disadvantages of simplified methods such as taking tracer gas samples in bags are in the limited amount of information obtained and the fact that analysis and data collection cannot easily be automated. These limitations may not be important as analysis is easy and rapid. The information gathered may well also be comparable with automated constant concentration techniques if a few instantaneous samples can be taken to investigate how the ventilation rate in a specific area varies from the mean, under differing weather conditions and ventilation opening configurations.

Figure 1 EQUIPMENT USED: SF_6 CHROMATOGRAPH AND INJECTION/SAMPLE PUMP & GAS BAG



SF_6 CHROMATOGRAPH (Ai Model 505)



PERISTALTIC PUMP

GAS BAG

3. EXPERIMENTAL PRINCIPLES

The experimental method investigated involves injecting a continuous flow of sulphur hexafluoride into the room being measured. The gas is metered by a peristaltic pump and is supplied from a gas bag (FIG. 1, PAGE 4). The speed of the pump can be altered, as can the diameter of the peristaltic tubing. This results in a large variety of flow rates being available, typically from 6cc/hr to 1 l/hr. A small fan is used to provide initial mixing, thus ensuring no layering of the tracer gas due to density differences. Gas samples are taken from the atmosphere with similar peristaltic pumps, collecting a sample in the attached gas bags.

These must be positioned so that the samples are collected only when the tracer gas is well mixed with the air. No representative samples can therefore be taken from the immediate vicinity of the injection point. The variation in flow rate available with the pumps enables collection of adequate samples over time intervals of 1/2 hr to 14 days. Instantaneous samples are easily obtainable by manually pumping air into a collection bag. Many samples are taken at different heights and positions in the room being measured. Typically, 12 samples points are used simultaneously.

Analysis is performed with an Analytical Instruments SF_6 detector/chromatograph. Typical equilibrium concentrations used in sampling are 10^{-2}ppm. The chromatograph has a useful measuring range of 10^{-4} to $5x10^{-2}$ppm.

By the use of gas bags to contain injection tracer gas, long term tests can be performed without the need to use large, hard to transport, gas cylinders and the risk of high pressure leaks.

4. EXPERIMENTAL DEVELOPMENT

Our aim in developing this method was to test it in increasingly difficult circumstances, gradually increasing the volumes of the test rooms. At each stage we compared the bag sampling method with constant concentration and decay measurements.

Initial tests were performed in a domestic dwelling, using a naturally ventilated room of $33m^3$ volume. A single injection point of 6.3cc/hr 10% sulphur hexafluoride was used in conjunction with three sampling positions, as shown in figure 2, page 7. Some variation in concentrations was noted in different parts of the room, depending on the amount of ventilation and mixing used. Simultaneous measurements of nitrous oxide and tracer gas decay rates were performed once equilibrium sulphur hexafluoride concentrations had been reached.

An increase in volume to a $100m^3$ room with a 2.5m ceiling height produced repeatable results of good correlation between equilibrium bag sample (with 31cc/hr pure SF_6 injection) and nitrous oxide decay measurements. The room was ventilated mechanically with six ceiling mounted supply terminals, and two ceiling mounted extract terminals (Fig. 3, page 7). Consistently low equilibrium concentrations at ceiling level demonstrated a considerable amount of short-circuiting between intake and exhaust terminals.

A laboratory of $650m^3$ with a ceiling height of 6m was the subject to much experimentation with injection and sampling configurations. New bag sampling experiments were continuously compared with conventional decay and constant concentration methods. For these experiments, an autovent apparatus was used. It has 12 computer controlled injection and sample ports, each pair of which was associated with a volume of approximately $50m^3$ within the laboratory (Fig. 4, page 8). The injection rate of sulphur hexafluoride for equilibrium experiments was 73cc/hr pure sulphur hexafluoride.

Figure 2 SEGAS TEST HOUSE—BEDROOM 3

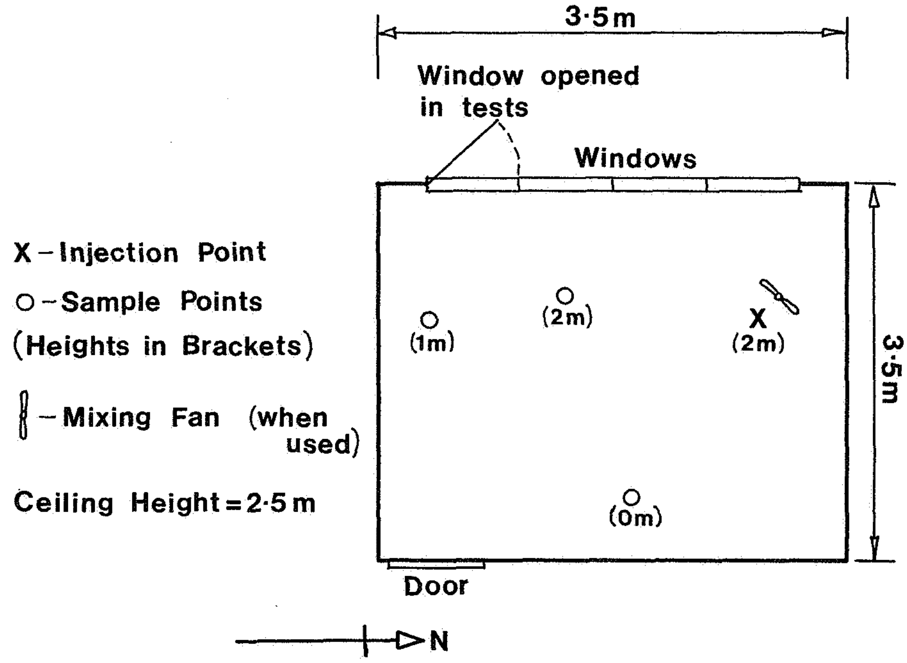


Figure 3 GUILDFORD UNIVERSITY METALLOGRAPHY LABORATORY
(NO EXTERNAL WALLS)

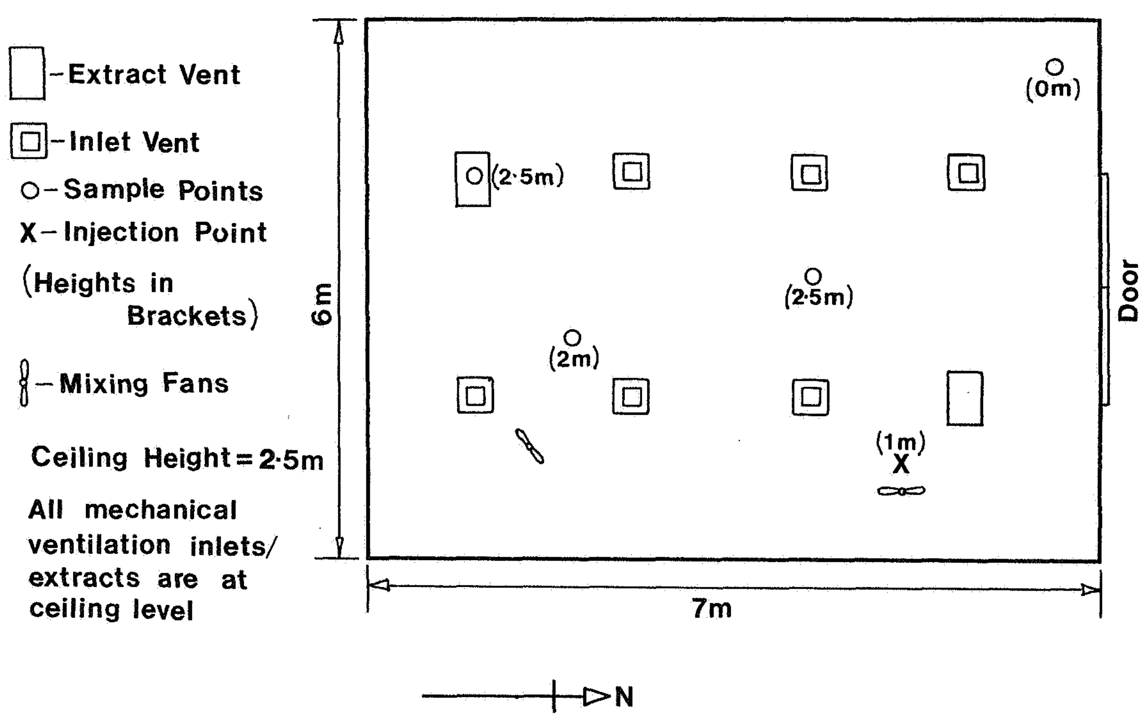
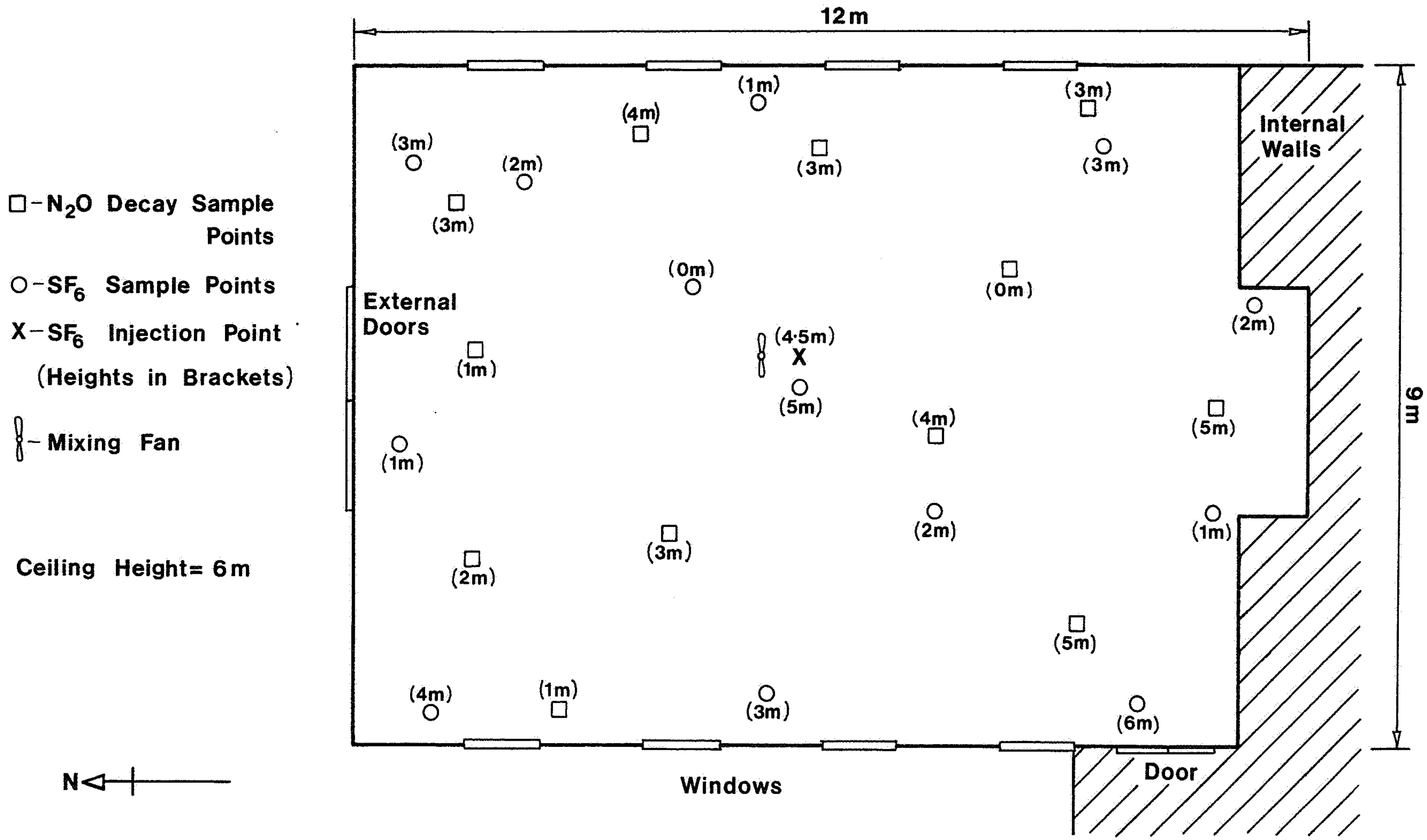


Figure 4 SEGAS CENTRAL LABORATORIES; AERODYNAMICS LABORATORY



5. PRELIMINARY RESULTS

5.1 Segas Test House, Central laboratories, Bedroom 3,33m^3 (Fig.2, page 7)

(Natural Ventilation; windspeed, ms^{-1}, wind direction)

SAMPLE POSITION	SF_6 EQUILIBRIUM CONCENTRATION (PPM)	EQUILIBRIUM VENTILATION RATE (ac/hr)	N_2O DECAY VENTILATION RATE (ac/hr)
a) FAN MIXING			
1)	4.5×10^{-2}	0.42	0.35
2)	4.5×10^{-2}	0.42	0.42
3)	4.8×10^{-2}	0.40	-
b) NO MIXING			
1) (WINDOW "A" OPEN)	9.2×10^{3}	2.1	4.6
2) (WINDOW "A" OPEN)	6.0×10^{-3}	3.2	4.8
3) (WINDOW "A" OPEN)	6.5×10^{-3}	2.9	-

Injection Flow Rate 6.3cc/hr 10% SF_6.

5.2 Guildford University Laboratory, $100m^3$ (Fig.3, page 7)

(Mechanical Ventilation System + 2 mixing fans)

SAMPLE POSITION	SF_6 EQUILIBRIUM CONCENTRATION (ppm)	EQUILIBRIUM VENTILATION RATE (ac/hr)	N_2O DECAY VENTILATION RATE (ac/hr)
1) UNDER SINK	$4.8x10^{-2}$	6.5	6
2) AT CEILING	$2.9x10^{-2}$	11	7
3) HEAD HEIGHT, MID ROOM	$4.1x10^{-2}$	7.5	7.5
4) AT EXTRACT TERMINAL	$4.2x10^{-2}$	7.5	8

Injection Flow Rate 31cc/hr SF_6

5.3 Segas Central Laboratories: Aerodynamics Laboratory, $650m^3$,(Fig.4, page 8)

(Natural ventilation; windows open; wind speed, ms^{-1}, wind direction; single for mixing).

SAMPLE POSITION	SF_6 EQUILIBRIUM CONCENTRATION (ppm)	EQUILIBRIUM VENTILATION RATE (ac/hr)	N_2O DECAY VENTILATION RATE (ac/hr)
9) (MINIMUM N_2O DECAY)	$1x10^{-2}$	11.2	11.6
4) (MINIMUM SF_6 CONCENTRATION)	$0.85x10^{-2}$	13.2	12.2
12) (MAXIMUM N^2O DECAY)	$1x10^{-2}$	11.2	14.2
1) (MAXIMUM SF^6 CONCENTRATION	$1.55x10^{-2}$	7.2	13.2
MEAN		10.1 (13 SAMPLES)	12.8 (12 SAMPLES)

Injection Flow Rate 73cc/hr

6. DISCUSSION

The bag sampling equilibrium method seems to work fairly well when compared to standard methods. Agreement between equilibrium and decay results is good under conditions of thorough mixing.

In both experiments A) and C), equilibrium ventilation results are less in agreement with decay results than in experiment B), in which there is a high degree of mixing. The only result in experiment B) which does not closely agree is position 2), at the ceiling. This is because of ventilation short-circuiting between inlet and exhaust mechanical ventilation terminals situated on the ceiling. This implies that the equilibrium method used is more sensitive to local high ventilation rates than standard decay methods.

Many practical problems have been encountered in attempts to increase the accuracy of the bag sampling method in the $650m^2$ building. Problems have also been encountered in measuring local ventilation rates with "autovent" apparatus in order to verify the bag sampling experiments.

By providing good initial mixing for tracer gas decay experiments and allowing induced air movement to subside before sampling the tracer gas at many points simultaneously (see Fig. 4), a useful representation of local ventilation rates can be obtained. Figure 5, page 12, shows such local ventilation measurements in the Segas Aerodynamics Laboratory in an easterly wind of $4ms^{-1}$. Figure 6, page 12, shows the influence of an operational conventional flue in the laboratory in a $2ms^{-1}$, westerly wind. The highest ventilation rate measurement in the vicinity of the flue indicates that inadequate mixing is occurring, as there is no source of fresh air by the flue entrance at ground level. Both these results show that the NE corner of the laboratory is not well sealed. In figure 5, the higher ventilation rate in an easterly wind indicates more air is entering there. In figure 6, the lower ventilation rate in a westerly wind indicates more air is leaving the laboratory by that corner.

Constant concentration experiments using various mixing methods produced overall ventilation results which agreed closely with the overall decay results, but local ventilation results were affected seriously by "pockets" of high concentration of inadequately mixed tracer gas drifting around the building. This made the computer control of the concentration locally unreliable, and no satisfactory method of overcoming this problem has been found.

Figure 5 SEGAS CENTRAL LABORATORIES; AERODYNAMICS LABORATORY N_2O DECAY DISTRIBUTION RESULTS; EAST WIND, $4ms^{-1}$.

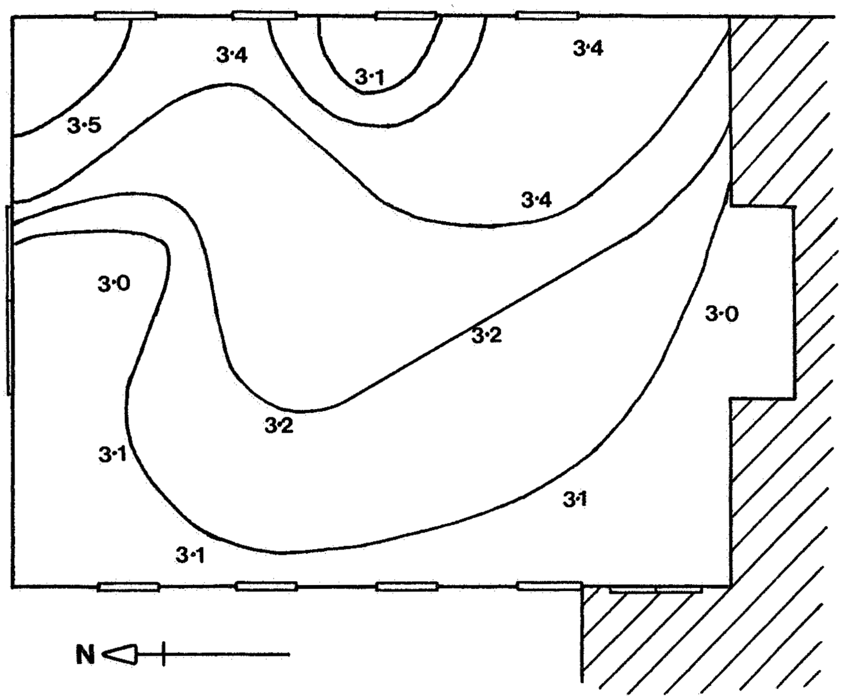
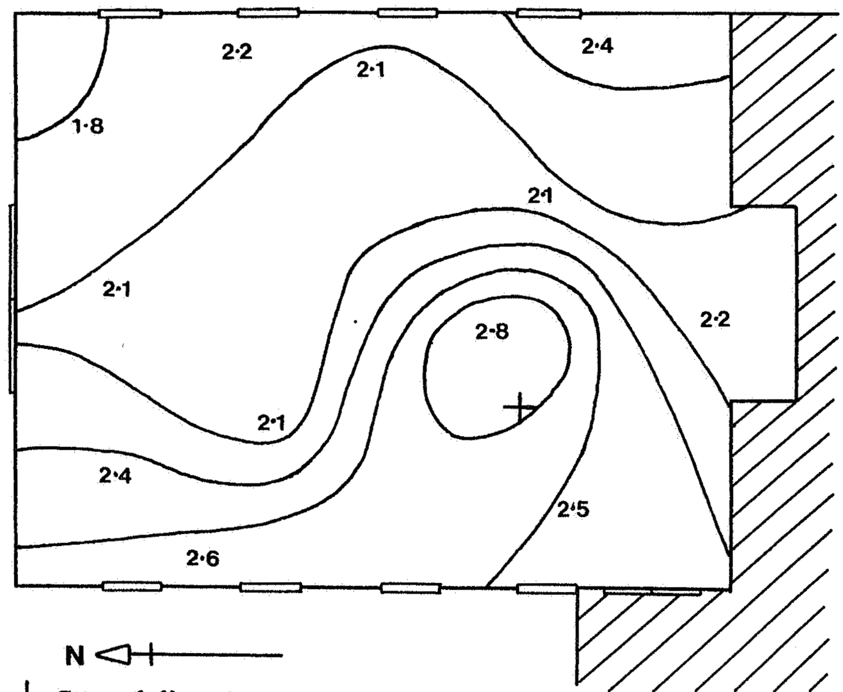


Figure 6 SEGAS CENTRAL LABORATORIES; AERODYNAMICS LABORATORY N_2O DECAY DISTRIBUTION RESULTS; WEST WIND, $2ms^{-1}$.



+ Site of flue in use.

The largest problem encountered with bag sampling methods again was mixing. It is easy to provide a large amount of mixing which destroys the natural air patterns in the building and produces an even concentration of tracer gas throughout all of the sample bags, but this gives no idea of local ventilation rates. When mixing is reduced to a very low level, concentrations vary hugely within the building. The most effective method found so far has been a single small mixing fan at the injection point to ensure sufficient tracer gas mixing such that the sulphur hexafluoride is not subject to settling towards the floor of the building because of its high molecular weight. A high injection point in the centre of the building with the fan pointing down will ensure adequate mixing without the internal stack effect of the building keeping most of the tracer gas at high level. A low injection point with a horizontally orientated mixing fan also produces reasonable mixing, but is more likely to influence local equilibrium tracer gas concentrations at the edges of the building. It may also be susceptible to stack effects resulting in low tracer gas concentrations close to the injection point.

When sampling these low tracer gas concentrations (1×10^{-2}ppm) adsorption of the gas into internal surfaces of the peristaltic pump and gas bag is possible. This was checked by comparing new bags and pumps with sample collectors that had been in use for two months, measuring consistent concentrations of tracer gas. The new sample bags were found to give consistently lower readings of between 1 & 5% at sample sulphur hexafluoride concentration of 0.02ppm. The surfaces in contact with the sample are about $20cm^2$ silicone rubber tubing in the peristaltic pump and $600cm^2$ of aluminised gas sample bag.

After about two weeks of continuous running, a crystalline deposit forms in the tubing of the peristaltic pump. This deposit restricts the flow rate of the pump, but does not appear to affect the concentration of the sample taken. Initially, it was thought it could be a product of decomposition of the tubing on contact with sulphur hexafluoride. However, these deposits build up to the same extent in bags injecting pure sulphur hexafluoride, and sample bags sampling 0.02ppm sulphur hexafluoride. It would therefore appear that these deposits are a product of mechanical breakdown of the tubing, which would normally be used for pumping liquids, and therefore have a means of internal lubrication.

The manufacturers have been approached to see if alternative tubing can be provided which is not subject to such serious mechanical degradation when used "dry".

Without thorough mixing, ventilation measurements are very susceptible to short circuiting. i.e. Air entering the building and thus contributing to the ventilation rate may have a short residence time, and not reach a doped tracer gas concentration equivalent to the theoretical figure, which should be closely attainable with good mixing.

This results in a higher equilibrium concentration in other areas of the building. It is this short circuiting, or local high ventilation rate which it is desirable to detect. Mixing destroys this effect, but gives a reasonably accurate mean. Detection can only take place with a large number of sample points. This will result in the interception of these high local ventilation airstreams, and give a representation of the airflows involved.

Satisfactory measurements have now been made in a $650m^3$ building with a 6m ceiling, and we are confident that this method can usefully be applied to larger buildings.

FUTURE WORK

It would be ideal to rely upon diffusion to carry the tracer gas to different parts of the building, therefore not relying on mixing fans which inherently destroy the characteristics it is desirable to investigate.

In such an ideal situation, air currents would cause deviations from a symmetrical distribution of tracer gas concentrations and this could be used to lend interpretation as to whether a local area was a cource of fresh air, or an extract of used air.

It may be possible to approach this ideal situation with many injection points of lower concentration tracer gas, relying on diffusion only on a small scale, and identifying important air currents individually. For example, injecting tracer gas into identified fresh air streams may prove a useful technique, although susceptible to changing weather conditions.

Here, there is also scope for use of multiple tracer gases to indentify the exchange of air between different part of the building, or for "labelling" of particular fresh air streams and their subsequent distribution.

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1) See for example proceeding of 1st, 2nd and 3rd, AIC Conferences 1980, 81, 82.

2) JACKMAN, P.J. - "Astudy of the natural ventilation of tall office buildings" JIHVE August 1970,38,103-118.

AIR INFILTRATION REDUCTION IN EXISTING BUILDINGS

4th AIC Conference, September 26-28 1983, Elm, Switzerland

PAPER 6

AIR LEAKAGE IN INDUSTRIAL BUILDINGS - PRELIMINARY RESULTS

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1. INTRODUCTION

In the Swedish Building Code there are recommendations for the maximum air leakage in dwellings, one-family houses as well as multi-family-houses. Most new Swedish one-family houses meet the recommendations. There are no recommendations for industrial buildings. Up to now very little has been known about the air tightness of industrial buildings and very few persons have worried about it.

In the middle of 1980 the National Testing Institute was asked by a manufacturer of building materials if we were able to carry out pressurization/depressurization tests of large industrial buildings. At that time our available fan capacity was about 8 000 m^3/h at 60 Pa. To reach this flow we used two axial fans equipped with measuring ducts with pitot tubes. Depending on our limited measuring resources we had to answer our client, that we could only carry out the measurements on industrial buildings of moderate sizes.

The test objects were selected only by our client. The design of the buildings followed two structural principles: firstly light concrete elements attached to a pre-fabricated concrete frame, secondly sheet metal attached to steel frame, with thermal insulation of mineral wool.

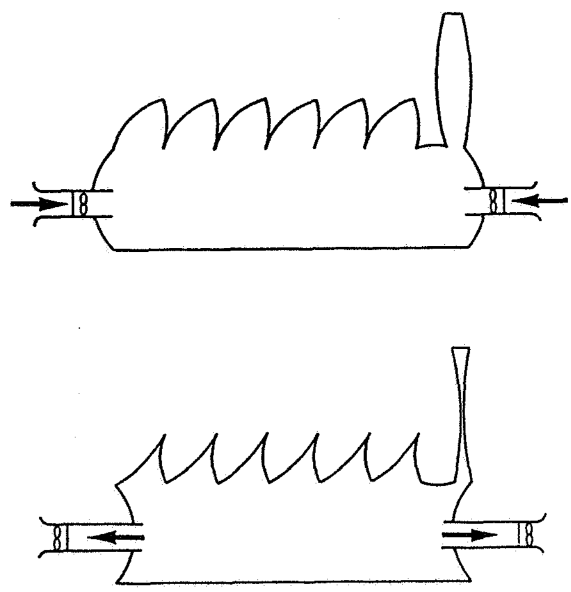

Fig. 1 Pressurization/depressurization tests of industrial building, two fans

Some of the buildings were very leaky and some were very tight. These results caused an animated discussion between manufacturers of building materials, contractors and our building authorities. During that period the National Testing Institute made the decision that equipment for measuring large industrial buildings should be developed. At the same time NORD-TEST asked for a test method especially adapted to industrial buildings.

2. DESCRIPTION OF THE EQUIPMENT

In order to fulfil the demands we could expect that the capacity of the equipment had to be 75 000 m^3/h at 60 Pa. This would mean a large fan and an enormous measuring duct. We had to think of another construction instead of the traditional measuring duct. Tracer gas was the solution to the problem. This way a long measuring duct is unneeeded. By injecting a known constant flow of tracer gas into the air flow upstream the fan and at the same time measuring the concentration of tracer gas in the air flow downstream the fan you can easily calculate the air flow:

$$Q = \frac{q}{c} \cdot 1\ 000\ 000$$

where

Q = air flow through the fan, m^3/s
q = injected tracer gas upstream the fan, m^3/s
c = tracer gas concentration downstream the fan, ppm

The tracer gas injection and mixing device is designed as two rings of tubing located in a short duct of the same diameter as the fan duct. In the walls of the tubing holes with a very small diameter are located radially. This device will inject tracer gas into the whole duct area and give a nearly perfect mixing.

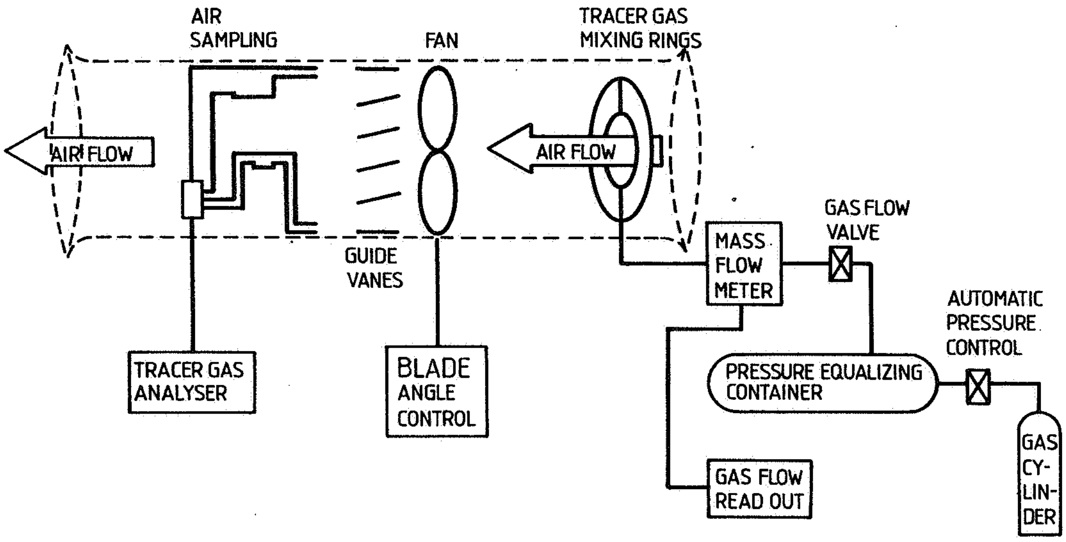

Fig. 2 Schematic view of equipment

The fan is an axial fan type AXICO, size 1 000 mm diameter. The air flow rate is changed by changing the blade angle of the fan. This can be done continuously while the fan is running. In order to measure the tracer gas flow there is an electronic mass flowmeter connected to the injection rings. A steady constant tracer gas flow is obtained by using a pressure equalizing container installed between the gas cylinder and the gas flow meter. The pressure equaling container is equipped with an automatic pressure control. The injection system is working at a pressure of 0,3 MPa.

Downstream the fan four air sampling tubes are located in a duct of the same diameter as the fan duct.

The concentration of tracer gas in the air downstream the fan is measured by an IR-analyzer. As a tracer gas N_2O is used. The fan unit containing the tracer gas injection system and sampling system is mounted on a special trailer. An undercarrige running on rails allow the fan unit to be moved backward and forward and also turned around easily on the trailer. All controls and measuring devices except for the mass flow meter are located in a van. To connect the fan unit to a building there are special connecting boxes.

3. DESCRIPTIONS OF TESTED BUILDINGS

Till now we have carried out three measurements on large buildings using our new equipment. In the following you will find a short technical description of each building.

3.1 Building A

Light-concrete elements attached to a pre-fabricated concrete frame. On the roof there are two rooms, which contain parts of the ventilation system. Those rooms are made of sheet metal attached to a steel frame. Inside the building there is a mechanical workshop.

During the measurement the ventilation system was shut down and sealed off on the outside of the building. All exterior doors were shut, but not sealed off. Internal doors were kept open.

Sizes:	Floor area	4 137 m^2
	Volume inside	36 373 m^3
	Building envelope area, inside walls and roof	6 796 m^2

3.2 Building B

Light-concrete elements attached to a pre-fabricated concrete frame. The building is new and is used as a wholesale store. During the measurments the building was sealed off in the same way as Building A.

Sizes:	Floor area	6 524 m^2
	Volume inside	61 127 m^3
	Building envelope area, inside walls and roof	9 876 m^2

3.3 Building C

Steel-frame with pre-fabricated wall-elements attached to it. The wall elements are made of polystyren covered on both sides with plaster board. The facades are made of sheet metal. The thermal insulation on the roof is made of mineral wool. The roof structure is on both sides covered with sheet metal. The building has a welded plastic air/vapor barrier.

The building was about two years old and used as a tennis hall with six tennis courts and service spaces.

During the measurements the building was sealed off in the same way as Building A.

Sizes:	Floor area	4 236 m^2
	Volume inside	31 622 m^3
	Building envelope area, inside walls and roof	5 809 m^2

4. EXPERIMENTAL RESULTS

In the following you will find the results.

4.1 Building A

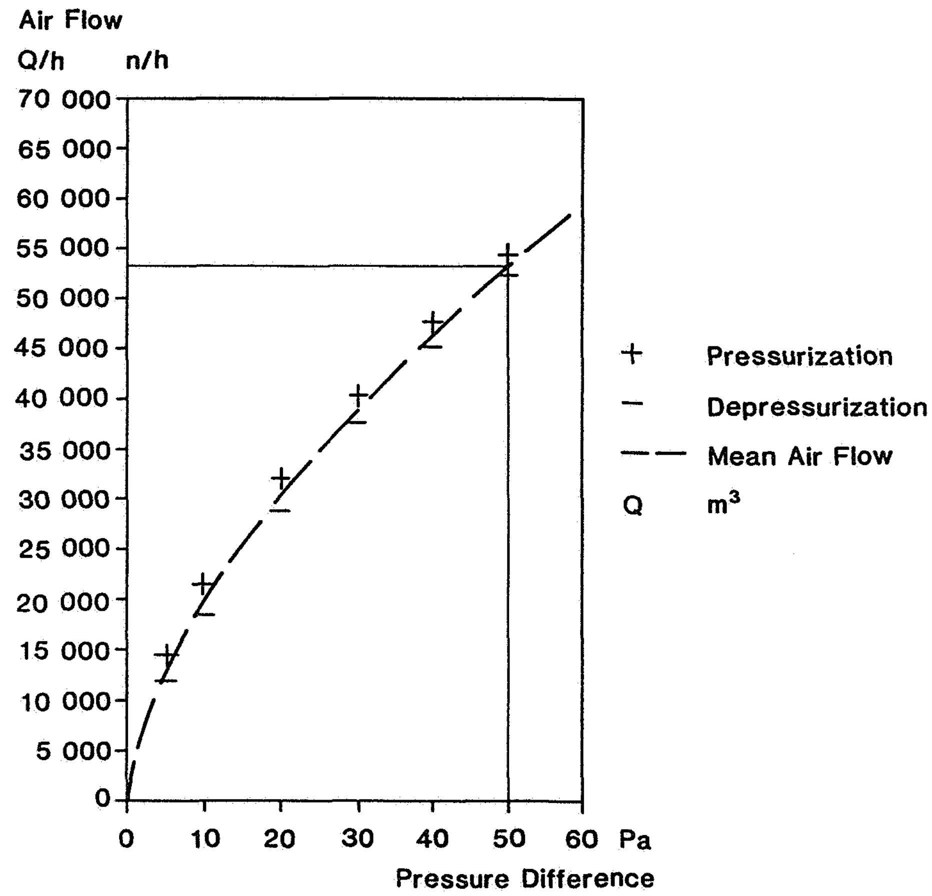

Fig. 3 Air flow as a function of pressure difference

ACH at ±50 Pa: 1,5

Air flow per m^2 of building envelope at 50 Pa (pressurization): 8,0 m^3/h

Air flow per m^2 of building envelope at 50 Pa (depressurization): 7,7 m^3/h

Mean air flow per m^2 of building envelope at ±50 Pa: 7,9 m^3/h

4.2 Building B

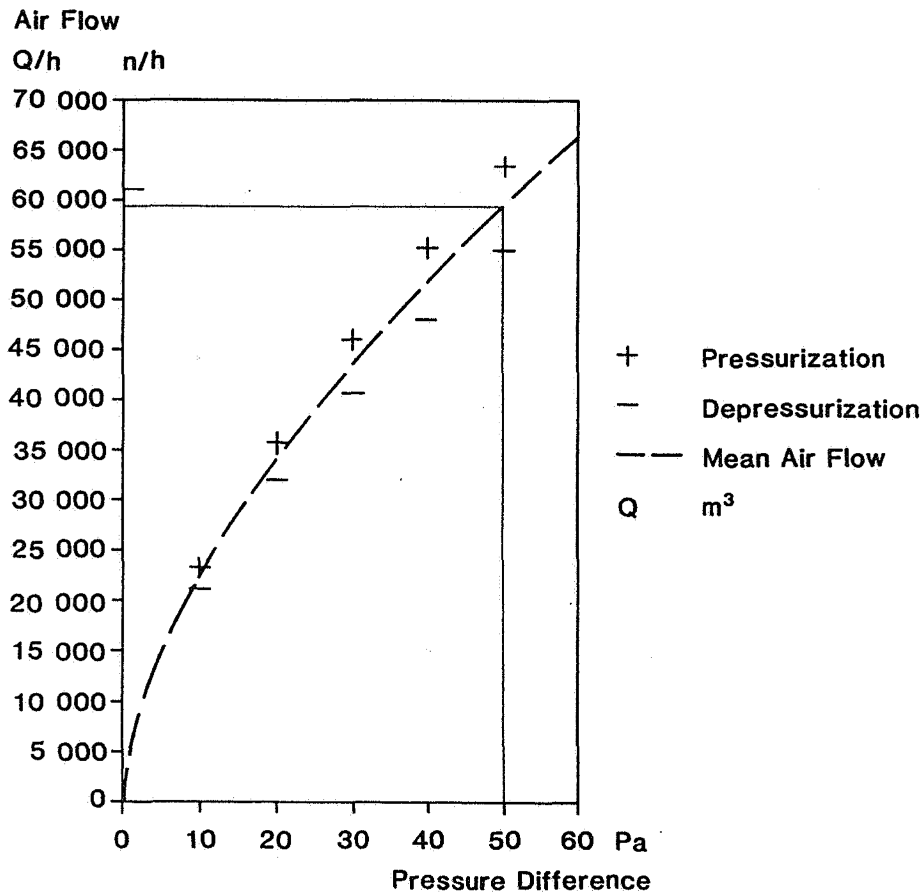

Fig. 4 Air flow as a function of pressure difference

ACH at ±50 Pa: 1,0

Air flow per m^2 of building envelope at 50 Pa (pressurization): 6,4 m^3/h

Air flow per m^2 of building envelope at 50 Pa (depressurization): 5,6 m^3/h

Mean air flow per m^2 of building envelope at ±50 Pa: 6,0 m^3/h

4.3 Building C

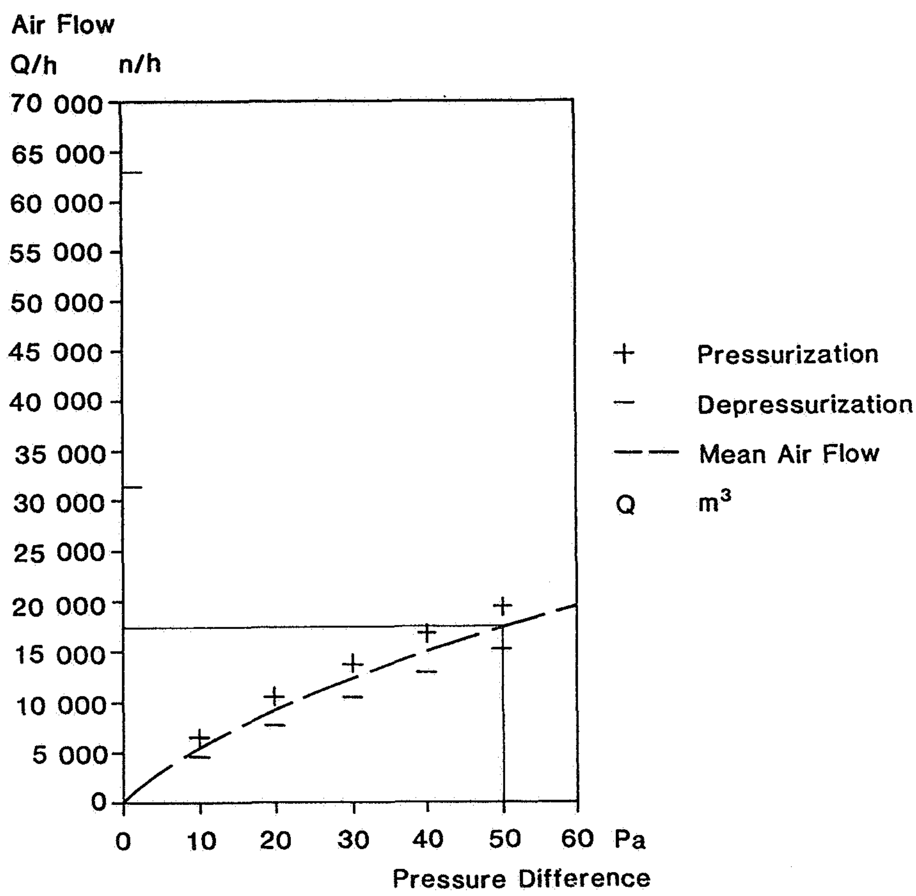

Fig. 5 Air flow as a function of pressure difference

ACH at ±50 Pa: 0,6

Air flow per m^2 of building envelope at 50 Pa (pressurization): 3,4 m^3/h

Air flow per m^2 of building envelope at 50 Pa (depressurization): 2,7 m^3/h

Mean air flow per m^2 of building envelope at ±50 Pa: 3,0 m^3/h

A typical one-family house (1) which meets the recommendations in the Swedish Building Code will have an air leakage in the order of 4,5 $m^3/h/m^2$ of building envelope, at ±50 Pa.

5. CONCLUSION

The tests were performed during a week in June 1983. These preliminary results indicate that the envelopes of industrial buildings can be as tight as the envelope of a one-family house, i.e. a house meeting the recommendations in the Swedish Building Code.

Our goal was to see if we were able to perform pressurization tests on large buildings. The performed measurements show that we have a pressurization measurement system with a capacity of 75 000 m^3/h at 60 Pa. The system can easily be operated by two persons.

There are questions concerning the benefit of testing large buildings. We think that the test results will be a valuable contribution to the knowledge of how to design air tight industrial buildings. It has been claimed that air tight industrial buildings are unneeded, as their ventilation systems will cause large air flows and there are a large number of door openings during the day. This is partly true, but the fact is that most factories are not in use 16 hours a day. The time the factory is closed down the building is of course still heated. Therefore one way to save energy in industrial buildings is to reduce the air infiltration by making them air-tight.

6. REFERENCES

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Royal Institute of Technology, Sweden, No 15, 1977

AIR INFILTRATION REDUCTION IN EXISTING BUILDINGS

4th AIC Conference, September 26-28 1983, Elm, Switzerland

PAPER 7

AN OVERVIEW OF VENTILATION RESEARCH IN LARGE NON-RESIDENTIAL BUILDINGS

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SYNOPSIS

A short treatment of the concepts and aspects that play a role in ventilation is followed by a brief description of the investigation methods employed. A concise survey of the equipment and mathematical models used is given. The ventilation research carried out by the IMG-TNO is reviewed. Objects treated are factories, laboratories, hospitals, auction halls and similar buildings.
In the evaluation and conclusions it is suggested that:

* almost no research into local ventilation provisions has been carried out;
* the choice between natural and mechanical ventilation is a difficult one;
* there is a lack of knowledge regarding the influence of turbulence on ventialtion.

1. INTRODUCTION

Ventilation of buildings means the removal of stale air and the supply of fresh air. Stale air contains not only CO_2 due to human respiration and body odours, but also pollutants of many kinds released by processes carried out in buildings, that can in some cases be merely a nuisance but in certain circumstances can be posionous.
This publication, however, takes a wider view of ventilation. It is concerned with the area of knowledge that covers the transport of air through buildings, to which the control of air pressure differences and air flow devices is inherent.
In the last few years, partly as a result of the energy crisis, a great deal of knowledge concerning the ventilation of dwellings has been acquired. Relatively little is known regarding buildings other than dwellings. In most cases the research that has been carried out can be regarded only as "case studies". There is almost no question of systematic research covering the whole field.
On the basis of the investigations carried out by the IMG-TNO over the last 10 years, and an evaluation of these, an attempt is made to indicate the fields for future investigation.
The investigations described in the survey are confined to the aspects of air exchange, and the transport of air and the pollutants it contains. Investigations more concerned with comfort are only touched upon in the survey.

2. THE VENTILATION OF BUILDINGS

2.1 General

Ventilation of buildings is produced by differences in air pressure that cause air to be transported.
Such differences in air pressure can arise from natural "forces", such as wind and temperature differences, but also from mechanical "forces" such as fans.
Very often both types of forces are concerned. The correct balancing of the two is a matter than deserves particular attention. Designers frequently opt for mechanical extraction in large buildings in order to meet the requirements for ventilation. Natural ventilation is scarcely considered. This is due to the lack of insight into the process of ventilation and the lack of means for calculating the ventilating effect as a function of wind speed, wind direction and temperature difference.
When mechanical extraction is used, fresh air is supplied via natural ventilating devices such as grilles, open windows or cracks and joints. The building is then subject to excess pressure with respect to the atmosphere or neighbouring buildings. In such cases the opening of an outer door or a connecting door can cause an undesirable flow of air.

Another aspect of building ventilation is the movement of air in a space due to ventilation. At certain points clean air will enter, while at other points polluted air will often be extracted. Air extraction has little influence on the movement of air within the space. The supply of air, however, can have an overwheling effect. This must be taken into account so far as the distribution of pollutants and/or heat is concerned. The extraction of pollutants or excess heat can then best be effected by removing them at source as far as that is possible.

In general, the ventilation of buildings depends on:
- the exterior conditions (wind and temperature);
- the building (geometry, design, situation, position of openings);
- the purpose of the building;
- the presence or absence of mechanical ventilation.

2.2 Pressure Differences

2.2.1 Wind

Due to the presence of atmospheric pressure differences movements of air take place (winds). The extent of such movements depends partly on the roughness of the earth's surface. When the wind strikes a building, a part of the kinetic energy will be converted into a pressure. A surface facing the wind (windward) will experience a higher pressure than the opposite (leeward) surface, and than an surface more or less horizontal to the wind (the roof). See figure 1.
This can be expressed as:

$$\Delta p = k.\tfrac{1}{2}\, v^2 \rho \qquad (1)$$

where

Δp =	pressure difference on an external wall	[Pa]
k =	a dimensionless pressure coefficient depending on the form of the building and the exposure	[ ]
ρ =	air density	[kg/m^3]
v =	wind velocity	[m/s]

2.2.2 Stack Effect

Temperature differences between inside and outside cause differences in air density and result in pressure differences. This can be expressed as:

$$\Delta p = (\rho_c - \rho_w).g.h$$

where

Δp =	pressure difference (stack effect)	[Pa]
ρ =	air density	[kg/m^3]
c =	cold air	
w =	warm air	
g =	gravitational force	[N/kg]
h =	height between inlet and outlet openings	[m]

Figure 1 Natural ventilation by ....

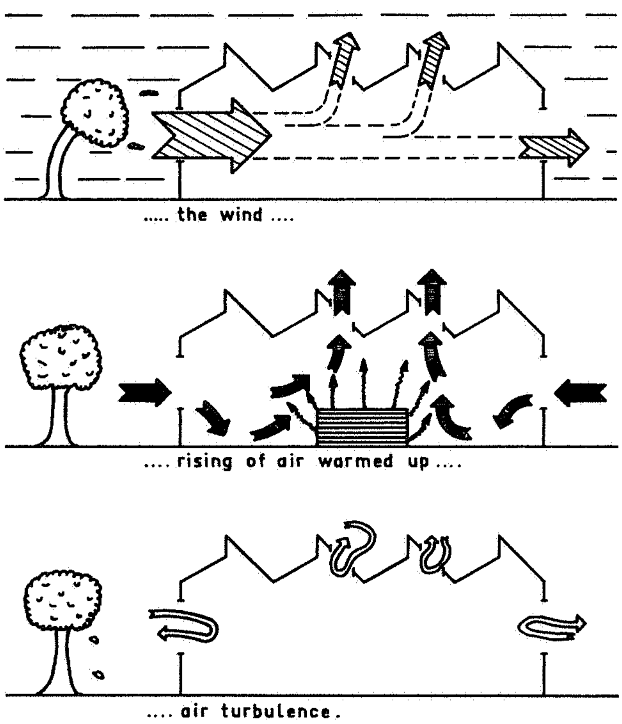
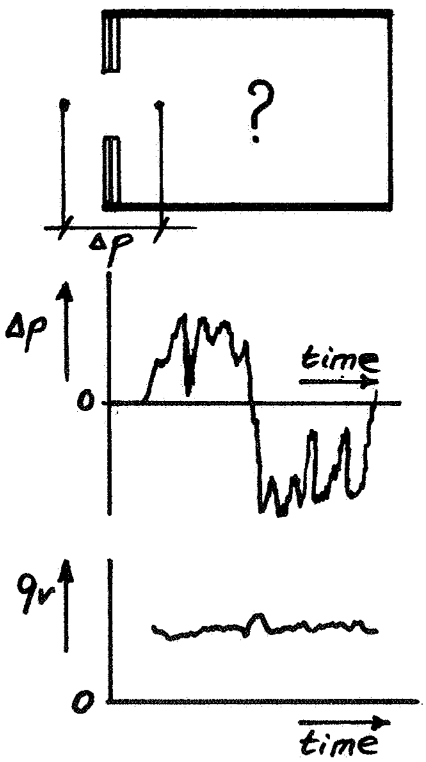


Figure 2. Turbulence



Building with one

ventilation opening

Pressure difference

sometimes positive
sometimes negative

mean pressure is zero

ventilation

For building ventilation the following factors are important in relation to pressure differences:

- the pressure on the exterior of a building as a function of wind velocity and direction;
- the pressure differences across all ventilation openings as a result of the pressures on the exterior and the distribution of the openings, both in the outer skin and in the interior walls;
- the effect of immediately adjacent buildings or vegetation on the pressure differences;
- the effect of the situation on the pressure differences (for example, building density, coast/inland, high/low);
- the effect of the form of the building;
- the effect on the ventilation of fluctuating pressures resulting from turbulence (figures 1 and 2).

2.3 Air Flow through Openings

In addition to air pressure differences, ventilation also requires openings.

Inevitable joints, cracks and gaps, but also special ventilation provisions such as ventilation windows, grilles or ducts are the cause of an air flow through the building. The relationship between the individual air flows through any opening and the pressure difference across the latter can be expressed as:

$$q_v = C(\Delta p)^{\frac{1}{2}} \qquad (3)$$

where

q_v = volume flow rate of air [m³/s]
C^v = air-flow coefficient, defined as the volume flow rate of air at a pressure difference of 1 Pa [m³/s at 1 Pa]

C = f(A)
A = superficial area [m²]
p = pressure difference across opening [Pa]
n = a coefficient between 1 and 2, depending on the character of the flow
n = 1 for pure laminar flow
n = 2 for pure turbulent flow

For the purposes of investigating ventilation, knolwedge of the location and the size of all openings in the building is therefore required.

3. INVESTIGATION METHODS

3.1 General

The organization of the investigation is determined by the nature of the problem, and by whether it is to be carried out in the

design phase (prediction) or on an existing building (usually troubleshooting).
In the case of a predictive investigation in the design phase, the ideal situation would be:

Determination of the pressure distribution in a wind tunnel, using a model of the building and simulation of the immediate surroundings.
The carrying out of calculations with the aid of a mathematical model.

The mathematical model, using as input the pressures determined in a wind tunnel, allows a parameter study to be made with which pressure differences, volume flows, air flow directions, ventilation volumes, air velocities and the concentrations of pollutants can be studied in relation to each other.

With investigations of existing buildings, measurements can also be made, depending on the nature of the problem. It is usually impossible in the case of fairly large buildings that are not intended as dwellings, to solve a problem solely by measurements. The results of measurements on existing buildings or installations are often dependent on weather conditions, productive capacity, etc. In such cases the situation is determined for normally occuring circumstances, usually confined to a restricted area.
The aim is then to simulate the same circumstances as accurately as possible with the aid of mathematical models. A parameter study can then be performed on the mathematical model.

In some cases, particularly where concentration and temperature distributions, stratification and control of air flow directions are concerned, tests on scale models may be necessary. In such cases account must be taken of the model rules and the associated characteristic numbers such as the Froude, Grashof and Archimedes Numbers.

3.2 Measuring Equipment

In addition to mathematical models, scale models and a wind tunnel, a large number of facilities and instruments are available for ventilation investigations.
Up to 1975 recordings were made on multi-channel recorders. Since then, and almost without exception, use has been made of a data acquisition system consisting of a controller, DV meter and scanner.
A survey of the measuring equipment in use is given in Table 1.

TABLE 1 Measuring Equipment in Use

Quantity to be measured	Instrument
Air velocity	- Velocity meter - Vane anemometer - Thermoelectric anemometer - Pressure plate*
Air pressure differences	- Betz micromanometer - Electronic pressure sensor
Volume flows	- Pitot tube - Orifice plate
Ventilation factor	- Katharometer - Infrared spectrometer
Concentration	- Various instruments, depending on the component to be measured

* This is a instrument specially developed for measuring flows through large openings, with which the value and the direction of the flow normal to the flow area can be determined [1].

The IMG-TNO wind tunnel is of the open-return type with a cross section of 1,1 x 1,1 m at the measuring section. The ground roughness of the distant surroundings are simulated by strips over a length of approximately 6 metres. The direct surroundings of the building under investigation are modelled to scale.

3.3 Mathematical Model

A space in the model is called a junction. In the static case the sum of the incoming air mass flows at a junction must be equal to the sum of the outgoing air mass flows. In general there is a given pressure for each junction at which this will occur. The computer program iteratively calculates for each junction the pressure at which the air flows are balanced. In practice the pressure in a space will fluctuate somewhat in the conditions used by the computer program. The instantaneous values of the actual air flows will therefore be slightly out of balance, but the average values will be the same as those given by the computer program.

Because of these fluctuations the actual ventilation is somewhat higher than that calculated on the basis of the time-averaged pressures. The program includes an approximation calculation that allows the effect of such turbulent air exchanges to be calculated.

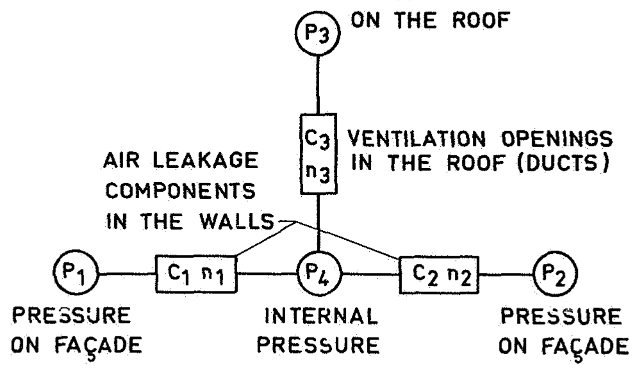
The program allows the use of fans to be simulated. The temperatures in the program are input values and do not change when the ventilation flow changes.

The program is intended primarily for calculating the ventilation of buildings. In these the air velocities in the spaces are so low that the pressures due to them can be neglected in comparison with the pressure differences across air leaks between spaces or across the facade [2,3].

The IMG calculation model for ventilation has been in use since 1977. Up till then use was made of an electrical analogue model specially developed for the purpose [4].

Figure 3

One-junction ventilation model



4. REVIEW OF INVESTIGATIONS UNDERTAKEN

This chapter provides a review of the most important investigations that have been carried out by IMG-TNO during the last 10 years.
The review includes investigations undertaken for third parties, for which results can not be published. In these cases an overall description of the problem and the approach is given, together with a fictional example of the results.

Before describing the investigation carried out for each type of building, a more general study will be discussed first.

4.1 Model Tests of Wind Pressure Distribution across some General Forms of Building

In this investigation [5, 6] the average wind pressures on the facades and roofs were measured with five types of building (see figure 4). The scale of the models was 1:200. The measurements were made with varying wind directions and three values of ground roughness. The influece of the immediate surroundings was also investigated. For this purpose a second building was placed at varying distances from the building under test. An approximation method for estimating pressures in situations different from those of the test is given. Some results are illustrated in figures 5, 6 and 7.

4.2 Factories

A total of five factory buildings were tested, having gross volumes of 40 000 m^3 to 108 000 m^3 [2, 7, 8].
The buildings concerned were a foundry, an ore-pelleting plant, an electrolytic plating plant, a fabric printing works and a chemical factory.

In almost all cases a significant part of the ventilation was provided by thermal "forces".
The nature of the problem varied only slightly from case to case. Pollutants generated by the production processes had to be removed. The distribution of pollutants had to be restricted. This meant studies not only of the mechanical extraction provisions but of the air flow patterns as well. The pollutants consisted of:

zinc oxide in the foundry;
fluorides and dust in the pelleting plant;
oil mist in the electrolytic plating plant;
white spirit and moisture in the printing works;
mercury vapour in the chemical factory.

In the pelleting plant and the plating plant measurements of the pollutants formed part of the investigation.
In almost all cases balancing of the possibilities for natural and mechanical ventilation was included in the investigation.
A very extensive scale model test was carried out for the electrolytic plating plant [9, 10].
No measurements of the effectiveness of the local extractors were made apart from determination of the extracted volume flows.
In all cases mathematical models were used to calculate the dimensions of the mechanical and natural ventilation systems.
The conclusions of the investigation can be summarized as follows:

- Observation of the air flows in four of the five cases allowed improvements to be indicated without having to measure the effectiveness of the local extraction equipment.

- The ventilation systems in use could in all cases be improved. In most cases this involved fitting sufficient, mutually matched and adjustable ventilation openings. These were usually too small by a factor of 5 to 10. In addition the distribution of the extraction and supply openings over the roofs and facades left something to be desired. The general tendency was to pay more attention to the roof openings than to adequate supply provisions, spread over several facades. This was in spite of the fact that mechanical extractors were already fitted.

Examples of the results of the investigation are given in figure 8 and tables 2 and 3.

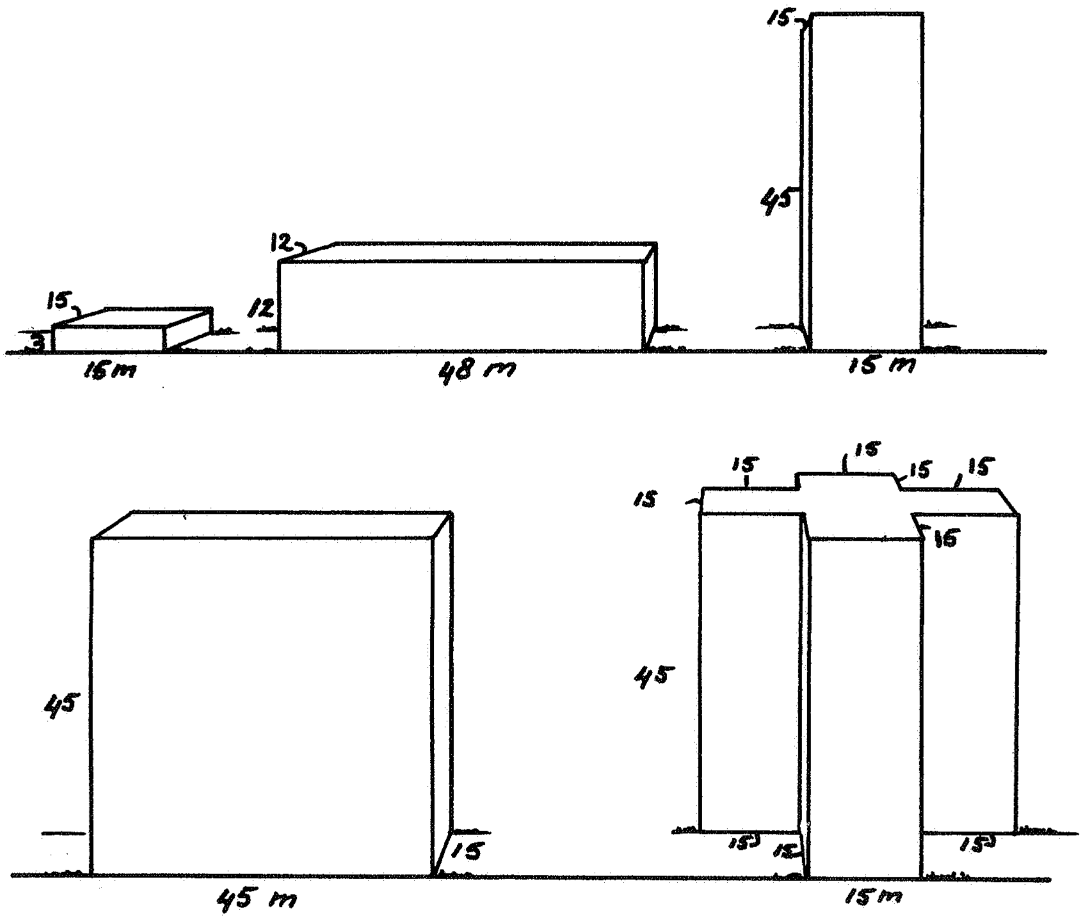


Figure 4 Building forms

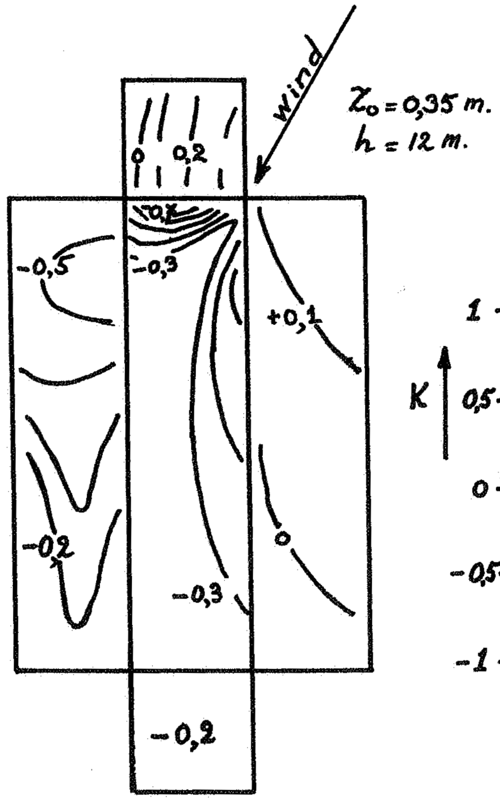


Figure 5 Pressure distribution

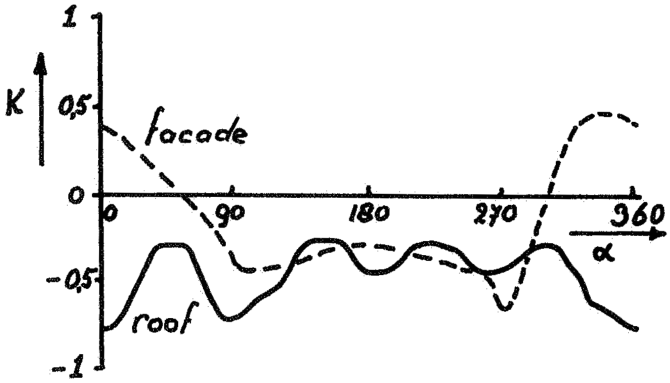


Figure 6 Direction dependent pressure differences

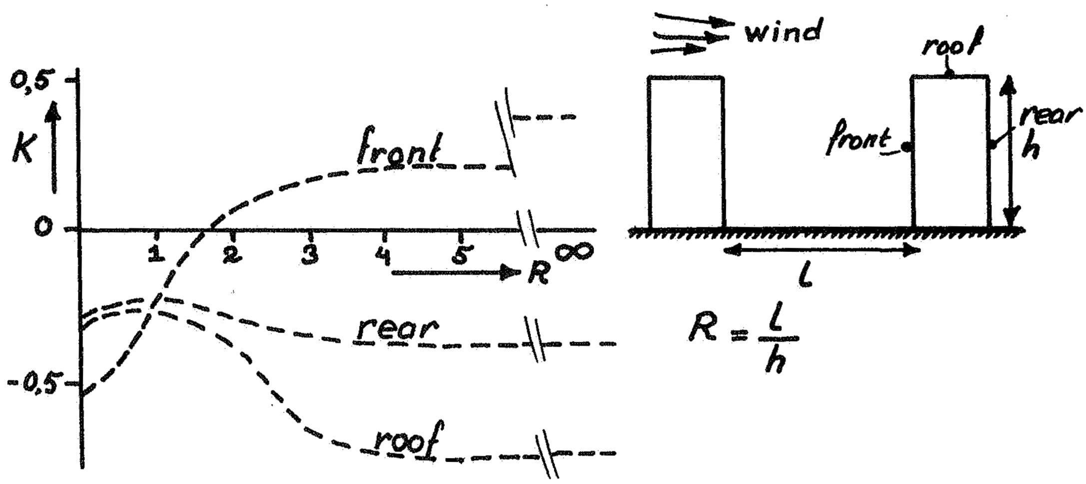


Figure 7 Influence of obstacles at various distances

TABLE 2

Mass flows based on	Q_1	Q_2 (kg/s)	Q_3	Q_4	Air change rate (h^{-1})
Velocity measurements	861	50	707	133	32
Pressure measurements	807	50	694	133	34
Calculation model	787	72	726	133	30

In a factory hall, with a capacity of about 87 000 m^3, a large number of measurements has been done to find the relation between the air-flow pattern, temperature distribution and spread of dust. [8]. In this factory hall the air velocity in every opening was measured during periods of about four hours. In total some hundreds of air velocities have been measured. From these velocities and the net area of the openings, the mass flow through the factory hall could be computed. Pressure differences across openings have been measured with the aid of five differential low pressure transducers. Also, the mass flow has been computed from these data. Finally the different mass flows and the resulting air change rate with the calculation method described have been predicted.

TABLE 3

Air change rate h^{-1}

Direction α			90°			60°			30°		
Ratios of ventilation openings			Wind velocity								
Windward	Leeward	Roof	2	6	10	2	6	10	2	6	10
1	1	1	33	40	64	33	39	61	33	34	52
½	1	1	30	32	34	30	32	32	30	31	30
1	½	1	31	40	60	31	38	58	30	34	50
½	1	½	19	20	33	19	20	32	19	19	27

ΔT = 7,5 K
Air change rate by the process = 4 h^{-1}
(velocity in m/s)

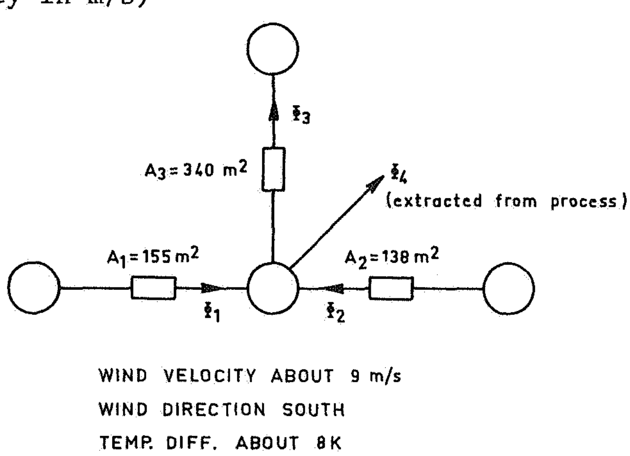


Figure 8
Ventilation model of the factory hall.

In figure 8 the model of the factory hall and the conditions in the hall are shown. From table 2 it can be seen that the measured and the calculated values agree rather well.

Table 3 shows values calculated with the method described above, especially for the engineering department of the factory. The air change rate (h^{-1}) is given as a function of:

- wind velocity
- wind direction
- position of the ventilation openings.

Figure 9, for the foundry, shows the measured pressure differences compared with those obtained from the calculation model, with a net mechanically extracted flow of 80 kg/s. The foundry has a gross volume of approximately 40 000 m^3. The pressure differences were measured:

- between the interior and the South facade;
- between the interior and the North facade;
- between the interior and the roof;
- between the foundry and the neighbouring building.

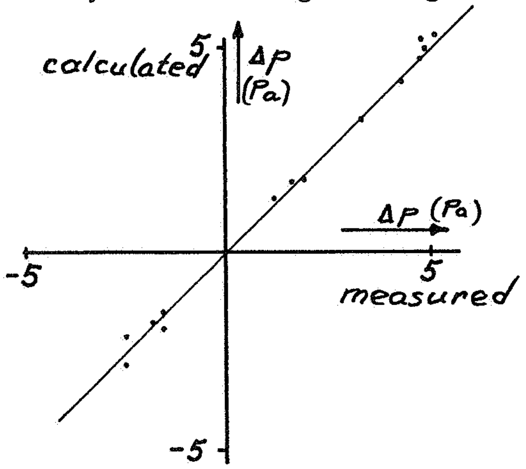


Figure 9 Comparison of calculated and measured pressure differences

The agreement between the calculated and the measured pressure differences can be considered as good. However, it should be remembered that a variation of 0,5 Pa in a pressure difference across a facade results in a mass flow variation of the order of 30 kg/s. With a total mass flow of approximately 100 kg/s in average circumstances, this represents a variation of 30%.

4.3 Laboratories

Nine investigations have been carried out, of which involved the ventilation characteristics of fume chambers [11]. In two cases the air management in the laboratory was investigated in combination with the operation of the fume chamber [12]. In the other two laboratories the problem was control of the air flows.

4.3.1 Fume Chambers

Most of the fume chambers investigated in laboratories were inadequate so far as the air velocity in the window opening was concerned, using a criterior of 0,25 m/s. The distribution of air velocities over the window opening also left something to be desired. In particular, the air velocity near the sharp-cornered edges was often too low.
With a number of fume chambers the volume of air extracted was not constant, depending on the size of the opening. This naturally had its effects on the air supply to the laboratory and, when the air supply system was inadequately compensated, influenced the pressure and the directions of air flow.

In some cases tests were made with tracer gases to determine the velocity in the opening at which egression of the gas took place. The tracer gases used were helium, carbon dioxide and Freon. It appeared that if an air foil is fitted (see figure 10) no egression of light or heavy gases can be expected so long as the velocity criterion of 0,25 m/s is satisfied.

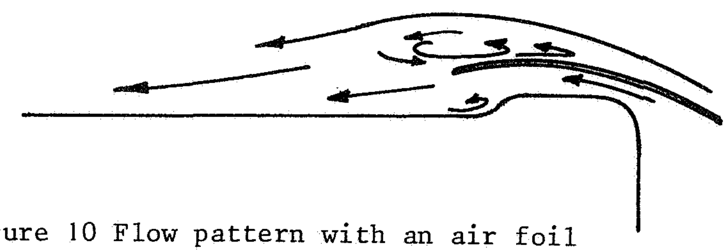


Figure 10 Flow pattern with an air foil

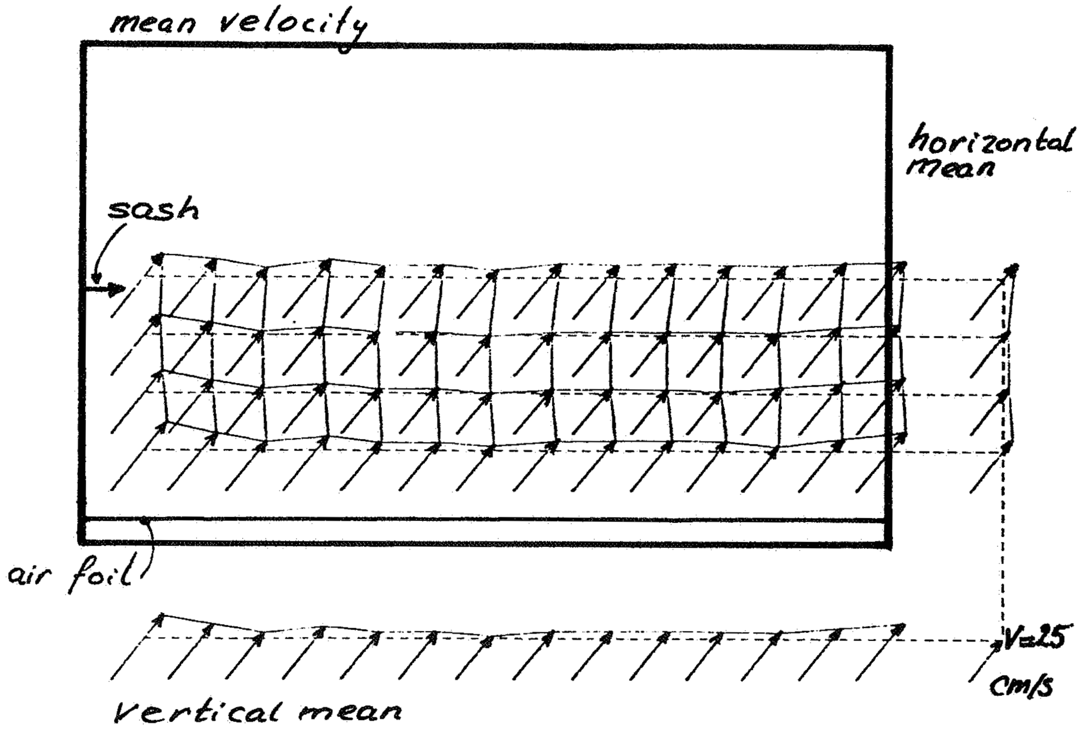
The effects of disturbances such as arm movements and passers by were also investigated.
A person sitting in front of the fume chamber and moving his arm through the plane of the window is exposed at nose height to concentrations of approximately 1.10^{-6} (1 ppm) when the concentration in the fume chamber was 1. Walking past the fume chamber can cause short-term increases in concentration to approximately 1.10^{-2} (about 1%).

It is not possible to prevent the egression of gas from the fume chamber by increasing the velocity through the window opening to about 0,4 m/s.

An examples of the air velocity distribution across the window opening, and the standard deviation of the velocities, is shown in figure 11.

4.3.2 The Prevention of Infiltration

The question in one still to be constructed laboratory was the prevention of infiltration, even under extreme weather conditions. Laboratory animals must be born in sterile conditions (without



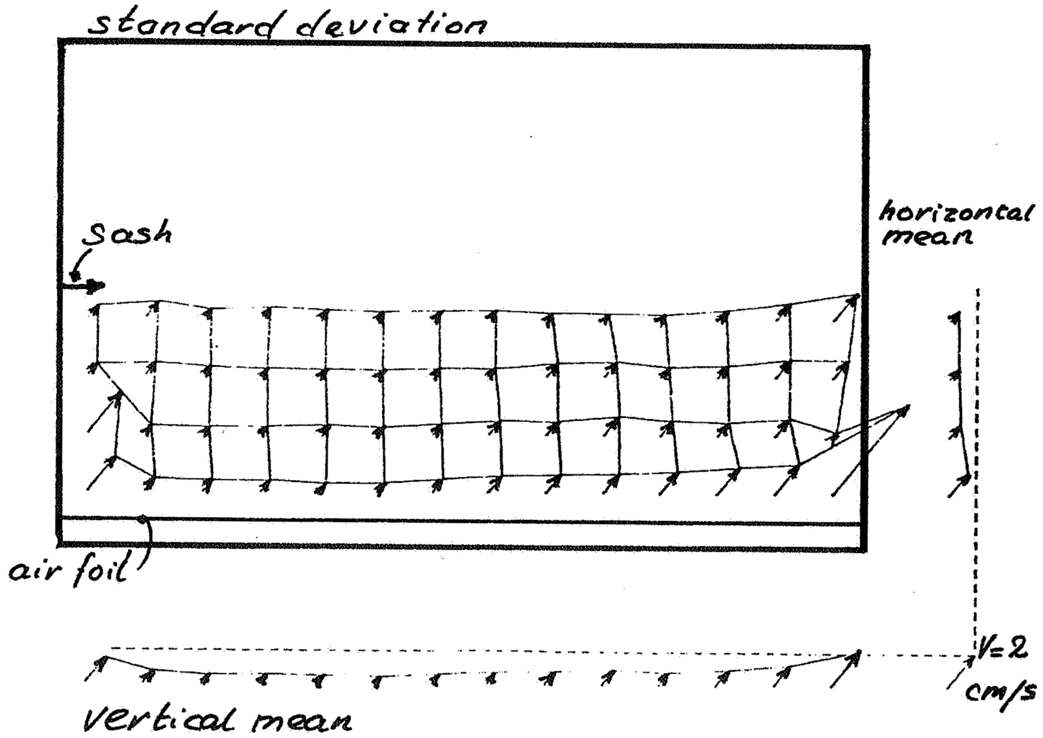


Figure 11 Air velocity distribution

contact with germs from outside) The criterion set was that infiltration must be prevented for 98% of the time. To reduce the influence of the wind on the building it was proposed to surround it with an earth wall. The effect of such a wall on the pressure distribution was tested in the wind tunnel. The flow distribution and the pressure distribution over the building was then examined with the aid of electrical analogue simulation. As a result of this investigation criteria were suggested to which the air handling system, including the filters, and the airtightness of the facades would have to comply. In the meanwhile the building has been completed and operates to the satisfaction of its users.

4.3.3 The Prevention of Exfiltration

A future laboratory was to be used for animal tests with virusses that were dangerous to human beings. The transport of unfiltered air to the exterior (exfiltration), and of germs from one room to another had to be prevented.
In this case account was taken of the hourly-average wind velocity of 24 m/s that is exceeded on the Dutch coast only 0,1% of the time.
The results of the investigation can be summarized as follows:
- the division of the building required modification at some points, access and location of clean and contaminated areas.
- Requirements regarding airtightness could be formulated, which had to be met not only the facades but also by the interior doors and walls.
- Requirements were laid down for the air handling installation, including the filters and regulation system.

4.4 Hospitals

In hospitals, as in laboratories, the control of pressure differences and air-flow directions plays an important role. The avoidance of cross-infection has been the subject of a large number of studies [13, 14, 15, 16]. In addition, extensive investigations have been made into the ventilation and air-flow aspects of operating rooms and surgical departments [17, 18, 19, 20, 21]. Air treatment installations, becuase of the large amount of space they occupy, can have a large effect on the height of the building and on the building costs. This has led to a study of the air duct system [22]. As a result of the study a large number of practical rules for achieving minimal total running costs has been obtained.

To conclude this paragraph on hospitals a further example is given, concerning a hospital for which an investigation was carried out in the design stage, and measurements made on the completed building [23].

In the design stage, the pressure distribution on the facade of the building was determined in the wind tunnel, and that in the interior by means of electrical analogue simulation. These pressure differences were later measured in practice (figures 12, 13 and 14).

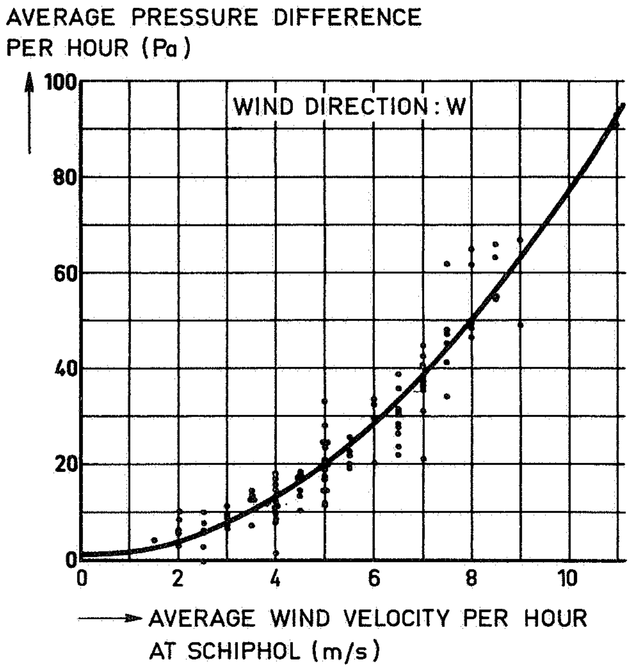


Figure 12a Relationship between the pressure difference measured and the wind velocity at Schiphol with west wind.

4.5 Parking Garages, Tunnels and Shopping Centres

Investigations have been made on three parking garages [24], three tunnels and three shopping centres.
The work consisted mainly of measurement of the pressure differences in the wind tunnel, and a parameter study with the aid of the IMG-TNO mathematical model for ventilation, or a specially-developed model in the case of tunnels.
The problem was concerned with the dimensioning of the ventilating facilites, and usually also with fume dispersal in regard to safe emergemcy exits. Stratification of fumes and the moment at which stratified fumes would be converted into turbulent mixtures played an important part in this case.

4.6 Auction Halls

A study of the possibilities for natural ventilation in auction halls in Bleiswijk has been made. For this purpose, calculations were carried out with a computer program specially developed for ventilation problems. As input data, results of wind tunnel tests were used [25].
For the auction, the ventilation must provide for:
a) discharge of solar heat as much as possible in the summer time because of the perishability of the products delivered (veget-

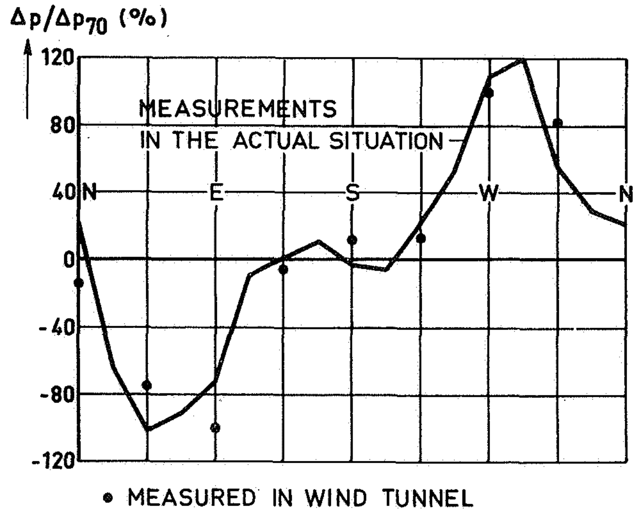
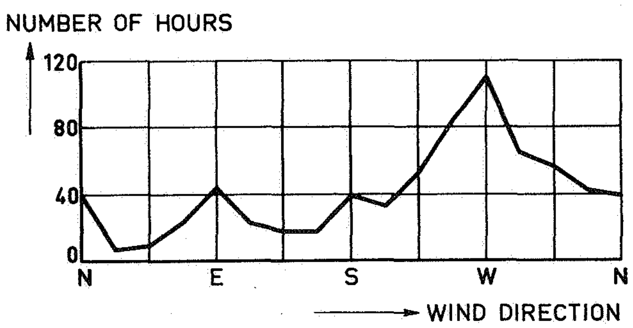


Fig. 12b *Pressure difference measured as a function of wind direction.*

Fig. 13 *Number of hours per wind direction*



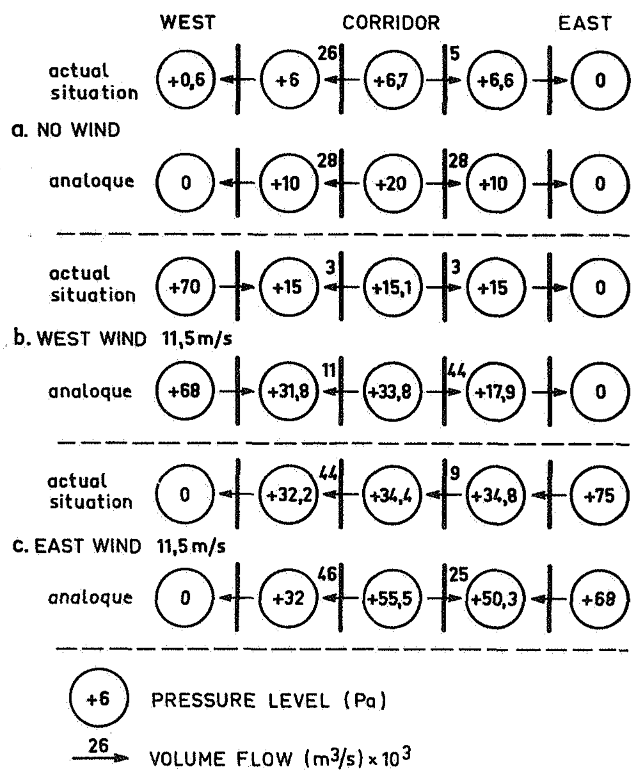


Figure 14
Measuring results on the 9h floor in north wing with closed windows.

ables) when exposed to higher temperatures (figure 15).
b) effective rarefaction of exhaust gases. These are produced by vehicles used for the supply, removal and internal transport of the vegetables (see figure 16).
Both demands are particularly pertinent for the ground level where persons will be exposed to the prevailing exhaust gases and the vegetables stored there to the local temperatures.

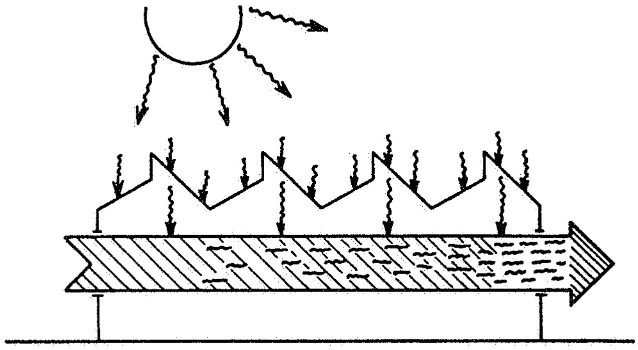


Fig. 15 Ventilation for removal of solar heat.

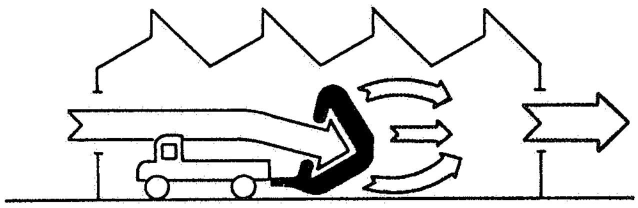


Fig. 16 Ventilation for dilution of exhaust gases.

The parts of the halls important for the investigation all have a length of 270 m, a width of 82 m and a mean height of ridge of 12,1 m.
The volume of such a part of a hall is about 200 000 m^3.

Some examples of results from this study are given in figures 17, 18 and 19.

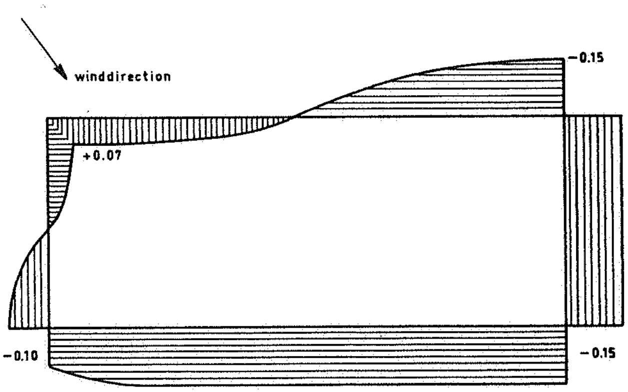


Fig.17 Wind pressure distribution on the fronts of hall 3 at easterly wind.

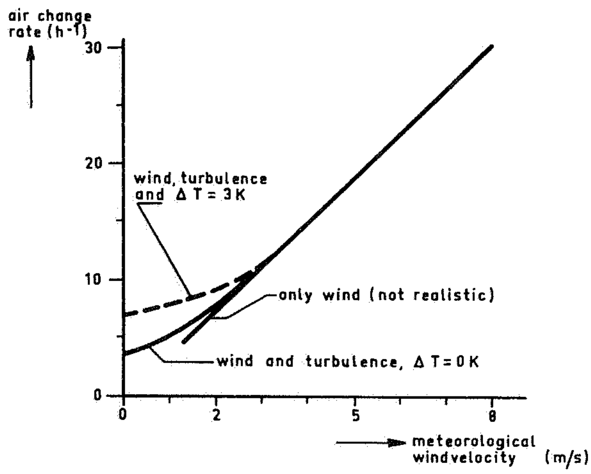


Fig. 18 Air change rate curves depending on wind, turbulence and temperature differences.

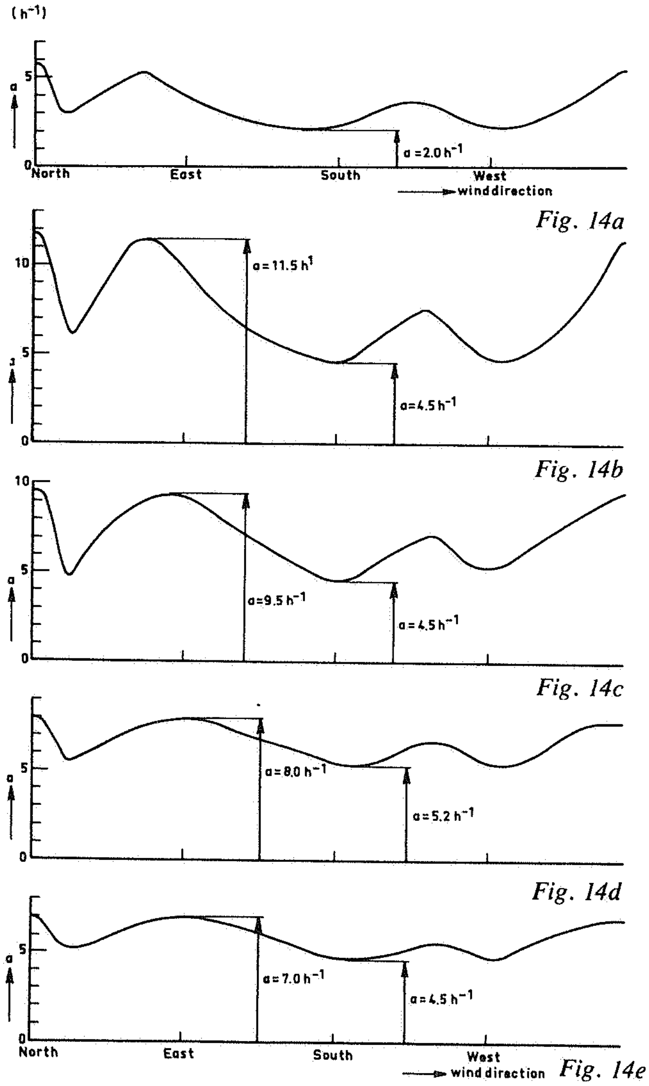


Fig. 19 Optimization of the size of the ventilating devices by means of the calculated course of the air change rate with the wind direction

By changing the ventilation design systematically and by determining the related changes in the degree of ventilation, an optimum ventilating system can be developed.
It appears that a natural ventilating system can be realized for the three vegetable auction halls by placing ventilating devices exclusively in the roof. The ventilation is then chiefly provided by the differences in wind pressure caused by the shape of the roof.

5. EVALUATION AND CONCLUSIONS

Study of the overview presented reveals that a relatively large number of studies have been made with regard to hospitals.
In the case of factories and other large buildings, investigations concerned with local provisions are relatively few. Nonetheless this certainly appears to be a field for deeper studies.
The reduction of pollutant concentrations in buildings involves the provision of facilities at the source of pollution [26]. Any other measures are generally less effective.
Local provisions include:
- enclosure of the source by means of covers, lids, etc;
- mechanical ventilation in or around the source;
- shielding of the source with a small air curtain;
- fitting an extractor hood around the source;
- combinations of the above.

Local provisions can have a negative effect on the ease of operating the process involved, but because of their positive effect on air pollution within the building their installation will in many cases prove to be a sound investment.
Since local provisions can not be used in every circumstance, the concentration of the residual pollution must be kep low by means of total ventilation of the building. It is usually the case that a large number of air changes (the ventilation factor) will be necessary.

Factories and halls are very often large in volume, resulting in large volume flows. Fitting large numbers of natural-flow inlets and outlets, distributed over the facade and roof, with regulation of the opening by simple manual means or by electric motors, offers the possiblity of large variations in ventilating flow due to thermal draught or wind pressure.

At this point it is relevant to quote from "Fundamentals of Industrial Ventilation" [27], in which Baturin had the following to say over the balance between natural and mechanical ventilation.

"Temperature differences and wind speed can cause the transfer of enormous quantities of air. For instance, measurements show that the natural air change in an open-hearth plant or a rolling mill amounts to about 20 million kg/hr. In forges, ironworks and other hot shops the air transfer may also be millions of kilograms per hour.
A very large consumption of energy would be required to move such quantities by mechanical means. The great economic importance of

natural ventilation is that it can bring about these air changes without expenditure of mechanical energy.
The time has long passed when it was necessary to demonstrate the benefits of natural ventilation and justify its application. The proofs were simple and very convincing. They were based on comparisons of mechanical ventilation and natural ventilation. In hot shops where all the emphasis was laid on mechanical ventilation, and natural air change, being regarded as unimportant, was not taken into account at all, it was found in all the tests that the volume of natural air change many times exceeded the volume of mechanical ventilation. This revealed the negligible role of general mechanical ventilation despite its heavy installation and running costs. Mechanical ventilation in thiese cases was best used as a corrective to natural ventilation, in the form of air curtains and local air supply or extraction.
In the hot seasons of the year natural ventilation can be used in almost every branch of industry, except the comparatively few industrial undertakings which require pretreatment of the air for technological reasons."

Turbulent influences have not yet been fully investigated. Knowledge of the effect of turbulence on ventilation is still lacking. This is particularly the case with industrial buildings with large openings for the purpose of natural ventilation. Air enters and leaves via these openings simultaneously, and with constant changes. Mathematical models are inadequate, even if they do take turbulent effects into account. Moreover, there is still no verification of their validity.

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AIR INFILTRATION REDUCTION IN EXISTING BUILDINGS
4th AIC Conference, September 26-28 1983, Elm, Switzerland

PAPER 8

IMPROVEMENT OF AIRTIGHTNESS IN FOUR SCHOOLS

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SYNOPSIS

Air leakage tests were conducted on four schools, before and after they were retrofitted, in order to determine the effectiveness of various measures for reducing leakage. Caulking wall joints will generally reduce air leakage and is worthwhile if the joints are accessible. Replacing leaky windows will also improve airtightness but may not be cost effective. Routine inspection of outside dampers of the air handling system can help ensure continued airtightness of schools.

1. INTRODUCTION

Since 1975, the Division of Building Research (DBR) has participated in a program of the Carleton Board of Education to reduce energy use in schools. One of the projects undertaken by DBR was to estimate the heating and cooling loads attributable to air infiltration in school buildings. To this end, air leakage measurements were made on eleven schools (Fig. 1)[1]. Additional tests were conducted on some of the schools to determine the contribution of the windows, doors and walls, and of the outside openings of the air handling systems, to the overall air leakage. On the basis of these tests, four schools (D, E, F and J) were selected by the School Board to be retrofitted for airtightness. A follow-up series of air leakage tests was conducted on the four

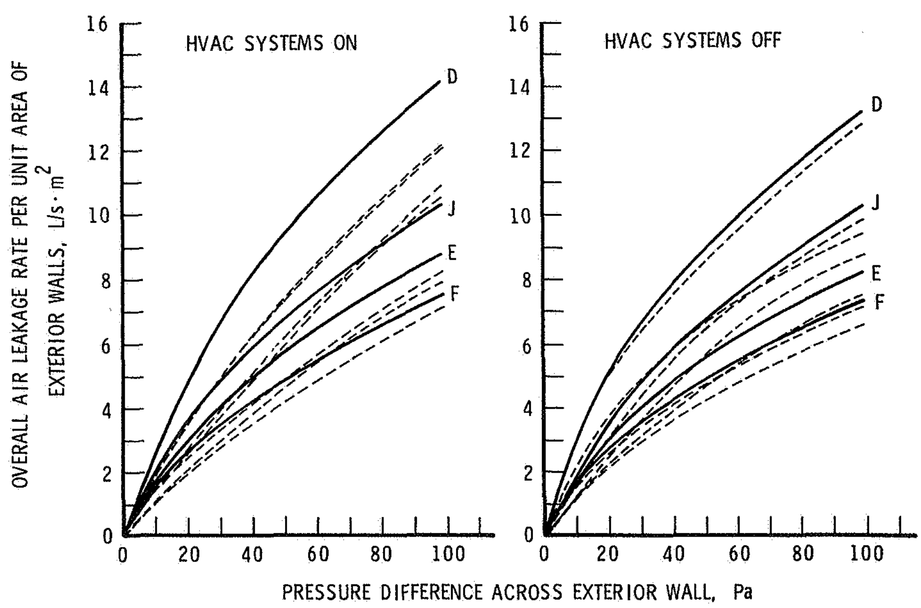

FIGURE 1
OVERALL AIR LEAKAGE RATES FOR SCHOOLS BEFORE RETROFIT

schools by DBR to assess the effectiveness of the applied retrofit measures. The results of the follow-up tests are reported in this paper.

2. AIR LEAKAGE TEST METHOD

The air leakage characteristics of the four schools were determined using the fan pressurization method described in Reference 1. A large-vane axial fan was used to produce a negative pressure inside the building. The fan airflow could be adjusted between 0 and 23 m^3/s. The intake side of the fan was connected by several lengths of 0.9 m diameter ducting to a plywood panel that replaced an entrance door during the tests. The airflow rate was measured upstream of the fan intake: total pressure tubes were used to measure high airflow rates and an orifice plate to measure low airflow rates.

The reference pressure difference across the building enclosure was the average pressure differential across the exterior walls measured at the middle of each wall with a portable pressure meter.

The four schools were tested both with the air handling system in operation and with the system shut down, to permit comparison of leakage characteristics before and after retrofit, for both conditions. An additional test was conducted on School J with the air handling system shut down and all system openings to the outdoors sealed, in order to obtain the leakage characteristic of the exterior wall alone. This corresponds to a similar test conducted in the original series.[1]

3. RETROFIT MEASURES AND RESULTS

The original air leakage tests on the eleven schools were performed by DBR in 1976. Inspection of the schools, selection, and execution of retrofit measures in four schools were undertaken by the School Board between 1976 and 1980. The four schools, D, E, F and J, were retested by DBR in October 1980.

Since the retrofit measures in the four schools were not identical, each school is described separately. The descriptions of these measures were obtained from work order statements and from conversations with Board staff members. The quality of workmanship, therefore, could only be inferred by spot inspection of the schools. The following descriptions include some cost figures. These costs should not be used to evaluate the relative worth of the different measures taken, but should be looked upon only as a measure of the effort expended in each school.

Air leakage characteristics of the four schools, before and after retrofitting, are presented in Fig. 2.

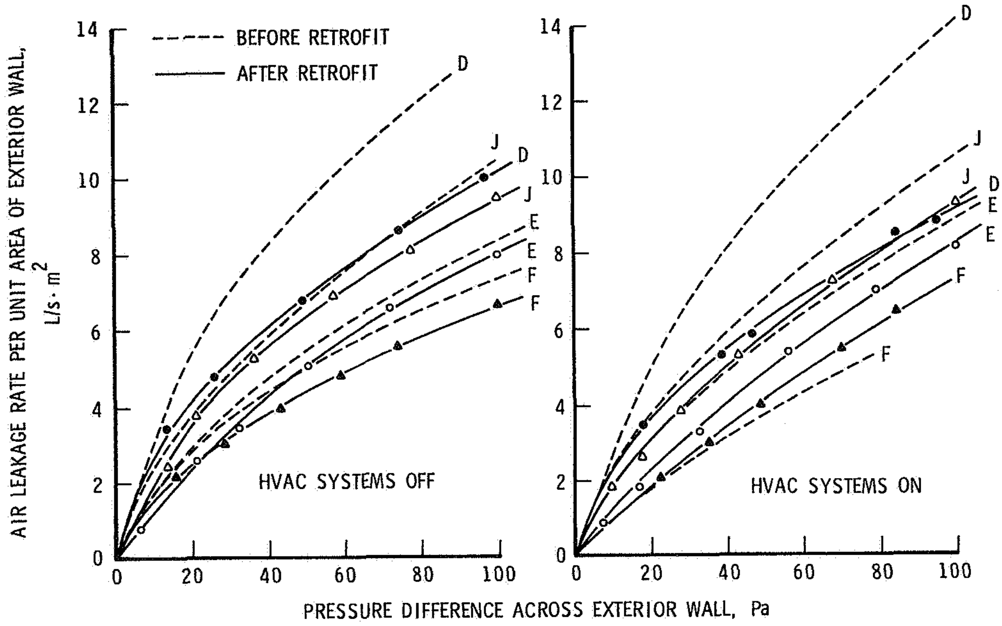

FIGURE 2
OVERALL AIR LEAKAGE RATES BEFORE AND AFTER RETROFIT

3.1 School D

This single-storey school had the highest overall air leakage rate of the eleven schools originally tested. Investigation of the wall construction revealed many unsealed openings at the intersection of roof joists and exterior wall. Retrofit measures consisted of the following:

3.1.1 Polystyrene insulating boards (5 cm thick) were fastened to the inside surface of the exterior wall, between the suspended ceiling and the roof slab. An attempt was made to fit the boards around the joists.

3.1.2 Caulking was applied around the window frames but not around the insulating boards.

The total cost for the two measures was approximately $1300 for labour and materials. As indicated by Figs. 2 and 3, the leakage after retrofit was 73% of that recorded before, with the air handling system shut down. With the system operating leakage was reduced to 67% of that measured before. Unfortunately, the relative benefits of the two retrofit measures cannot be inferred from these results. Although the percentage reduction in leakage due to retrofit was large, this school still had a comparatively high leakage rate.

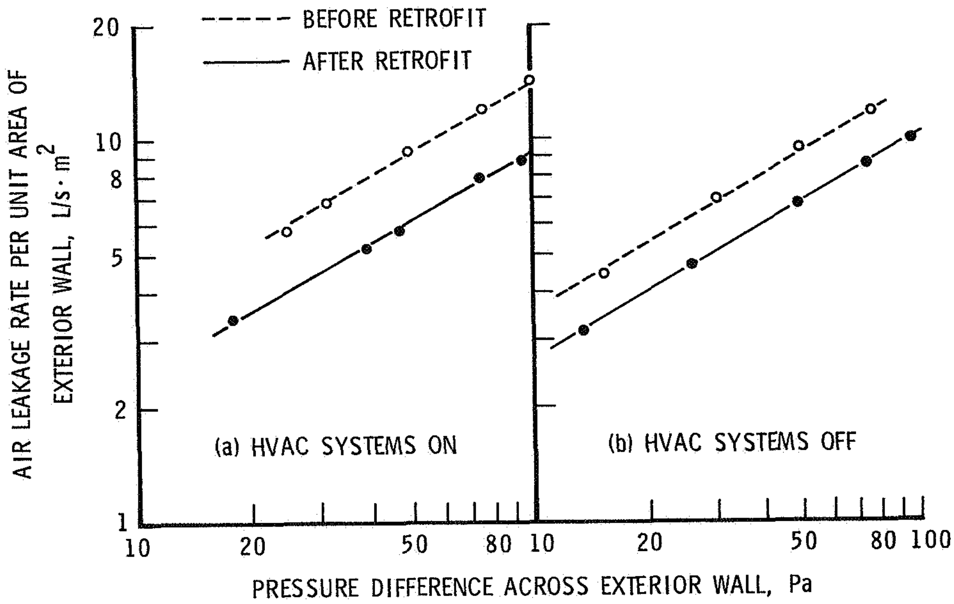

FIGURE 3

OVERALL AIR LEAKAGE RATES BEFORE AND AFTER RETROFIT FOR SCHOOL D

3.2 School J

This is a large open-plan building with an office and a gymnasium block attached to one corner. The ceilings in the office, and in corridors and vestibules were plastered. Classroom ceilings were plastered next to the exterior walls to cover the joints between wall and roof. Every exterior doorway was recessed inward from the plane of the exterior wall. The soffit over the doorway was an extension of the ceiling inside.

The previous study[1] showed that this school had very leaky exterior walls: nearly 81% of the total leakage occurred through the walls. Visual inspection revealed no obvious cracks or openings. A pressurization and smoke test, however, revealed air leaking out through numerous openings in the exterior block facade, and through the recessed light fixtures in the soffits over the doorways.

An attempt was made to caulk some of the joints in the exterior block facade, and to reduce leakage at the light fixtures by covering them up with metal plates. This effort at exterior sealing was not successful. Figure 4(a) compares the leakage characteristics of the wall alone between the 1976 and 1980 tests. The wall now registers slightly more leakage than before.

Inspection of the roof-top air handling units had revealed that one of the fresh air dampers was not closing properly, and this deficiency was corrected prior to the latest tests. The reduction in leakage shown in Fig. 4(b, c) can probably be attributed to the damper adjustment.

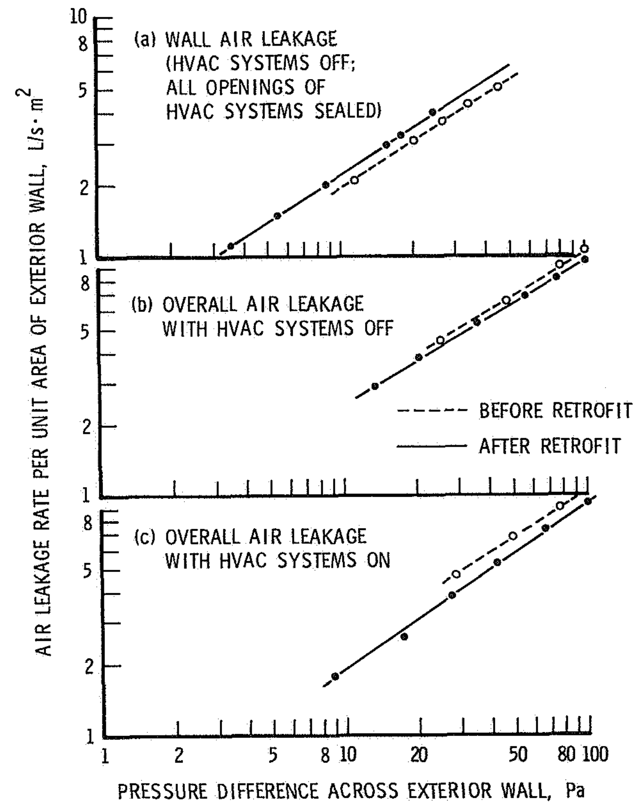

FIGURE 4

AIR LEAKAGE RATES BEFORE AND AFTER RETROFIT FOR SCHOOL J

3.3 School E

The school consists of a two-storey classroom wing and a single-storey block containing the gymnasium and offices as well as classrooms. The exterior facade of the two-storey wing consists of steel wall panels set in aluminum framing. Aluminum windows are set in the steel panels. All joints between framing, panels and windows had been sealed with caulking compound at construction, nearly 20 years prior to the original tests.

The one retrofit measure undertaken in this school was to replace the defective caulking for the joints in the exterior facade (approximate cost $500). Fig. 5(a, b) indicates that leakage after the retrofit measure was approximately 70% of that before at the lower pressure difference. This also suggests that exterior sealing has a finite life, and should be replaced periodically as part of a maintenance schedule.

3.4 School F

This single-storey U-shaped building has a window-to-wall ratio of 30%. After the original test in 1976, School Board staff conducted air leakage tests on the windows and found that those in the west wall were especially leaky. At a cost of approximately $18 000, the thirty-two windows in the west wall were replaced. This represented approximately a third of the total windows in the school. Figure 6(a) indicates a 20% reduction in leakage with the air handling system off: Fig. 6(b) shows no apparent reduction with the system on. The window replacement program was influenced mostly by a need to replace windows that had deteriorated with time.

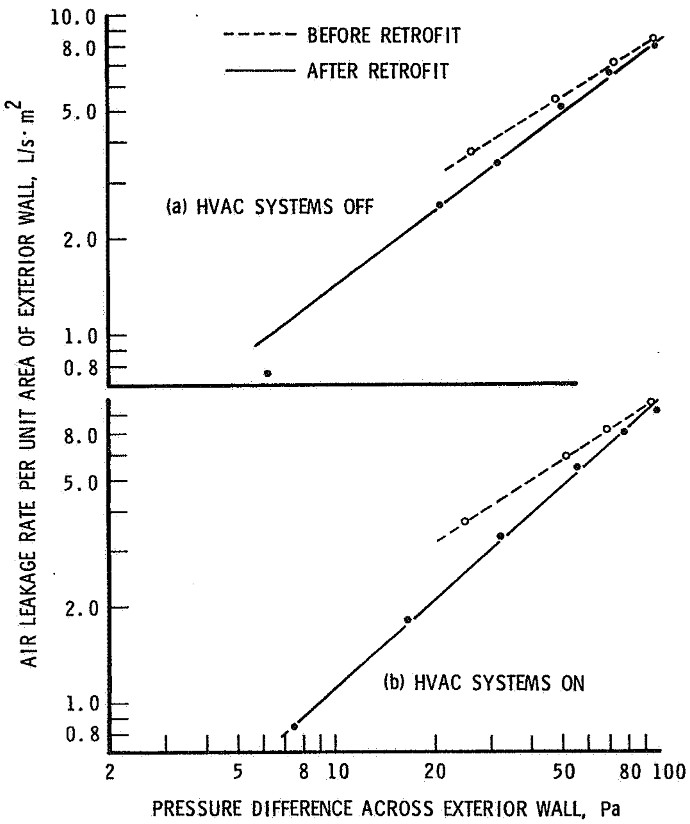

FIGURE 5

OVERALL AIR LEAKAGE RATES BEFORE AND AFTER RETROFIT FOR SCHOOL E

4. SUMMARY

Four schools received varying degrees of retrofit in an attempt to improve their airtightness. The lessons learned from this can be summarized as follows:

4.1 School D. Sealing of leakage openings between wall and roof joists, and between wall and window frames effected a significant reduction in leakage.

4.2 School J. Sealing ill-defined leakage openings on the exterior face of the walls did not result in any improvement. Repairs to a defective damper in the air handling system did, however, reduce air leakage.

4.3 School E. Sealing of defined leakage openings in the exterior facade did improve airtightness.

4.4 School F. Replacement of approximately one third of the windows with tighter ones did not reduce air leakage appreciably.

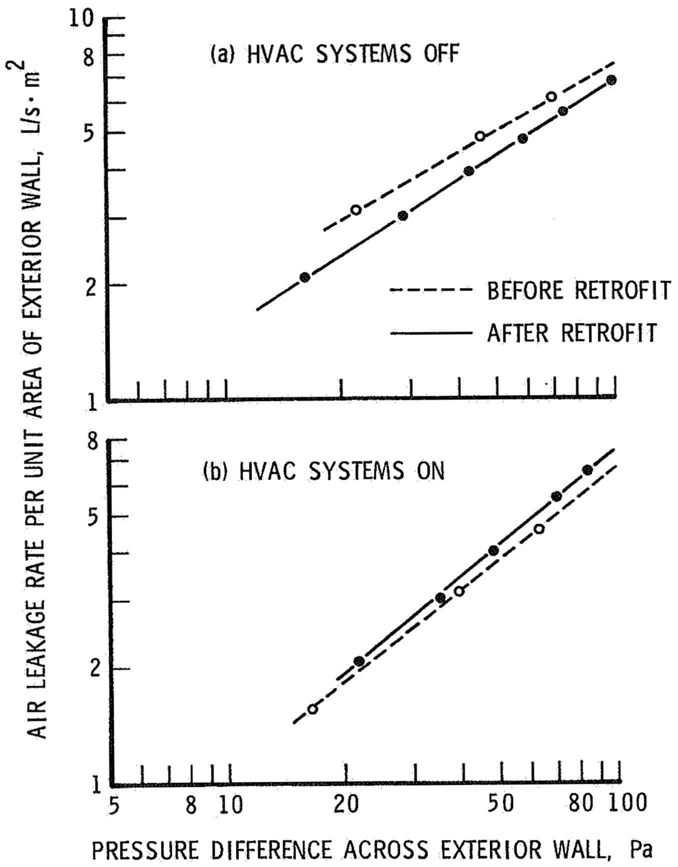

FIGURE 6

OVERALL AIR LEAKAGE RATES BEFORE AND AFTER RETROFIT FOR SCHOOL F

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AIR INFILTRATION REDUCTION IN EXISTING BUILDINGS

4th AIC Conference, September 26-28 1983, Elm, Switzerland

PAPER 9

AIR INFILTRATION IN HIGH-RISE BUILDINGS

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SYNOPSIS

The prediction of infiltration rates in high-rise buildings caused by superposition of wind pressure across the building skin and stack effect along the building height is a complex problem. For this study, we performed tracer gas measurements and fan pressurization experiments on an eight-storied student residence building in order to determine the influence of wind as well as of the stack effect upon air infiltration. Measured pressure and tracer gas distribution were compared with those from a predictive infiltration computer model for high-rise buildings. To study the influence of the air flow pattern around the building, we adapted the calculated air flow pattern in the stairwell to the measured tracer gas concentration with the aid of various wind velocity profiles characteristic for urban areas and different sets of upwind dependent surface pressure coefficients. This comparison showed, that a satisfactory correlation can only be obtained by application of local pressure coefficients from wind tunnel experiments matching the wind velocity profile as well as the surrounding pattern as close as possible. On the other hand the need for easy to handle examination procedures in building standards asks for more simplified methods.

Keywords

Infiltration, high-rise building, stack and wind effect, leakage area, fan pressurization, tracer gas, wind velocity profiles and surface pressure coefficients, critiical comparison wind tunnel experiments/full-scale measurements

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NOMENCLATURE

c_i	surface pressure coefficient for i-th surface
D	air-permeability: flow coefficient, volumetric air flow rate, at a unit pressure difference for a specified building area ($m^3/Pa^n h$)
in	index: inside
lee	index: leewardside
$\dot{m}$	air mass flow (kg/h)
n	pressure exponent, between 0.5 and 1
NPL	neutral pressure level
out	index: outside
p	pressure (Pa)
$\dot{Q}$	volumetric air flow (m^3/h)
v	wind speed (m/s)
wind	index: wind or -wardside
z	z-coordinate or height of the building (m)
α	exponent in the power-law for the vertical wind velocity profile, depending on terrain roughness
Δ	difference in conjugated item
ρ	density (kg/m^3)
θ	temperature (^oC)

1. INTRODUCTION

To predict possible condensation zones and to optimize the energy conservation in buildings, the measurement and control of air movement through a building structure has become more and more important. But probably one of the deficiencies in most computerised methods to predict energy requirements of buildings is the lack of reliable algorithms to model air infiltration sufficient precisely. In contrast to the relatively steady process of heat transmission, infiltration is more strongly influenced by rapid changes in weather conditions. Moreover, infiltration is nonlinear, depending primarily on wind pressure and thermal buoyancy (stack-effect), and therefore difficult to model.

Infiltration is an important component of the space-conditioning load, especially in houses with above average shell thermal performance. As houses are made tighter to reduce infiltration losses, the maintenance of acceptable indoor air quality begins to be an issue of concern[1]. Balancing the competing demands of energy conservation and air quality may require a target ventilation rate for a structure. This, in turn, demands the existence of inexpensive instrumentation to measure infiltration or a model that will accurately predict air movement in buildings[2].

Infiltration, the random flow of air through openings in the building surface, is for a single-family house largely independent of the house type and structure. This flow process is dominated by the leakage structure of the building rather than by structural type. Air flow is the consequence of pressure difference due to wind pressure and thermal buoyancy. Besides these driving forces, the infiltration rate, however, depends on the air-permeability of the building structure and on the distribution of leakage areas throughout the building.

A prediction of the infiltration for high-rise buildings is a more complex problem. The pressures that drive the flow are the result of the superposition of wind pressure that depends on the elevation and orientation and the stack-effect. Recent works on prediction models for one-family houses[3,4] demonstrate the strong influence of the stack-effect on the infiltration rate. The latter is even more important for high-rise buildings because of the magnitude of the building height[5].

2. AIR INFILTRATION DUE TO STACK- AND WIND EFFECT

Air flow through a building shell is a combination of laminar and turbulent flow through openings and cracks. The former is proportional to the pressure difference over the envelope whereas the latter varies with the square root of the pressure difference.

Two differenct driving mechanisms are primarily responsible for natural air flow in buildings -- wind pressures and buoyancy forces. Compared to the static pressure in the undisturbed wind velocity pattern, the pressure field around a building is characterized roughly by regions of overpressure on the windward façade and underpressure on façades parallel to the air stream or on the leeward side of the building respectively.

$$p_{wind} = 1/2\ \rho(z,T)\ v^2(z)\ c_i(z)$$

The c_i-values ("shielding coefficients") can be determined either from measurements on full-scale buildings or on corresponding small-scale models in a boundary-layer wind tunnel[6,7].

Excluding thermal stratification, the vertical profile of the mean wind speed in the atmospheric boundary layer depends primarily on the surface roughness and shows an increasing velocity with height above ground, approximated by a power-law expression[8].

$$v(z)\ /\ v(z_0) = (z/z_0)^{1/\alpha}\ .$$

Usually, $v(z_0)$ is a meteorological reference wind speed recorded at a standard height of z_0 = 10 m above ground.

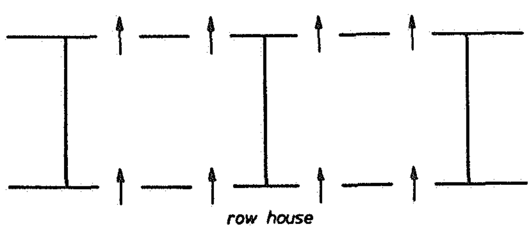
Pressure gradients between inside and outside of the building also arise from changes in air density due to temperature differences between ambient air and air inside (stack-effect)

$$\Delta p_{stack} = g\ (\rho_{out} - \rho_{in})\ (z - z_{NPL})\ ,$$

with z_{NPL} as the neutral pressure level, the height on the building façade where the interior pressure equals the exterior. The stack-effect pressure gradient only depends on the absolute inside/outside temperature, whereas the height of the NPL will be determined by the air leakage distribution. In practice the NPL height is rarely knwon and stack pressure is normally expressed relative to the lowest opening.

Referring to infiltration, a building can roughly be described with the aid of the four following border-line cases[5]:

a) row house
b) detached house



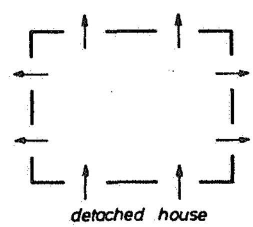


Fig. 1a:

Subdivision of the building type according to the permeability ratio (leakage area of the leeward windows and doors compared to the corresponding value over the total building shell)

c) story-type construction
d) shaft-type construction

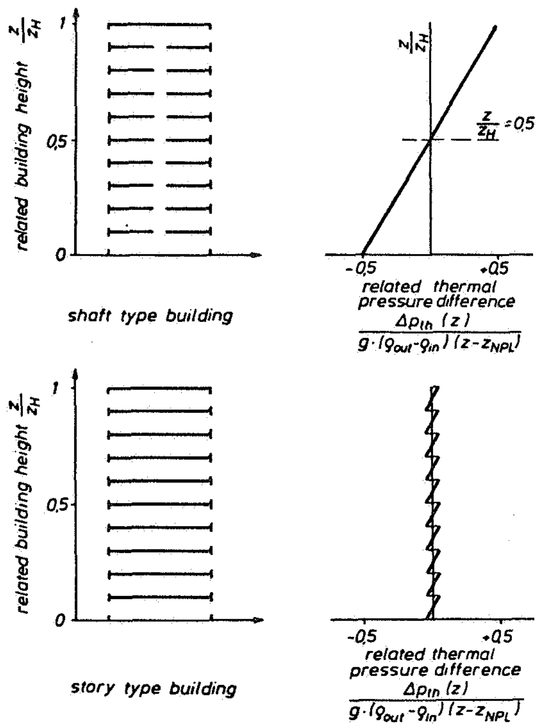


Fig. 1b:

Thermal pressure difference as a function of the type of construction for $t_{in} > t_{out}$ and the air leakage uniformly distributed over the building shell

This subdivision into four basic categories is based on a comparison of the permeability behavior of a building as function of its location (influence of wind effect) as well as of its construction type (influence of stack-effect).

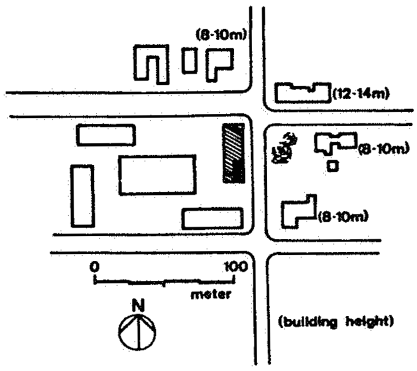
The influence of wind flow on the building with overpressure on the upwind and underpressure on the separated walls will be determined by the permeability ratio R (= total permeability walls separated from wind flow / overall permeability building façades). Row houses can be described with an average R-ratio of 0.5, whereas the corresponding value for detached houses rises up to 0.7.

In a shaft-type building the buoyancy forces will grow up extremely strong contrary to the story-type counterpart with its small stack effect only within each story.

3. EXPERIMENTS

3.1 Test building - location and layout

The four dormitories comprising Unit I of student housing for the University of California at Berkeley occupy a 0.9 ha site two blocks south of the campus. The surrounding blocks are mostly three-story residential apartments. The dorms are identical nine-story buildings, arranged on the periphery of the block, oriented both north/south and east/west. The structure is reinforced concrete with metal curtain walls and cast stone grills on the exterior wall of the utility rooms.



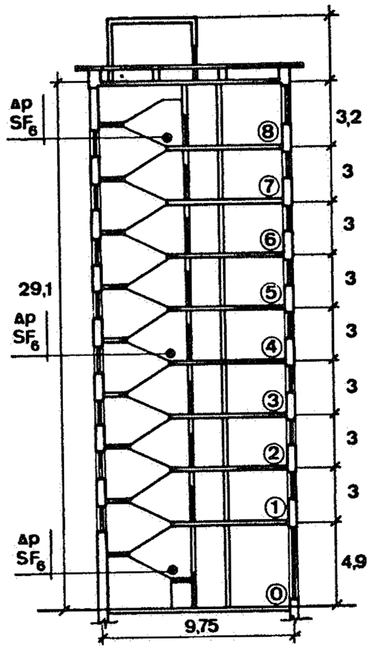
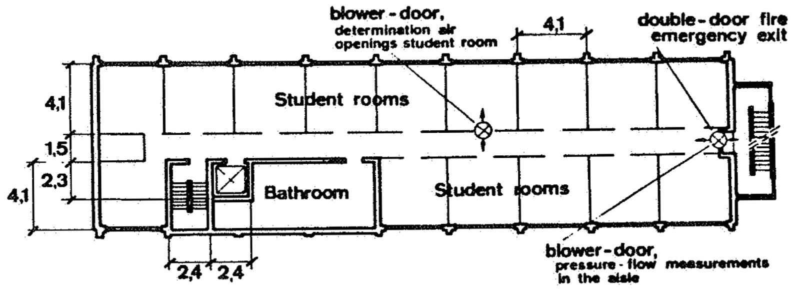


Fig.2: Building location, staircase section and typical floor plan



3.2 Blower-door measurements

The pressure-flow characteristics for specific building parts were measured using a door-mounted, variable-speed fan capable of moving large volumes of air into or out of a structure. Natural infiltration is typically driven by pressure differences across the building shell in the range of 0 Pa to 10 Pa and is characterized by large, short-term fluctuations. When Δp is larger than 10 Pa, fan flow dominates natural infiltration and the latter may be disregarded. At a given Δp and a fan speed, the flow of air is determined indirectly by means of a previously established calibration curve (i.e. from flow vs. RPM characteristics at different pressure differences). With the aid of measurements at discreet Δp's in the over- as well as underpressure region (-70 Pa to +70 Pa), the parameters D and n are fitted to the following equation characterizing the air flow through a leaky building shell:

$$\dot{Q}(\Delta p) = \dot{Q}_{fan}(RPM, \Delta p) = D\,(\Delta p)^{n} .$$

As example the following graph demonstrates the different pressure-flow regimes in the stairwell due to changes in leakage area by opening previously sealed air cracks.

Boundary-conditions	Press D ($m^3/Pa^n h$)	Press n -	Depress D ($m^3/Pa^n h$)	Depress n -
-all doors sealed	262	0.52	241	0.63
-emergency exit unsealed	362	0.47	264	0.61
-emerg. exit and roof door unseal.	345	0.49	323	0.61
-all doors unsealed	690	0.47	456	0.62

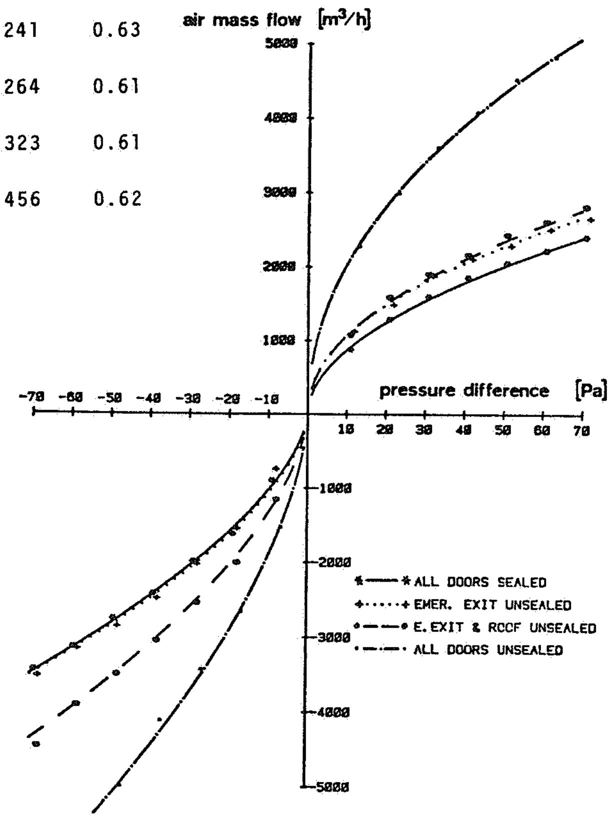


Fig.3: Pressure-flow characteristics and air leakage parameters for different structure parts of the stairwell (blower-door measurements)

3.3 Tracer gas and pressure measurements

The air flow in the stairwell was determined using a tracer gas technique. Injecting SF_6 at the ground-floor at an electronically controlled constant flow rate, its concentration at the 1st, 4th and 8th floor were recorded together with pressure differences (ground-floor and 8th floor) and temperatures as a function of time. Multiple sampling throughout the stairwell crossections provided properly averaged measurements of the SF_6 concentrations at the selected floor levels.

The tracer gas concentration itself was determined from infrared transmission losses in an 1.5 m gas cell.

A capacitive potentiometer with a thin, prestressed metal diaphragm as variable, sensitive element was used as differential pressure sensing element.

4. COMPUTER SIMULATIONS

The calculation of natural ventilation rates in a building is a complex task. Simulation programs using an iteration method are normally based on a network containing a large number of non-linear equations. Therefore, the only useful tool to get a solution is a digital computer[9].

A routine, developed at the Hermann-Rietschel-Institute[10,11] and which was the framework for the computer model used in this study, calculates solutions of its non-linear equations system using Newton's iterative method. The building to be examined will be subdivided in zones with the aid of a threedimensional scanning field. The grid elements are represented by nodes each associated with a zone pressure. These nodes are connected among themselves via the zone boundaries characterized by their permeabilities, exponents of the pressure difference and mass flows. With floors, stairwell and elevator shaft represented by a series of rooms (nodes), each at a specific pressure and temperature, the movement of air through the building will be computed by a program based on steady-state pressure dependent mass flow balances at each floor as well as in the two shafts (elevator shaft and stairwell). The net mass flow between in- and outgoing air through the air openings of the r-th surface will be calculated by:

$$\dot{m}_r = \rho\, D_r\, (\Delta p)^{n_r}$$

with experimental permeabilities D_r and pressure exponents n_r from blower-door measurements.

In a first run, the wind-induced pressure field around the building was calculated using an exponential wind velocity profile for urban areas ($\alpha \sim 3$[12]) and mean pressure shielding coefficients of 1 for the upwind and -0.3 for separated flow regions (sides, rear, flat roof). According to meteorological data from the measuring period the mean wind direction for calculations was selected to be from east. For such wind directions perpendicular to a main building façade, the wind pressure at a specified height will normally be idealized by width-undependent pressure coefficients for each surface orientation. Therefore, at each floor, all rooms with equal door- and window permeabilities and the same orientation as for the façade, can be mathematically treated as one room. Since permeabilities are additive like conductances in an electrical network, such a simplified room can be attached to a resulting permeability. Hence, the flow resistance for a window and a door located in series as e.g. in the student rooms will be calculated to

$$R = D_{tot}^{-1} = (D_{window}^{-1/n} + D_{door}^{-1/n})^{n}$$

In the building to be investigated, a storey containing all student rooms, lounge/loundry and aisle, except the corresponding portions of the stairwell and elevator shaft, can be described by substitute resistances related to each façade. The stack-effect pressure gradient was calculated on the basis of temperature induced air density differences.

The following figures will outline principal results obtained from the calculations of the air flows in the building and the pressure gradients in the construction as a function of different weather conditions. Considering the net ingoing air flow for the entire building without referring to any special building surface, at 0 m/s wind speed and an averaged ambient air temperature of 13°C, there will be no infiltration loss in the building due to ventilation except for stories lower than the 6th floor.

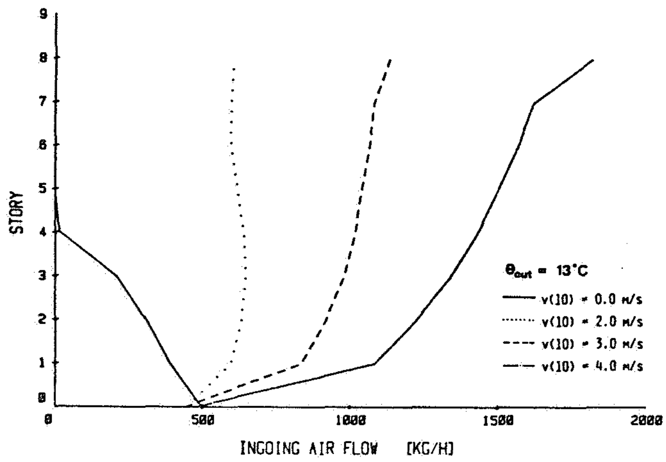


Fig.4: Influence of wind velocity on air flowing into the building (θ_{out} = 13°C)

With increasing wind speed the shape of the ingoing air flow curve will be more and more influenced by its power-law velocity profile. It is remarkable that the air flow at the ground-floor will not be influenced by changes in wind speed. In the elevator shaft -- independent from wind speed -- air from floors below the 5th level flows to the shaft, whereas the emanation of air from higher levels increases to its maximum at the 8th floor. Therefore, as a consequence of conservation of mass, an air current in the elevator shaft will transport groundfloor-air to higher levels. Such an air exchange in the building may have undesired accompaniments such as the transport of air pollutants[13] or of odors in apartment houses. Moreover, for the safety of occupants, such studies are a helpful tool to estimate the smoke movement in a building during a supposed fire.

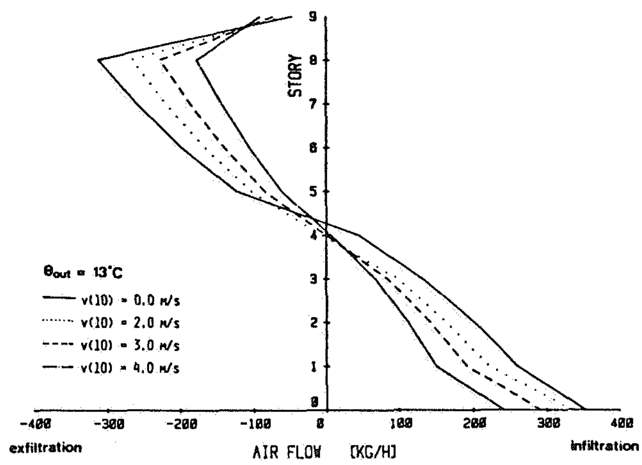
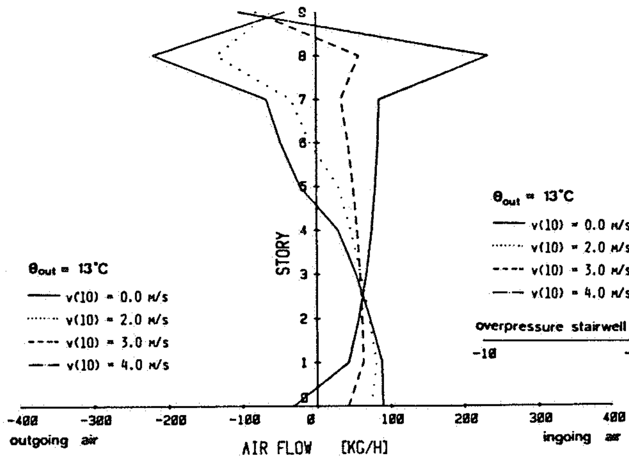


Fig.5: Air flow through openings of elevator shaft for different wind speeds (θ_{out} = 13°C)

On the other side, the air flow in the staircase demonstrate a quite different behavior. To study this flow regime, we plotted the calculated data for both the air flow from the staircase through the windward (outside) wall air openings and the air current staircase-adjoining floors. The flow regime in this part of the building is governed on one side by air flowing into the structure at lower levels and on the other side, with increasing wind speed, by a decreasing air loss at higher levels. The neutral air flow level rises up with increasing wind velocity. Higher wind forces at the façade due to wind speeds larger than about 3 m/s will press ambient air into the staircase, even at the top of the building. This additional air flow increases the inside pressure to such a degree that the ground-floor staircase pressure will even exceed the outside pressure at this height, leading to an outflow of air.



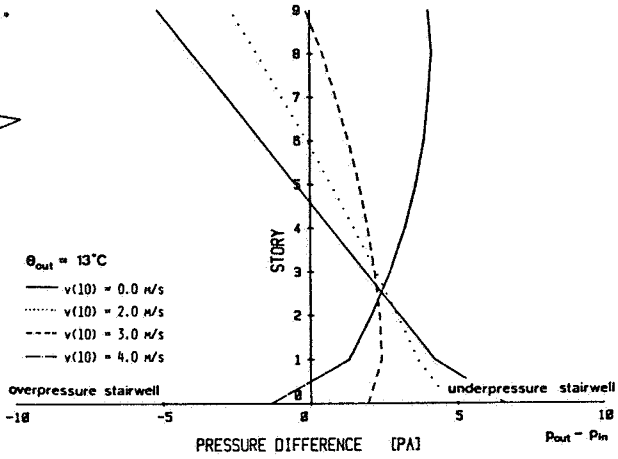


Fig.6 and 7: Computer calculated in-/exfiltration flows in the staircase through air leakages in the outside windward surface of the building (left) and their driving pressure difference forces $\Delta p = p_{out} - p_{in}$ (right) as function of the building height (θ_{out} = 13°C)

Higher wind speeds cause air flows from the shaft into the corridors through all staircase doors, whereas at wind speeds smaller than 2 m/s indoor air from the student rooms and the corridors is pressed into the shaft only at lower levels. There will be no air exchange between the different floors through the staircase.

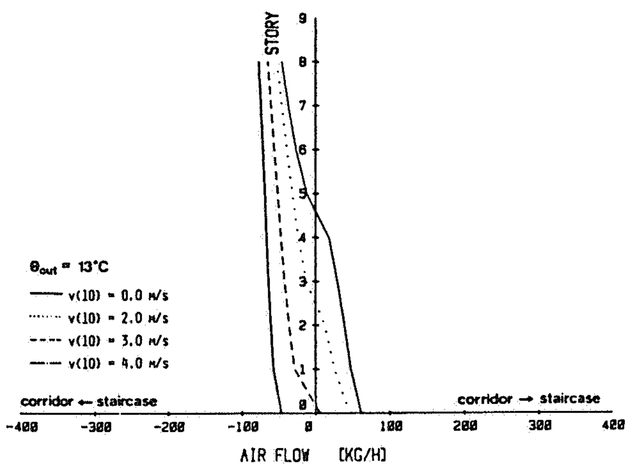
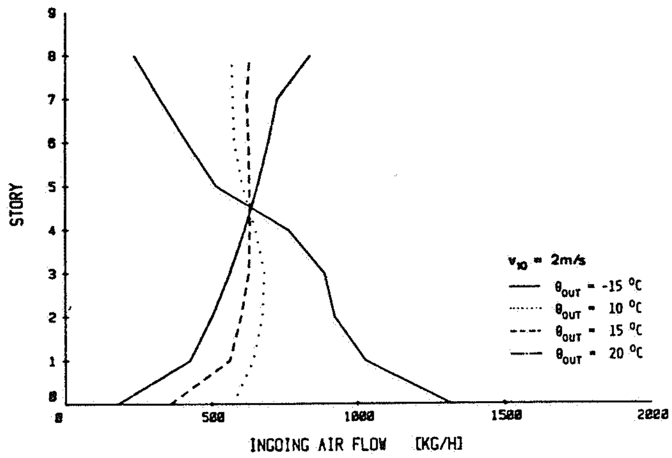
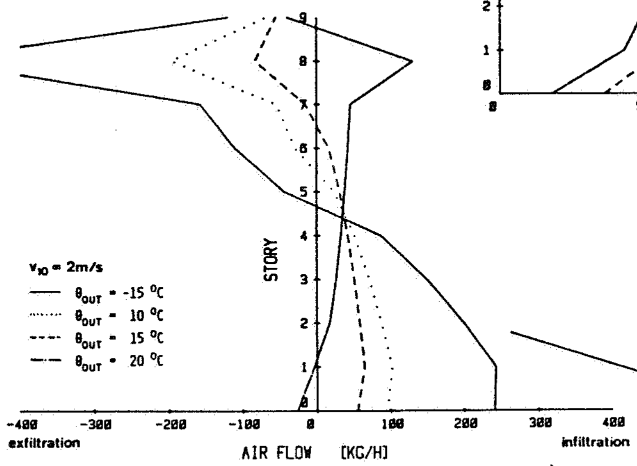


Fig.8: Wind effect onto the air current from the corridors to the staircase at different floor levels (θ_{out} = 13°C)

The temperature dependence of the net air flow throughout the whole structure demonstrates a well known phenomena for low temperatures. Especially in areas characterized by low winter temperatures, the overall energy demand for a heating period to equal the ventilation heat load at the ground-floor due to natural ventilation will be at least a few times higher than the equivalent amount needed to heat the top floor[14]. In our building, at a supposed outdoor temperature of θ = -15°C, the above-mentioned ratio would rise up to 5.5. On the other hand smaller temperature differences lead to a more balanced air current as a function of building height.





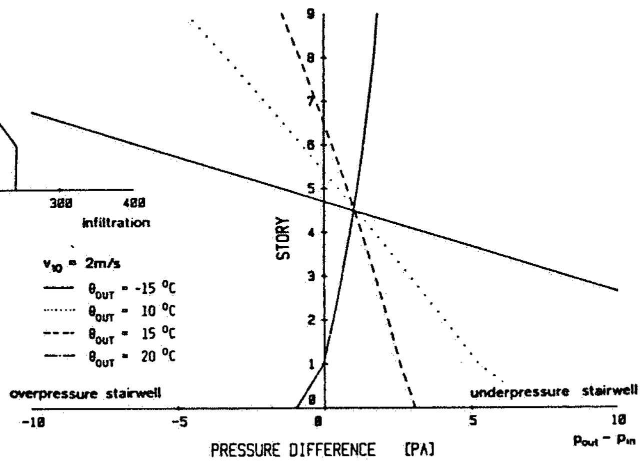


Fig.9/10/11: Temperature- and height dependence of
- total air flow into the building (top)
- air flow through openings in the outside surface of the staircase (middle)
- pressure differences between windward building façade and staircase (bottom)

This calculation example clearly shows, that space conditioning due to natural ventilation losses calls for a very sensitive control of the room heating system.

5. COMPARISON - MODEL AND MEASUREMENTS

5.1 Wind and surface pressure coefficients

Since there exists no mathematical expression to calculate accurately the air flow pattern around a building, the latter is still difficult to predict and changes for the same building shape from location to location due to the influence of nearby structures. Especially the flow pattern in front of the windward façade will be strongly affected by upstream structures. This streamline pattern striking the front of a tall building will be divided in an upwind flow at higher levels and a lower region governed by downstreaming wind, both separated by a stagnation zone. The second one separates from the building façade before reaching the ground level, creating a standing vortex near ground with sometimes high internal wind velocities. Therefore, especially near ground level, the wind pressure pattern has to be examined very carefully.

Before discussing the tracer gas measurements we outline the difficulties using height independent surface pressure coefficients. A first comparison showed that e.g. the pressure differences measured at the ground- and 8th floor level cannot be explained by our previous and rough calculations.

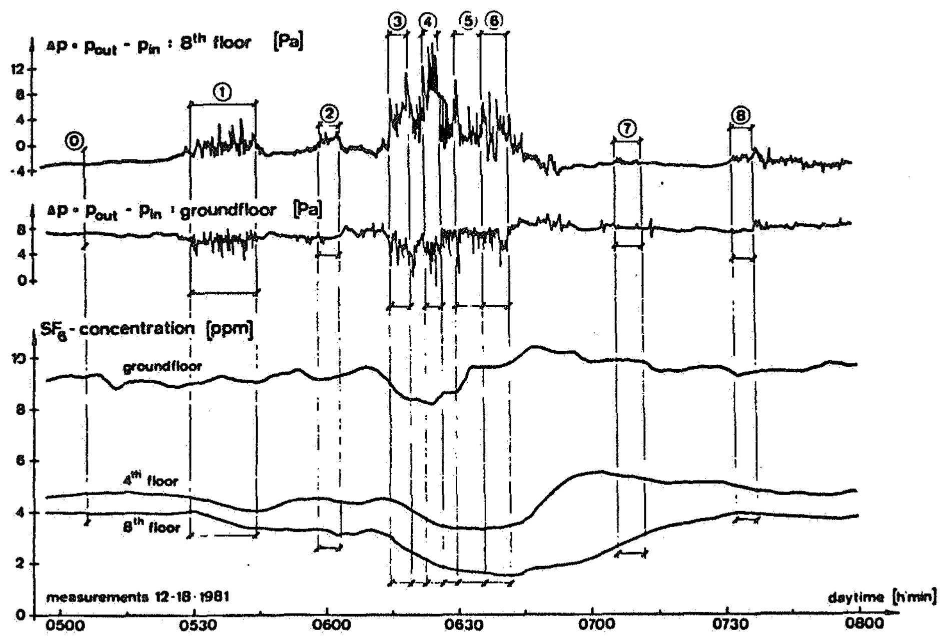


Fig.12: Extract from pressure- and tracer gas measurements at the dormitories, average outside temperature $\theta_{out} = (12 \pm 1)^{o}C$

Based on this outcome, in a first step, an arbitrary modification of the wind velocity profile taking into account higher wind pressures near the ground (0 m < z < 10 m) led to a much better agreement but was still not satisfactory. Calculations with averaged pressure coefficients from Akins et al.[15] and ASHRAE Fundamentals[16] based on a reference wind velocity measured at the roof level as well as height dependent surface coefficients from Jackman and Tech[17] even led to increasing pressure differences $\Delta p = (p_{out} - p_{in})$ for both levels - groundfloor as well as 8th floor - with increasing wind velocities.

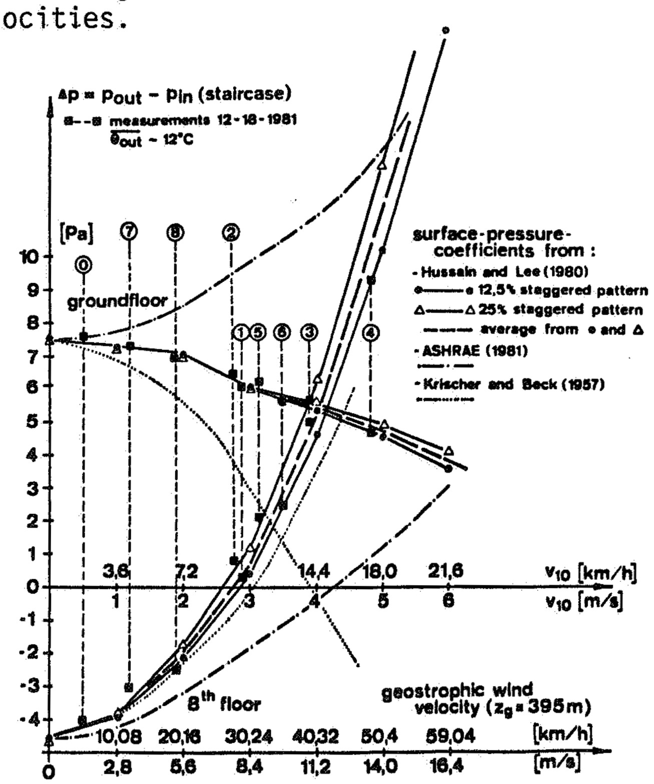


Fig.13: Comparison of the calculated pressure differences at the ground- and 8th floor for different surface pressure profiles.

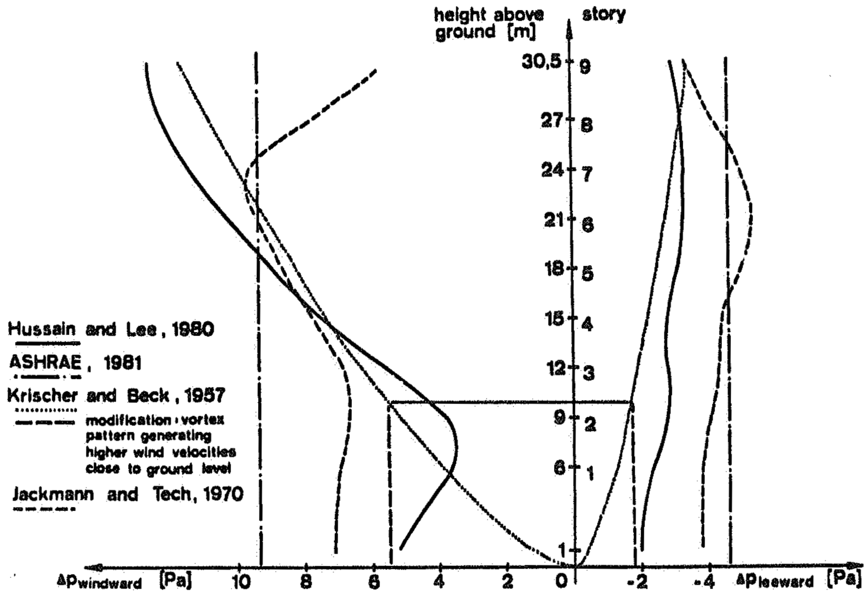


Fig.14: Comparison of the different wind pressure profiles tested in this computer simulation study (v_{wind} (10 m) = 3 m/s)

Only a critical analysis of the built environment and the application of boundary-layer wind tunnel results from Hussain and Lee[6] yielded satisfactory results over the whole observed wind speed range. These authors have studied the surface pressure profiles on a high building as function of different upwind patterns and various height ratios (central building height to average height of the surrounding structures). Since there exists no experimental values for a staggered pattern of about 18%, corresponding to the upwind built-up area in front of the student residence building, we took average values from 12,5% and 25% staggered pattern experiments at a height ratio of 3. In such a way it was possible to correlate pairs of measured pressure differences in the wind velocity range of 0 km/h to 18 km/h at 10 m above ground.

This study clearly demonstrates the discrepancy between the overhasty application of simplified and constant surface pressure coefficients in combination with an exponential equation for the wind velocity profile. Representative average surface pressures - even combined with a questionable correction for the lower wind velocities near ground level[16] - seem not to be the right tool to calculate air in-/exfiltrations, especially for high-rise buildings with near ground vorticity effects and/or large roof overhangs.

5.2 Tracer gas measurements

Fitting the tracer gas equation to the measured SF_6 concentration curve with the aid of an inductance variation, we can extrapolate for calm weather conditions an air exchange rate at the groundfloor of the staircase of 3,5 h^{-1} and an effective space volume of about 75 m^3. The latter is about two times larger than the expected physical volume of space at the injection place. This discrepancy can be explained either by the attached stairwell space communicating with the injection anteroom or by a non-recognized significant nearby air leakage participating in the air exchange and thus increasing the effective volume. On the other side, together with an approximated physical space volume of 30 m^3 for the two anterooms of the stairwell (entrance from the lobby and through the rearward ground-floor emergency door), we estimate an air flow of 105 m^3/h from the ground floor to the first floor. This estimation agrees well with the computed value (table I). Regarding the mixing time the ground floor SF_6 concentration calculated by the fitted tracer gas equation reaches after 50 min 95% of the equilibrium concentration. The parameter matching for the time behavior of the SF_6 concentration at the 4th and 8th story shows a time delay of the "theoretical" onset of the gas mixing of about 20 min and 45 min respectively.

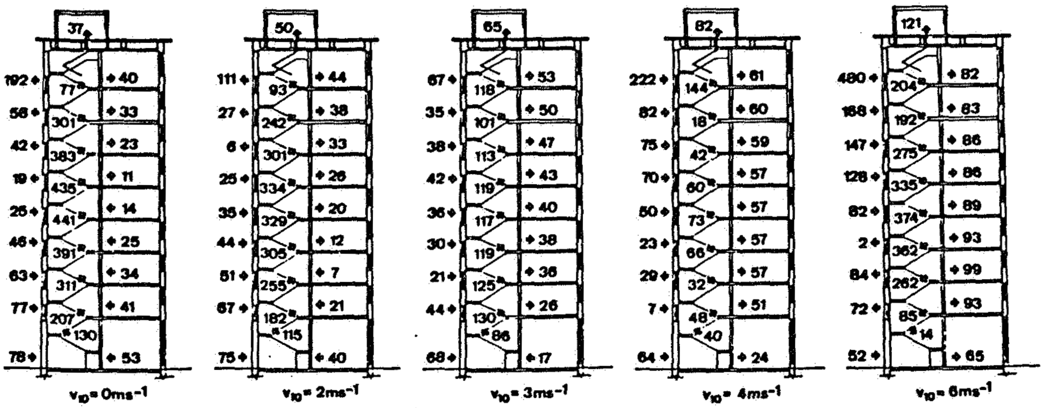


Table I: Air mass flow (m^3/h) throughout the stairwell for wind speeds v_{10} of up to 6 m/s, $\overline{\theta_{out}} \sim 12^{o}C$

The tracer gas measurements (figure 12) prove the following behavior: With increasing wind speed, the SF_6 concentration at the ground-floor shows a slowly increasing trend up to a wind speed of 4 m/s to 5 m/s where the gas content decreases due to outside air which is pressed down through the staircase. Also at the 4th and 8th level we observe the same behavior but already at lower wind speeds because the flow regime at higher levels is much more influenced due to higher wind pressures on the building. A summary of the calculated air mass flow in table I clearly demonstrates how the flow regime, dominated by the stack effect at low speeds, changes over to a reversed situation, where, principally due to wind effect a lot of air is pressed into the building through the windward air leakages at the upper levels and pours out at lower stories. At a wind speed of about 3 m/s a homogenous intermediate state is built up where air is pressed into the building along the whole windward façade and no air flow downwards the staircase can be observed. For wind speeds v_{10} lower than 3 m/s only small changes in the tracer gas concentration at the different test levels were observed (figure 12, period 0, 1, 2, 7 and 8). The latter values are according to order in agreement to the SF_6 content estimated from the computed air mass flows. Referring to table I the flow regime at the 4th floor changes from up-to downwards at wind blowing with 3 m/s to 4 m/s (compare e.g. end of period 1 in figure 12). With increasing wind pressure matching the measuring periods 3 and 4, all gas concentrations show a decreasing trend, also the ground-floor value. This is due to the change in the air flow direction in the stairwell between story 0 and 1 in the wind speed range of 4 m/s to 6 m/s. With less wind in the following observation intervals, the SF_6 concentration at the injection place starts to increase whereas the adequate values in agreement with the flow situation represented in table I still slowly decrease. Meanwhile the ground-floor SF_6 level shows an increasing trend, the tracer gas content for the 4th level stays nearly constant due to the change in the direction of flow around 3 m/s to 4 m/s, but still decreases at the 8th floor because at every floor air containing SF_6 is lost into the aisles (period 5 and 6). The last regime only changes when the wind pressure collapses and the buoyancy behavior for low wind speeds starts to be dominant in the staircase.

6. CONCLUSIONS

To predict energy saving infiltration reductions with the aid of air flow calculations it is necessary to know the actual pressure distribution along the building façades. This can only be done by using local pressure coefficients from wind tunnel experiments matching the wind velocity profile as well as the surrounding building pattern as close as possible.

The characteristics of natural wind are well understood, but the local influences of surrounding topography are difficult to predict. Coefficients based on wind tunnel experiments performed on simple building shapes are widely available but may not be applicable to buildings shielded by local obstructions. Much work is still required to develop simple rules to cope with this problem.

On the other hand the need for easy to handle examination procedures in building standards asks for more simplified calculation methods, e.g. the application of constant surface pressure coefficients combined with a wind velocity profile modified at lower levels and the edges of the roof taking into account the environmental pattern and the upwind landscape structure.

In the future, more research will also be needed in
- transport mechanisms in the building (e.g. air movement room to room with large openings; convective air flow)
- air infiltration in rooms of the same building but with different heights and orientations.

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AIR INFILTRATION REDUCTION IN EXISTING BUILDINGS

4th AIC Conference, September 26-28 1983, Elm, Switzerland

PAPER 10

CASE STUDY OF RETROFITTING A 14-STOREY OFFICE BUILDING IN OSLO

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1. SYNOPSIS

The purpose of an energy conservation project carried out in Norway 1979 - 82 was to demonstrate in practice how energy consumption may be reduced both significantly and cost-effectively in existing buildings. The project included 28 commercial and institutional buildings.

One of this buildings was a 14-storey office-block in Oslo, built in 1971. The main reduction in energy consumption in the building was achieved by thightening air leaks between concrete wall elements and windows. The thightening was done by applying sealing compound in two critical type of joints in the facades.

The energy consumption has been measured one year before and after the retrofitting. Thermography was used to find the air leaks and to verify the tightening afterwards. In addition pressure tests were carried out by using the buildings ventilation system, in order to obtain an estimate of the total infiltration. The leakage at 50 Pa was reduced from about 6,3 ach to about 3,0 ach.

The retrofitting including some changes in the ventilation systems and running time resulted in a reduction in the energy consumption with 705.500 kWh/year or 95 kWh/m^2 year. The payback period (including all project costs) was 1,2 years.

2. THE MAIN PROJECT

This energy conservation project was a co-operation project between research organisations, HVAC-contractors and -consultans and building owners. The purpose was to demonstrate in practice how energy consumption may be reduced both significantly and cost-effectively in existing commercial and institutional buildings.

The project was co-ordinated by NVEF (the Norwegian assosiation for HVAC-contractors and -producers) and included 28 buildings spread all over Norway. Each building got a project team consisting of HVAC-contractor, -consultant, -control contractor and -user. The Norwegian Building Research Institute assisted the project teams with measurements and computer calculations.

The project was carried out in 1979-82. In this period the project teams suggested a total of 327 energy saving measures with less than 3,5 years payback period. Because some building owners did not manage to finance all suggested measures only 170 measures were carried out in the project period. This reduced the energy consumption in 27 of the buildings with 12,5 mill kWh/year = 74,4 kWh/m^2, year which corresponds to 23% reduction.

The project is documented in a main report and a short version report[1] in Norwegian covering all 28 buildings.

2.1 The building in this case study

Construction. 14 storeys, tot. floor area = 7400 m^2. Tot. heated volume = 24.200 m^3 = 1729 m^3/storey. Concrete wall-elements of sandwich-type. Concrete floors and columns. Double glazed windows. Built in 1971.

Heating. All electric. Electric room units (induction units) under all windows. Outdoor design temperature = -20 ^{0}C.

Ventilation. 2 main systems with rotary heat exchangers, 70% efficiency. Electric main batteries. Separate system for floor no. 14 with recirculating air at night. Induction units under all windows, diffusers in inner zones. Ectraction = control valves in all rooms.

Fig. 1. The case building. Herslebs gate 19, Oslo

3. RETROFITTING MEASURES

3.1 Reducing air infiltration

The first site visit revealed high air infiltration rates through slots between the wall elements. This was later documented with thermography and pressure tests. Because of the infiltration it was impossible to keep the rooms sufficient warm in the winter time with the electric room units. Therefore the ventilation had to run all night at outdoor temperatures below 0°C. Even with rotary heat exchangers this costed a lot of energy for heating the supply air.

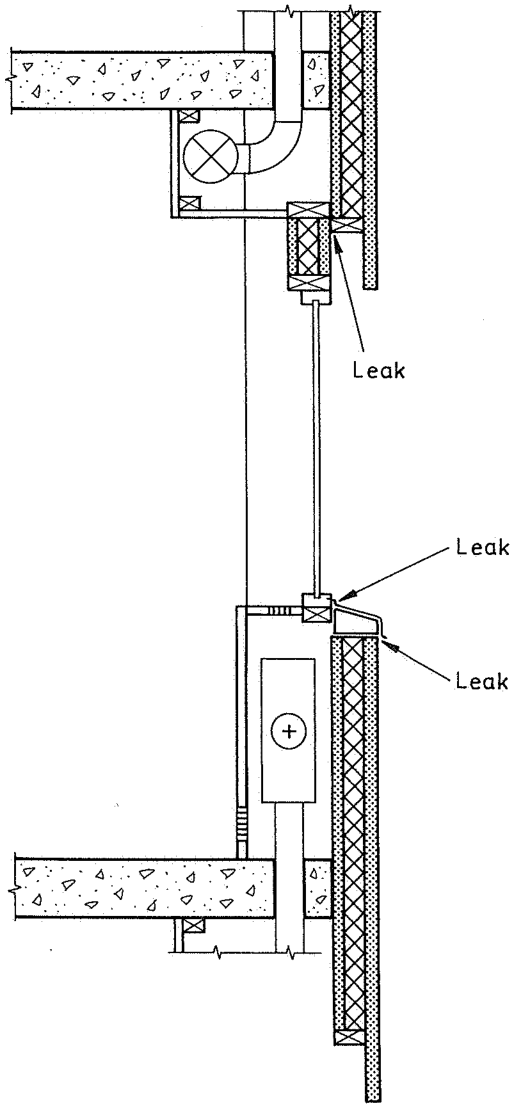

Fig. 2
Wall construction and leak points

The two leak points (slots) under all windows was tightened by applying sealing compound from inside. Easy access was made by removing the front panels of the induction units.

The leak point over the windows was very difficult to reach and was therefore left untightend.

The cost for the tightening including removing and replacing of front panels was kr. 85.000,- for the whole building.

After the tightening the indoor temperature was over 20 °C all the winter with the ventilation turned off in the nights and weekends.

The reduction in infiltration and ventilation energy was approximately 340.000 kWh/year.

3.2 Other measures

Humidification stopped. Before the project started the humidifiers in the ventilation systems was set to give 60% R.H. The measure was here simply to turn the humidifiers completely off without telling the office workers. This saved approximately 200.000 kWh/year without any costs and with very few complains. Because of hygroscopic heat exchangers the humidity never got under 30% R.H.

Rebuilding top floor ventilation systems, recirculation. The top floor contained canteen, kitchen and meeting room with separate ventilation systems for outdoor air only without heat exchangers. These systems was running all the time. The measure here was: Rebuilding one of the systems to allow recirculation in nights and week-ends controlled by a time switch. The two other systems was simply turned off when not in use by mounting time switches. These measures costed kr. 16.400,- and saved approximately 165.500 kWh/year.

3.3 Payback time

The total energy reduction was 705.500 kWh/year corresponding to 28,6% reduction. The measured energy consumption for heating and ventilation the second heating season is here corrected to the same outdoor temperature-time as the first heating season.

With a price for electric energy of kr. 0,21/kWh (1980) this gives a net payback time of 0,7 years. Including project costs the payback time is 1,2 years.

4. AIR INFILTRATION ENERGY LOSS

The yearly energy consumption for ventilation and heating was measured together. Lack of information of running time for the ventilation makes it difficult to separate the different heat losses. Measuring the building leakage at 50 Pa before and after tightening allows however an approximate calculation of the infiltration loss. This was done with the computer program ENCORE[2], together with the cauculation of the transmission loss.

4.1 Measured pressure difference inside/outside

The measurements of pressure distribution was done in connection with the thermography before and after retrofitting, see fig. 3.

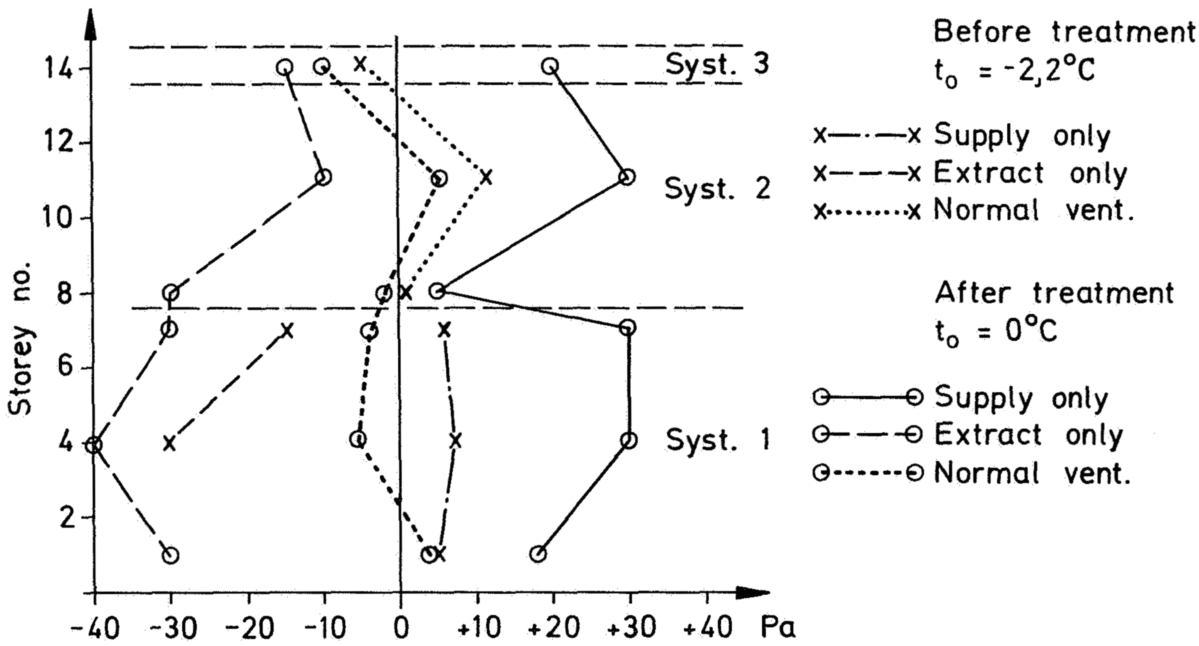

Fig. 3. Pressure distribution, inside/outside

4.2 Measured air flow

Syst. 1:	Supply, normal and extract fan stopped	=	25.900 m^3/h
	Supply, only extract fan running	=	800 "
	Extract, normal	=	28.200 "
Syst. 2:	Supply, normal	=	24.300 "
	Supply, only extract fan running	=	1.200 "
	Extract, normal	=	22.500 "
	Extract, only supply fan running	=	200 "
Syst. 3:	Supply and extract, design values	=	11.400 "

The air flow was measured the same day as the pressure distribution after treatment was measured. Method: Ducttraversing with calibrated hotwireanemometer, type TSI 1650, according to Nordic guidelines[3].

The air flow before treatment was measured by the project team in March 1979. These measurements correspond within ± 10% to our measurements in Dec. 1980.

4.3 Calculation of building tightness

Measurements of pressure differences inside/outside were carried out only as a control for the thermography and are therefore complete only in 4. - 7. storey. Using this data and measured air flow in system 1 it is possible to calculate approximate values of building tightness before and after treatment.
The formula used has been tested by Railio[4].

$$n_{50} = n_m \left(\frac{50\ Pa}{\Delta p_m}\right)^{0,7}$$

1. Before treatment:

a) Supply - extract (fan stopped) = 25.900-800 = 25.100 m^3/h

Air changes: n_m = 25.100/ (7 • 1729) = 2,07 h^{-1}

Measured over-pressure = (7 + 6)/2 = 6,5 Pa

Air changes at 50 P_a: $n_{50} = 2,07\ (50/6,5)^{0,7} = \underline{8,63}\ h^{-1}$

b) Extract - supply (fan stopped) = 28.000 m^3/h (approx.)

Air changes: n_m = 28.000 (7 • 1729) = 2,31 h^{-1}

Measured under-pressure = (30 + 15)/2 = 22,5 Pa

Air changes at 50 Pa: $n_{50} = 2,31\ (50/22,5)^{0,7} = \underline{4,04}\ h^{-1}$

c) Mean leakage number: n_{50} = (8,63 + 4,04)/2 = 6,3 h^{-1}

2. After treatment:

a) Measured over-pressure = (30 + 30)/2 = 30 Pa

$n_{50} = 2,07\ (50/30)^{0,7} = \underline{2,96}\ h^{-1}$

b) Measured under-pressure = (40 + 30)/2 = 35 Pa

$n_{50} = 2,31\ (50/35)^{0,7} = \underline{2,97}\ h^{-1}$

c) Mean leakage number: n_{50} = 3,0 h^{-1}

4.4 Energy consumption separated on the users

All the measured and calculated energy consumption for different use together with the measured (temperature-corrected) total comsumption before and after retrofitting is shown in fig. 4.

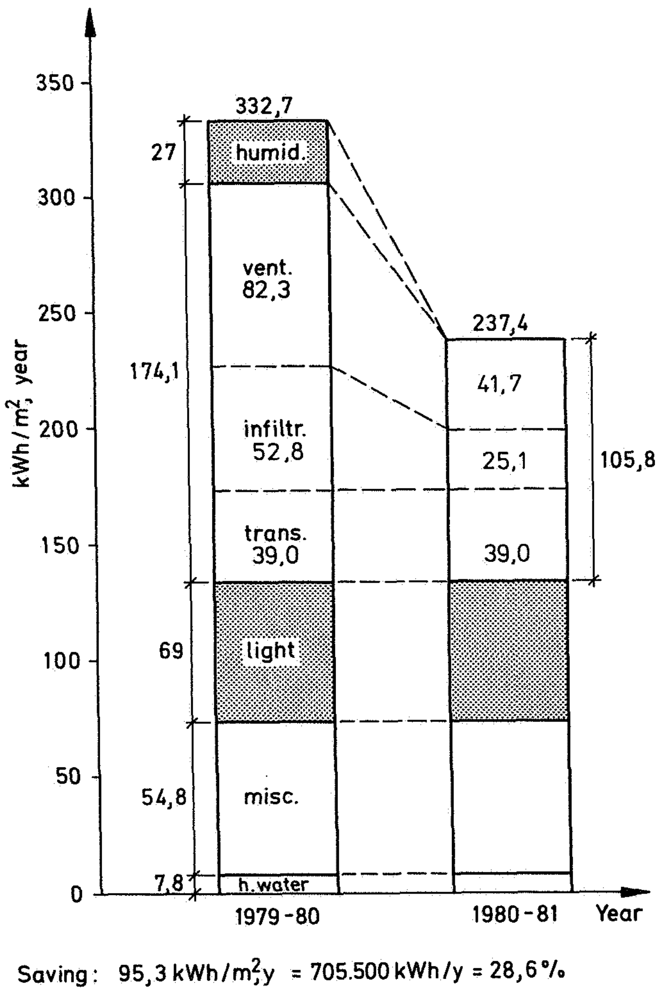

Fig. 4. Energy consumption before and after retrofitting

5. ACKNOWLEDGEMENT

The author wish to thank the leader of the main project, Odd Stokstad (NVEF), for all basic data for the calculations and helpful discussions.

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ENERGY EFFICIENT DOMESTIC VENTILATION SYSTEMS FOR ACHIEVING
ACCEPTABLE INDOOR AIR QUALITY

3rd AIC Conference, September 20-23 1982, London, UK

PAPER 11

AIR INFILTRATION AND AIR TIGHTNESS TESTS
IN EIGHT U.S. OFFICE BUILDINGS

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ABSTRACT

The National Bureau of Standards has undertaken the development of diagnostic test methods for evaluating the thermal integrity of federal office buildings. The purpose of this program is to develop test procedures which can be used for 1.) the verification of the thermal specifications of recently constructed federal buildings, 2.) the determination of applicable retrofit measures to existing buildings and 3.) the post evaluation of retrofit work. As part of this project, eight federal office buildings ranging in size from 3000 m^2 to 45,000 m^2 have been tested for their air infiltration characteristics. These buildings are located in Anchorage, AK; Huron, SD; Fayetteville, AR; Pittsfield MA; Springfield, MA; Norfolk, VA; Columbia, SC and Ann Arbor, MI. Tracer gas tests have been performed in these buildings during the fall, winter and spring in order to evaluate both the ventilation of these buildings during occupied periods and the natural air leakage under various weather conditions. Fan pressurization tests have been performed on these buildings using the supply and exhaust fans of the building and a tracer technique to measure the air flow induced by the HVAC fans. In addition, during the winter an infrared thermographic inspection of the buildings was performed which revealed the sites of building leakage.

1. INTRODUCTION

It has been found in the United States that many new buildings which were designed to energy conservation standards and specifications do not after construction perform according to the design due to either poor workmanship or a misunderstanding of the construction specification. It is difficult to determine by normal inspection techniques whether a building under construction will meet its design specification. There exist a need for in situ and nondestructive measurement techniques to verify the thermal integrity of the envelope system of office buildings under construction and during the post occupancy evaluation period when the building is under warrantee. In this period, thermal defects which can be identified and located would be the responsibility of the contractor to correct before departing from the site. Existing buildings degrade with age and require periodic maintenance. The potential for serious deterioration in the building will often produce thermal anomalies long before serious damage has occurred. The detection of these anomalies can lead to corrective action before costly repairs are required. To assure the quality of remedial actions taken to improve existing office buildings, inspection techniques are also required. Recognizing this situation, the General Services Administration (GSA) started a project at the National Bureau of Standards (NBS) to develop, assess and demonstrate measurement methods which would be applicable to its requirements for evaluating the thermal integrity of its office buildings. The inspection techniques being evaluated by NBS are: ground-based infrared thermographic surveys, aerial infrared surveys, tracer gas air infiltration measurements, pressurization tests for determining the tightness of the building envelope, energy audits using spot radiometers, quantitative measurement of the thermal resistance of sections of the building envelope using heat flow meters, a portable calorimeter box design by the National Research Council of Canada and an envelope thermal testing unit developed by Lawrence Berkeley Laboratory and the individual testing of the tightness of building components using pressurization. A description of these measurement techniques and this research program can be found in reference [1]. This paper will discuss the results of the measurements performed on eight federal office buildings as they related to air infiltration and building tightness.

2. DESCRIPTION OF THE EIGHT FEDERAL OFFICE BUILDINGS

The eight federal office buildings are located in the cities shown in the map in figure 1. In general these are new (less than 3 years old) buildings constructed to the U.S. federal energy guidelines of less than 630 MJ/M^2 per year of on-site energy and less than 1200 MJ/M^2 per year of off-site energy. The exception to this is the federal building in Fayetteville, AR which is 7 years old and was built before the energy guidelines for new federal office buildings was in effect. Though these buildings tend to perform better than most existing federal office buildings, none has meet the energy guidelines during its first few years of occupancy. For the purpose of this study the buildings in Anchorage, AK; Springfield, MA; Norfolk, VA, and Columbia, SC are considered large office buildings (over 10,000 M^2 of occupiable area). Columbia has a height of 15 stories, Norfolk, 8 stories; Anchorage between 2 to 6 stories depending on the module; and Springfield, 5 stories. The buildings in Pittsfield, MA; Huron, SD; Ann Arbor, MI and Fayetteville, AR are consider as small office buildings for the purpose of the study (lessthan 10,000 M^2 occupiable area). These small office buildings range in height from 2 to 5 stories. A summary of the characteristics of the buildings is given in table 1. Schematics and a photograph for each building are given in figures 2 to 9. All but two of the buildings have variable volumeair handlers in the major zones of the buildings. They are heated by perimeter heating systems which are usually hydronic. The building in Columbia has two air perimeter heating systems. In the building in Norfolk heaters and air conditioners have been added to the air system on floors which proved difficult to heat or cool. They all have central chiller systems for cooling the core spaces of the buildings. The buildings in Anchorage and Springfield have underground garages. The building in Norfolk has an exterior garage which occupies part of floors 1 to 4.

3. AIR INFILTRATION AND VENTILATION RATES

The air infiltration under natural conditions was measured using sulfur hexafluoride (SF_6) as a tracer. This test was designed for each building to produce a measure of the total air infiltration of the building and the air infiltration of the major zones of the building. Sample tubing and injection tubing was installed in each zone along with wiring for measurng interior temperatures, the status of the building's HVAC fans and for a weather station (wind speed, wind direction and exterior temperature). The automatic air infiltration system [2] previously designed by NBS for large buildings was installed in each building for a period of about a week during the fall, winter and spring (three automated air infiltration systems were used on this project). Tests were performed both during periods of occupancy and non-occupancy, and with the dampers opened and closed. To date, tracer gas infiltration meaurements have been made for a total of about 200 hours in each building. The air sample locations for these tests are given in table 2.

The results of these measurements are summarized in tables 3 to 10 and figures 10 to 12. The data has been categorized in the ventilation rates experienced during occupied periods, infiltration rates for wind speed less that 2.5 M/S and infiltration rates for wind speed greater than 2.5 M/S. Tables 3 to 10 give the average air exchange rates for various temperature bins. A study of the data in figure 10 and tables 3 to 10 show three distinct patterns in the ventilation rates in the eight buildings. The building in Huron shows little change in the ventilation rate during occupied periods over all temperature bins with the possibility that the ventilation rate raises for the temperature bin 10 to 20 °C. The building in Anchorage shows this raise in temperature clearly. The buildings in Norfolk and Ann Arbor have low ventilation rates at both low and high temperatures with increasing ventilation rates in the temperature bin 10 to 20 °C. This increase is due to use of outdoor air of cooling of the building. The building in Springfield has a fairly constant ventilation rate in the temperature bin 10 to 20 °C and an increasing ventilation as the temperature decreases.This is probably due to the increase in infiltration as the temperature decreases for this building (figures 11 and 12). These trends in the data are indicated by the dotted lines in figure 10. The minimum ventilation rates for these buildings are given in table 11. As can be seen by examining the data, some of these building under certain weather conditions violate these minimum ventilation rates.

The air infiltration rates for some of the buildings are show in figures 11 and 12. In general, though there is considerable variation in the data, it can be seen that lower exterior temperatures produce higher air infiltration rates and higher wind speeds produce higher air infiltration rates. Fitting a regression line to the data in figures 11 and 12 produce the following relationships between the temperature and air infiltration rates:

<u>Wind Speed less than 2.5 M/S</u>

Norfolk:

$$I = 0.59 - 0.0072\ T_{out} \qquad r^2 = 0.38$$

Springfield:

$$I = 0.58 - 0.0192\ T_{out} \qquad r^2 = 0.20$$

Ann Arbor:

$$I = 0.70 - 0.0056\ T_{out} \qquad r^2 = 0.03$$

Huron:

$$I = 0.20 - 0.0058\ T_{out} \qquad r^2 = 0.40$$

<u>Wind Speed Greater Than 2.5 M/S</u>

Norfolk:

$$I = 0.64 - 0.0085\ T_{out} \qquad r^2 = 0.60$$

Ann Arbor:

$$I = 0.80 - 0.0115\ T_{out} \qquad r^2 = 0.15$$

Huron:

$$I = 0.24 - 0.0021\ T_{out} \qquad r^2 = 0.07$$

4. BUILDING TIGHTNESS MEASURIZATIONS

The building tightness of the eight federal office buildings were tested using whole building fan pressurization and tracer gas techniques. The fan pressurization tests were performed during the fall of 1982 on seven of the eight federal buildings using the building's HVAC system fans. It was not possible to pressurize the federal building in Fayetteville because the outside air duct could not bring in a sufficient volume of air due to its limited size. In principle this building could be pressurized by use of an external fan however the shipment of this fan to Fayetteville was judged to be too expensive.

The results of the pressurization tests and the fall tracer gas air infiltration measurements (dampers closed) are shown in table 12. The most notable aspect of these data is the tightness of the buildings from the pressurization measurements. The pressurization test results are the air flow rates into the buildings, in units of building volumes or exchanges per hour, required to sustain a 25 Pascal (Pa) pressure difference between inside and outside. These flow rates are significantly larger than the ventilation rates during normal building operation or infiltration rates induced by weather. The 50 Pa (0.2 inches of H_2O) exchange rates of the buildings are roughly 1.5 times the 25 Pa (0.1 inches of H_2O) rates shown in the table. These 50 Pa leakage rates are very low compared to homes. U.S. homes range from about 5 volumes per hour (very tight) to greater than 20 (very leaky). Swedish and Canadian homes are being built with 50 Pa flow rates of less than 2 volumes per hour. Thus, the 50 Pa flow rate of these federal buildings correspond to very tight homes.

From the data in table 12, it can be seen that there is correlation between the pressurization measurements and the tracer gas test results. Bearing in mind that the tracer gas results are preliminary and made only under approximately the same weather conditions, infiltration rates have been plotted against pressurization results in figure 13. The correlation between the two measurements appears to be fairly strong. The slope of a line passing through all the points is roughly 0.5. If one adjusts the 25 Pa flows to 50 Pa flows using the rough correction factor of 1.5, then the slope of infiltration against 50 Pa flow is about 1/3. This compares to the slope for residential buildings which is about 1/20.

In comparing the pressurization test results of the federal buildings to each other and to residential buildings, the important factor of surface to volume ratio arises. Figure 14 shows the surface to volume ratios (S/V) for the federal buildings and two sample homes. The 1-story house is assumed to have a 120 M^2 square floor area and 2.5 M ceilings. The 2-story home also has a square floor plan with 100 M^2 on each floor and a 5 M building height. We see in the figure that the large sizes of the federal buildings generally lead to lower values of S/V than for homes. The Ann Arbor building is an exception due to its particular design.

One may adjust the pressurization test results in table 12 to take into account the different values of S/V amoung the buildings. Table 12 gives the 25 Pa leakage rate in building volumes per hour. This number divided by S/V, yields the 25 Pa flow rate in m^3/hr per m^2 of exterior surface area. This second flow rate is more of a measure of "construction quality" than the first flow rate. Figure 15 compares these two measures of leakiness. The vertical scale on the left shows the 25 Pa flows in exchanges per hour for the seven federal buildings and the two sample houses (2.0 exchanges/hr at 50 Pa, extremely tight). The vertical scale on the right shows the 25 Pa flows in $m^3/hr\text{-}m^2$ as discussed above. We see that in moving from exhcanges/hr to $m^3/hr\text{-}m^2$ the tightness ranking of the buildings changes significantly. Also, the spread in the leakage values using the second measure is larger than the spread in exchanges per hour. The most significant change occurs in the Ann Arbor building which is of average tightness as measured by exchanges per hour but is the tightest building in terms of $m^3/hr\text{-}m^2$. Thus, the Ann Arbor building has the tightest construction per m^2 of wall area, but its design leads it to appear relatively leakier than many of the other buildings as measured by the flow in exchanges per hour.

5. LOCATION OF AIR INFILTRATION SITES USING THERMOGRAPHY

Each of the federal office buildings was inspected using an infrared thermographic system during the winter. These inspections were performed from both the exterior and interior of the buildings at night. These inspection show the location of several classes of air infiltration sites in these buildings. These are summarized in table 13. Figure 16 shows some examples of the thermograms produced. A more complete discussion the the results of the thermographic surveys can be found in references 3 and 4.

6. CONCLUSIONS

The results of this study show that it is possible to perform air infiltration and building tightness measurements even in large buildings. In modern U.S. office buildings, the air infiltration rates due to environmental factors tend to be low and these office building can be classified as tight. During the operation of these buildings, there are periods of time when the buildings will have low ventilation rates which are below the accepted minimum requirements for occupied office buildings.

ACKNOWLEDGMENTS

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	Area (M^2)	Volume (M^3)	Zones	HVAC Type
Anchorage	48,470	174,000	6	VAV
Springfield	14,560	75,300	3	VAV*
Columbia	21,600	109,000	3	VAV*
Norfolk	18,570	60,300	2	VAV*
Pittsfield	1,860	8,520	2	CV
Huron	6,910	27,500	2	VAV*
Ann Arbor	5,270	33,400	3	VAV*
Fayetteville	3,660	20,400	6	CV

VAV - Variable Volume CV - Constant Volume

* Lobbies have constant volume air handlers

Table 1. Summary of Building Characteristics for Eight Federal Office Buildings

Anchorage
1. Module A
2. Module B
3. Module C
4. Module D
5. Module E
6. Module F
7. 5th Floor Module C
8. 3rd Floor Module C
9. 1st Floor Module C

Columbia
1. HVAC Return
2. 13th Floor
3. 11th Floor
4. 9th Floor
5. 7th Floor
6. 5th Floor
7. 3rd Floor
8. 1st Floor & Basement
9. Lobby
10. Courthouse

Springfield
1. North Return
2. South Return
3. Atrium/Lobby
4. 5th Floor - North
5. 4th Floor - North
6. 3rd Floor - North
7. 2nd Floor - North
8. 1st Floor - North
9. 4th Floor - South
10. 2nd Floor - South

Norfolk
1. HVAC Return
2. 8th Floor
3. 7th Floor
4. 6th Floor
5. 5th Floor
6. 4th Floor
7. 3rd Floor
8. 2nd Floor
9. 1st Floor

Ann Arbor
1. HVAC Return
2. 4th Floor Return
3. 3rd Floor Return
4. 1st & 2nd Floor Return
5. Lobby
6. Post Ofice

Fayetteville
1. 1st Floor
2. 2nd Floor
3. 3rd Floor
4. 4th Floor
5. 5th Floor
6. Courtroom - 5th Floor

Huron
1. North Return
2. East Return
3. 4th Floor - North
4. 3rd Floor - North
5. 2nd Floor - North
6. 1st Floor - North
7. 4th Floor - East
8. 3rd Floor - East
9. 2nd Floor - East
10. 1st Floor - East

Pittsfield
1. 1st Floor Return
2. 2nd Floor Return

Table 2. Location of Tracer Gas Sampling

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Dampers Closed (Wind < 2.5 M/S) (X/HR)	Dampers Closed (Wind > 2.5 M/S) (X/HR)
(-20 < -10)	0.33	0.27	0.31
(-10 < 0)	0.44	0.33	0.25
(0 < 10)	1.15	0.24	
(10 < 20)	1.29	0.27	0.63
(20 < 30)			

Table 3. Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods with Dampers Closed - Anchorage, AK

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Dampers Closed (Wind < 2.5 M/S) (X/HR)	Dampers Closed (Wind > 2.5 M/S) (X/HR)
(-20 < -10)			
(-10 < 0)	0.62	0.36	
(0 < 10)	0.54	0.44	0.49
(10 < 20)	1.69	0.41	
(20 < 30)			

Table 4. Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods with Dampers Closed - Columbia, SC

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Dampers Closed (Wind < 2.5 M/S) (X/HR)	Dampers Closed (Wind > 2.5 M/S) (X/HR)
(-20 < -10)			
(-10 < 0)	0.67	0.63	0.67
(0 < 10)	0.65	0.47	0.52
(10 < 20)	1.18	0.48	0.53
(20 < 30)	0.76		

Table 5. Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods with Dampers Closed - Norfolk, VA

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Dampers Closed (Wind < 2.5 M/S) (X/HR)	Dampers Closed (Wind > 2.5 M/S) (X/HR)
(-20 < -10)			
(-10 < 0)	1.02	0.62	0.78
(0 < 10)	0.93	0.52	0.77
(10 < 20)	0.68	0.36	
(20 < 30)	0.58		

Table 6. Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods with Dampers Closed - Springfield, MA

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Dampers Closed (Wind < 2.5 M/S) (X/HR)	Dampers Closed (Wind > 2.5 M/S) (X/HR)
(-20 < -10)			
(-10 < 0)		0.25	
(0 < 10)	0.74	0.30	0.27
(10 < 20)	0.92	0.29	0.34
(20 < 30)	0.59	0.45	

Table 7. Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods with Dampers Closed - Pittsfield, MA

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Dampers Closed (Wind < 2.5 M/S (X/HR)	Dampers Closed (Wind > 2.5 M/S) (X/HR)
(-20 < -10)	0.29	0.27	0.26
(-10 < 0)	0.26	0.24	0.26
(0 < 10)	0.25	0.16	0.18
(10 < 20)	0.23	0.12	
(20 < 30)	0.67		

Table 8. Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods with Dampers Closed - Huron, SD

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Dampers Closed (Wind < 2.5 M/S) (X/HR)	Dampers Closed (Wind > 2.5 M/S) (X/HR)
(-20 < -10)			
(-10 < 0)		0.43	
(0 < 10)	0.31	0.31	0.38
(10 < 20)	0.36	0.30	0.30
(20 < 30)	0.66	0.28	0.71

Table 9. Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods with Dampers Closed - Fayetteville, AR

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Dampers Closed (Wind < 2.5 M/S) (X/HR)	Dampers Closed (Wind > 2.5 M/S) (X/HR)
(-20 < -10)			
(-10 < 0)	0.60	0.57	0.79
(0 < 10)	0.64	0.70	0.81
(10 < 20)	1.92	0.56	0.62
(20 < 30)	0.43	0.46	

Table 10. Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods with Dampers Closed - Ann Arbor, MI

	Smoking	Non-smoking	Design	10% Outside Air
Anchorage	0.67	0.17	-	0.28
Pittsfield	0.42	0.10	0.42	0.32
Norfolk	0.69	0.17	-	0.25
Columbia	0.41	0.10	0.29	0.28
Ann Arbor	0.38	0.09	0.52	0.36
Fayetteville	0.41	0.10	0.94	0.57
Huron	0.49	0.12	-	0.31
Springfield	0.46	0.12	-	0.44

Assumptions: 7 people per 100 ^{2}
Smoking: 10 l/s per person
Non-Smoking 2.5 l/s per person

Table 11. Estimated Minimum Ventilation Rates Required

Building Location	Pressurization Flow at 25 Pa (volumes/hour)	Tracer Gas Decay* Infiltration Rate (volumes/hour)
Anchorage	0.80	0.20 to 0.30
Ann Arbor	0.86	0.55 to 0.65
Columbia	0.67	0.35 to 0.45
Fayetteville	----	0.35 to 0.45
Huron	0.45	0.10 to 0.20
Norfolk	1.36	0.45 to 0.55
Pittsfield	1.07	0.25 to 0.35
Springfield	1.00	0.30 to 0.40

* The values listed correspond to a range of measured infiltration rates with wind speeds less than 1.5 m/s and an outside temperature between 5 and 10 ^{o}C.

Table 12. Airtightness Measurement Results for Eight Federal Buildings.

	Air Penetration		Air Leakage		Joints		
	Walls	Ceiling	Doors	Windows	Wall Wall	Ceiling Wall	Floor Wall
Anchorage	*			*	*		*
Ann Arbor	*	*		*	*		*
Columbia	*	*	*	*	*	*	*
Fayetteville			*	*	*	*	*
Huron	*		*	*	*	*	*
Norfolk	*	*	*		*	*	*
Pittsfield	*	*		*	*	*	*
Springfield	*			*		*	*

Table 13. Dominant Locations of Air Leakage Sites as Revealed by Thermographic Inspections.

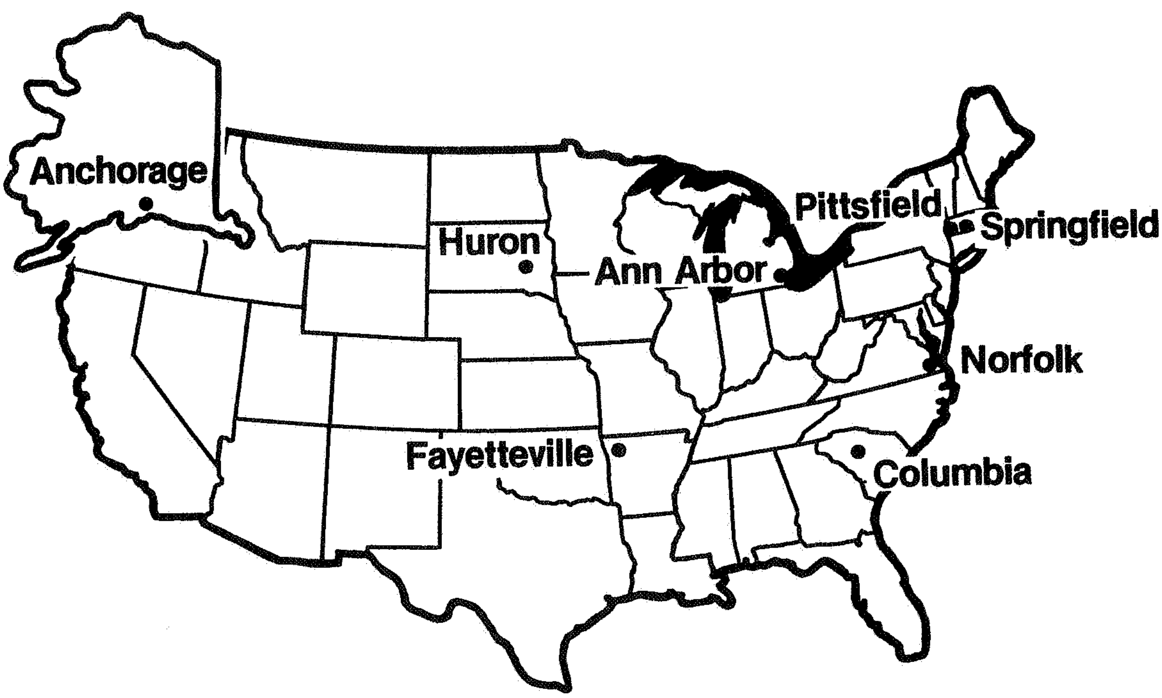


Figure 1. Location of Eight Federal Office Buildings in U.S.A.

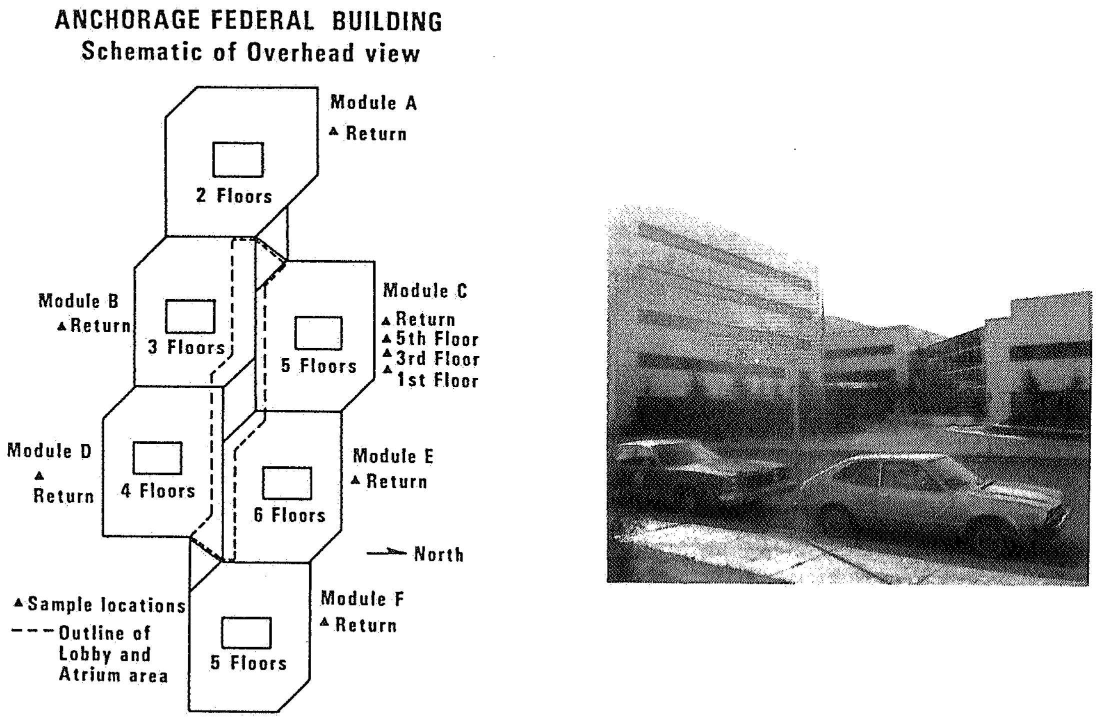
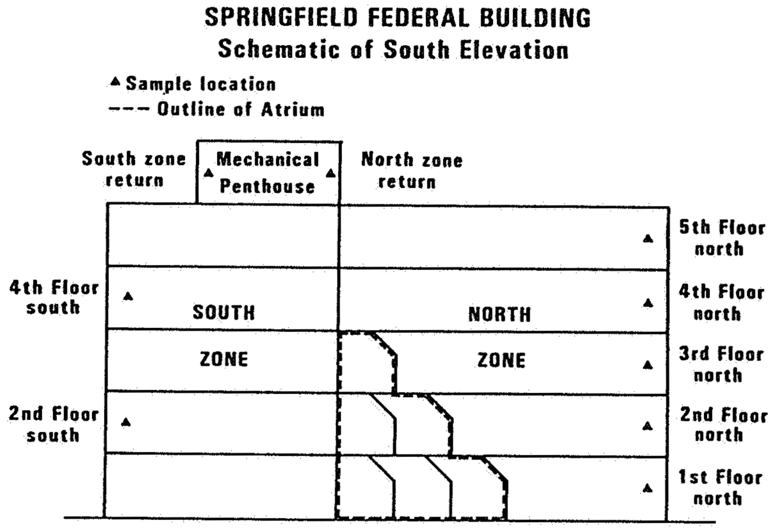
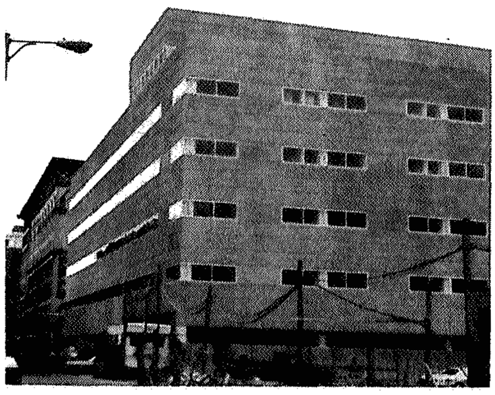


Figure 2. Schematic and Photograph of Federal Building in Anchorage, AK





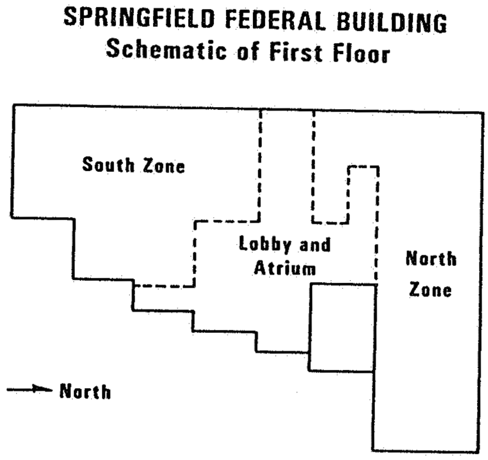


Figure 3. Schematic and Photograph of Federal Building in Springfield, MA

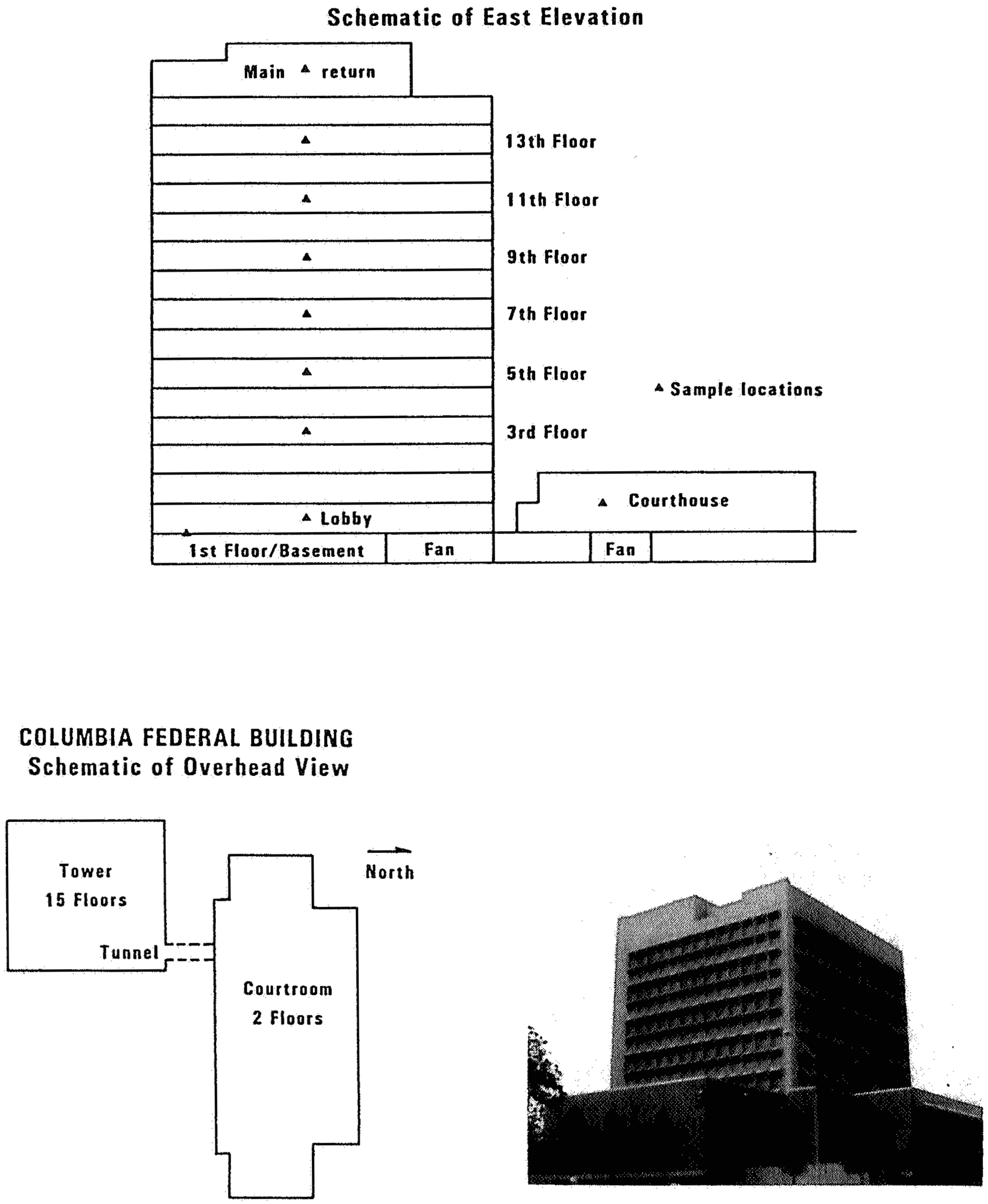


Figure 4. Schematic and Photograph of Federal Building in Columbia, SC

	Air Penetration		Air Leakage		Joints		
	Walls	Ceiling	Doors	Windows	Wall Wall	Ceiling Wall	Floor Wall
Anchorage	*			*	*		*
Ann Arbor	*	*		*	*		*
Columbia	*	*	*	*	*	*	*
Fayetteville			*	*	*	*	*
Huron	*		*	*	*	*	*
Norfolk	*	*	*		*	*	*
Pittsfield	*	*		*	*	*	*
Springfield	*			*		*	*

Table 13. Dominant Locations of Air Leakage Sites as Revealed by Thermographic Inspections.

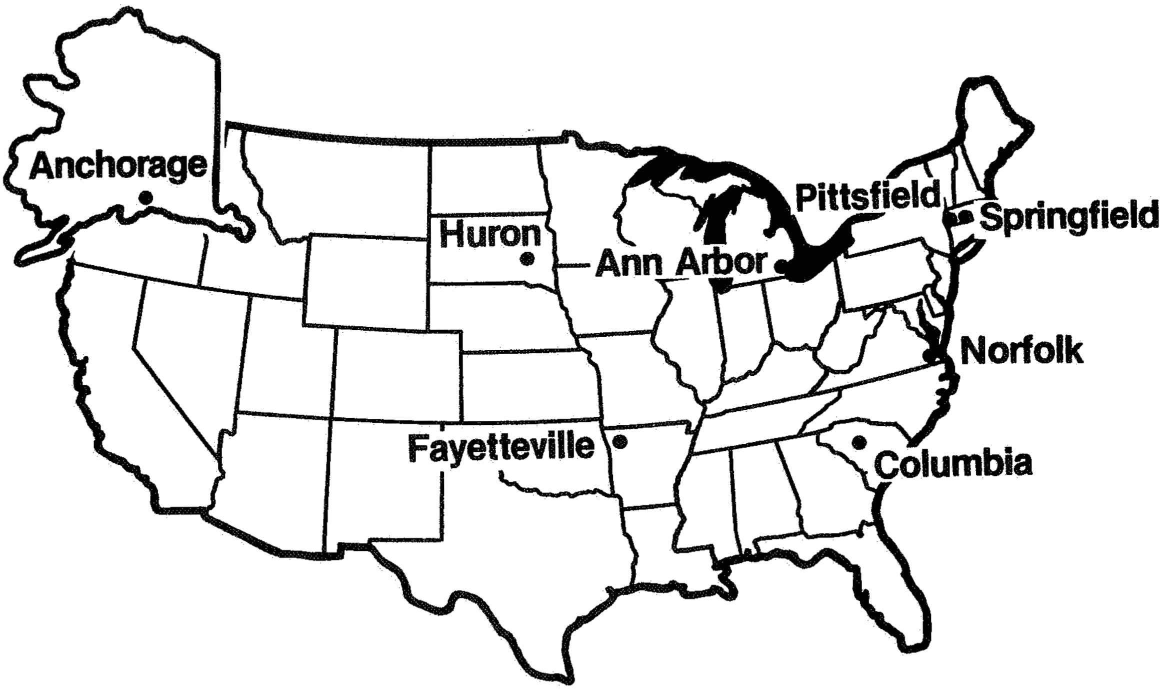
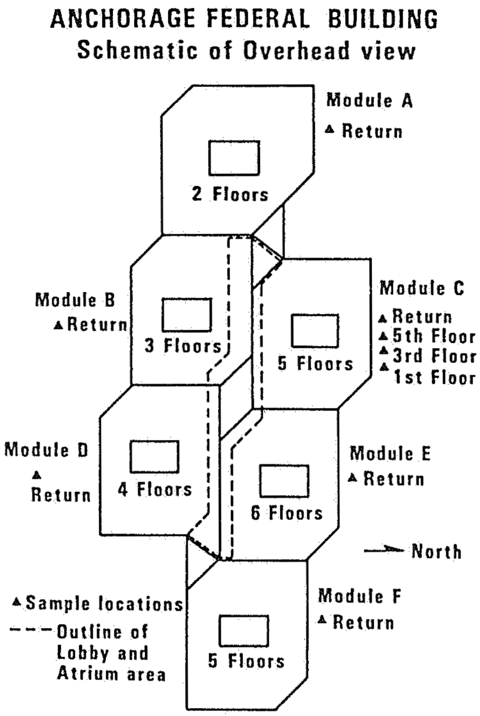


Figure 1. Location of Eight Federal Office Buildings in U.S.A.



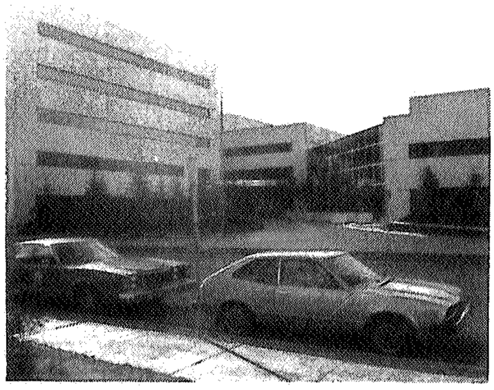
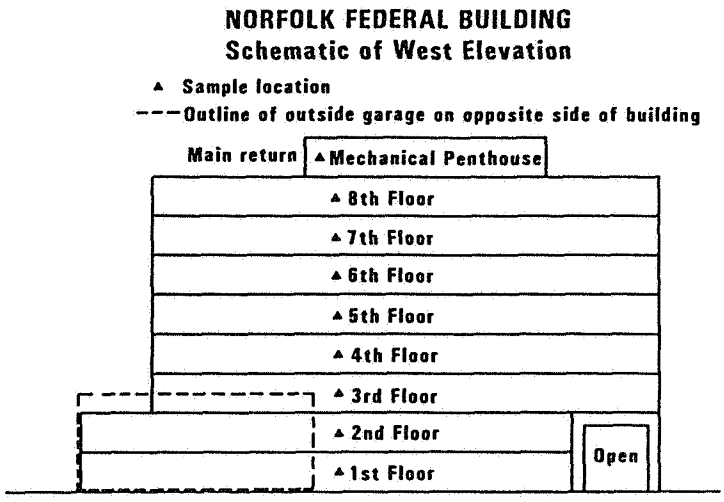
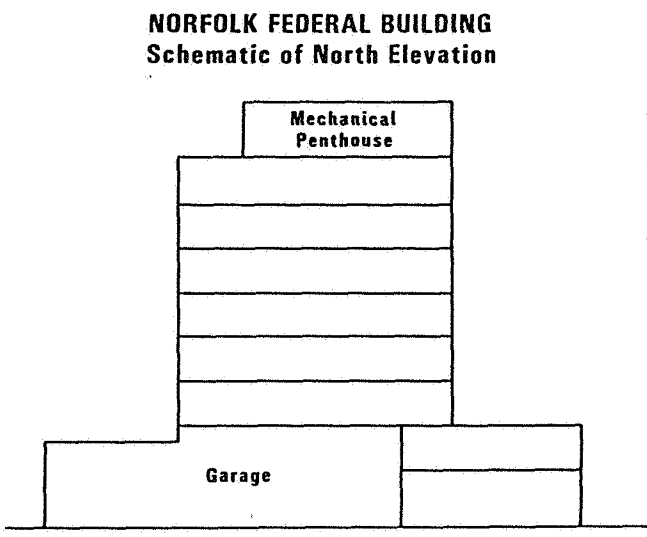


Figure 2. Schematic and Photograph of Federal Building in Anchorage, AK





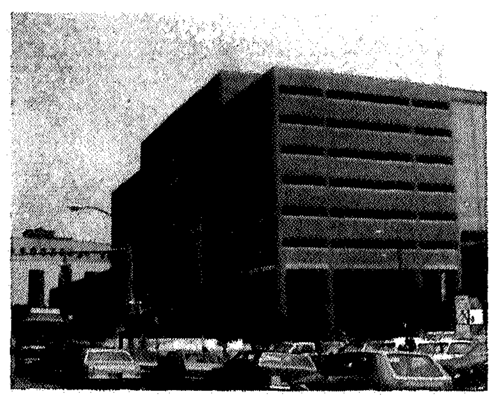
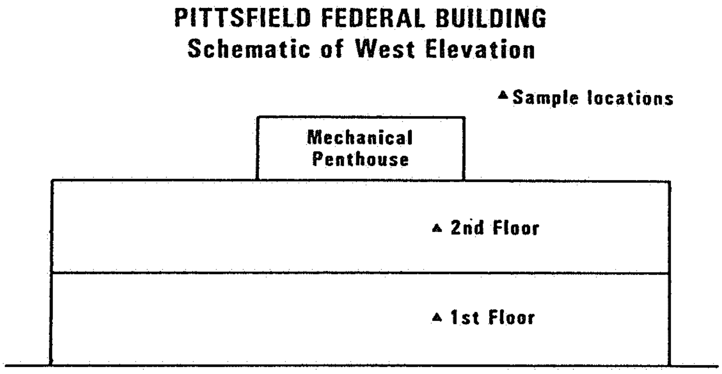
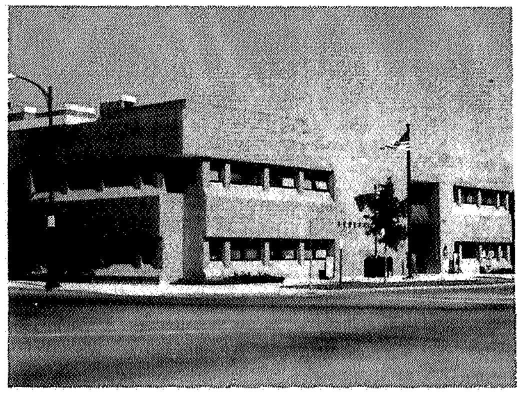


Figure 5. Schematic and Photograph of Federal Building in Norfolk, VA





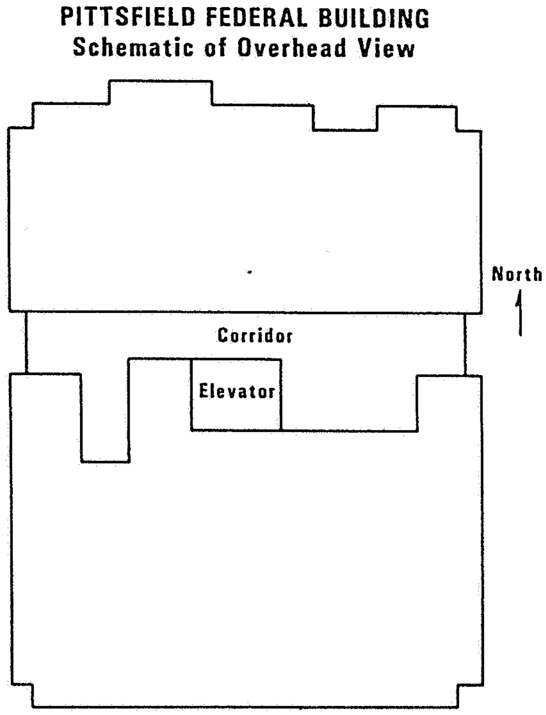
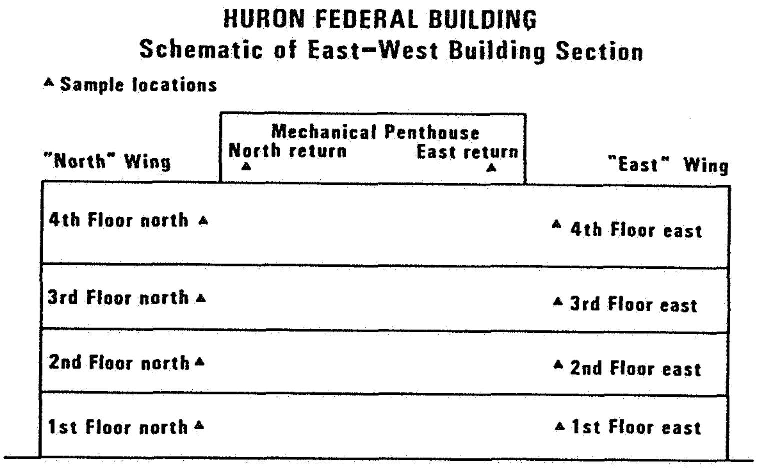


Figure 6. Schematic and Photograph of Federal Building in Pittsfield, MA



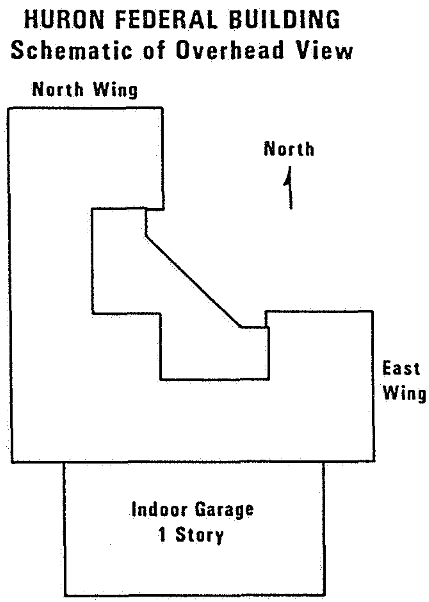
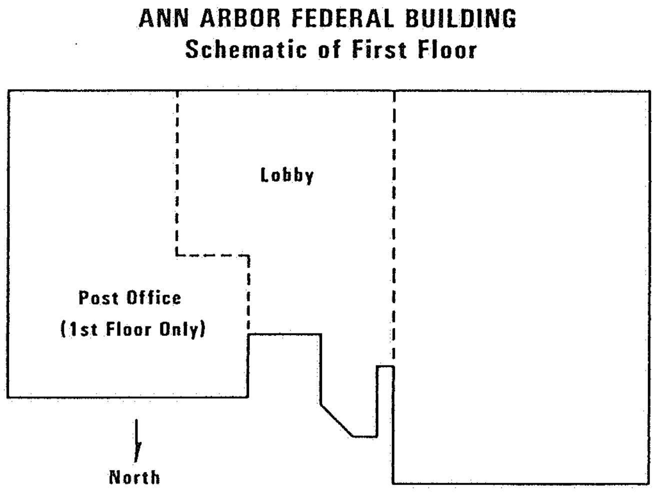
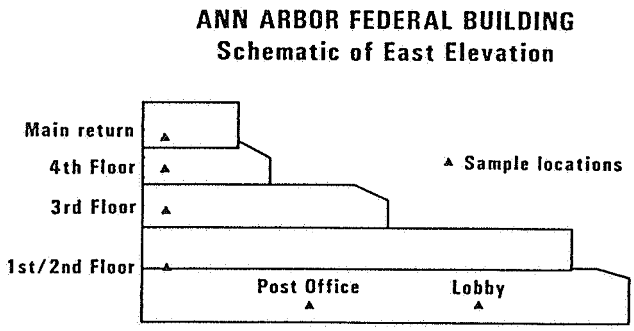


Figure 7. Schematic and Photograph of Federal Building in Huron, SD





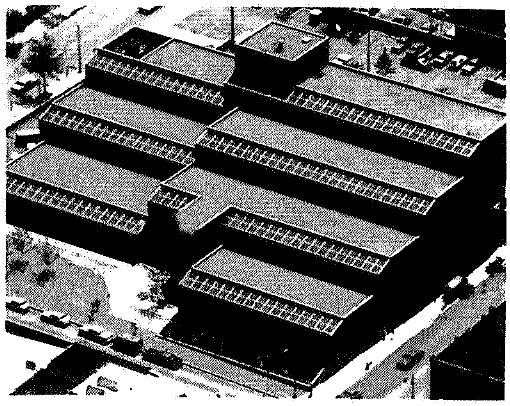
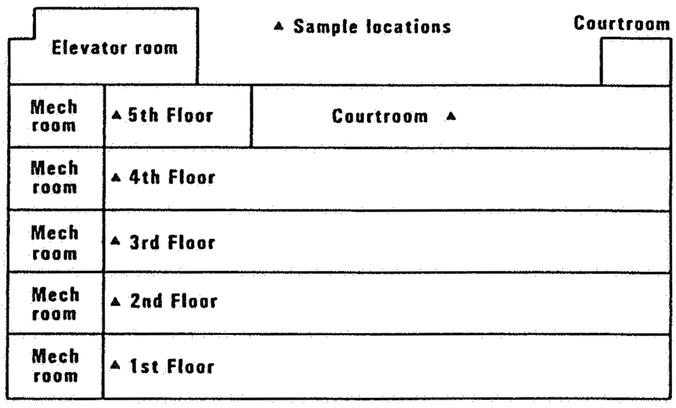
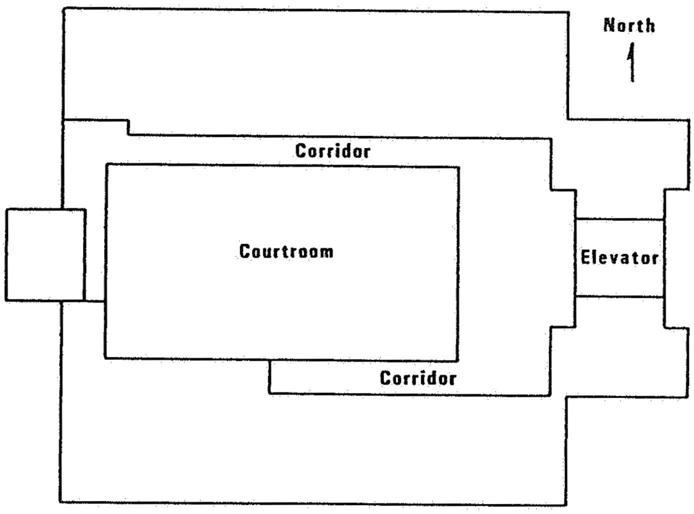


Figure 8. Schematic and Photograph of Federal Building in Ann Arbor, MI

FAYETTEVILLE FEDERAL BUILDING
Schematic of North Elevation



FAYETTEVILLE FEDERAL BUILDING
Schematic of Fifth Floor



FAYETTEVILLE FEDERAL BUILDING
Schematic of First Floor

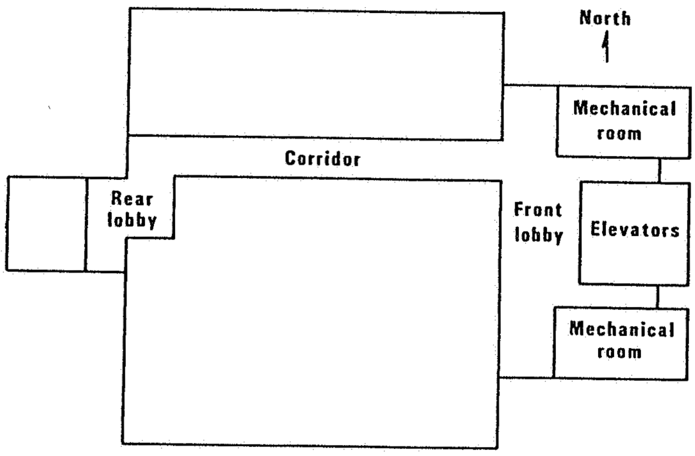


Figure 9. Schematic and Photograph of Federal Building in Fayetteville, AR

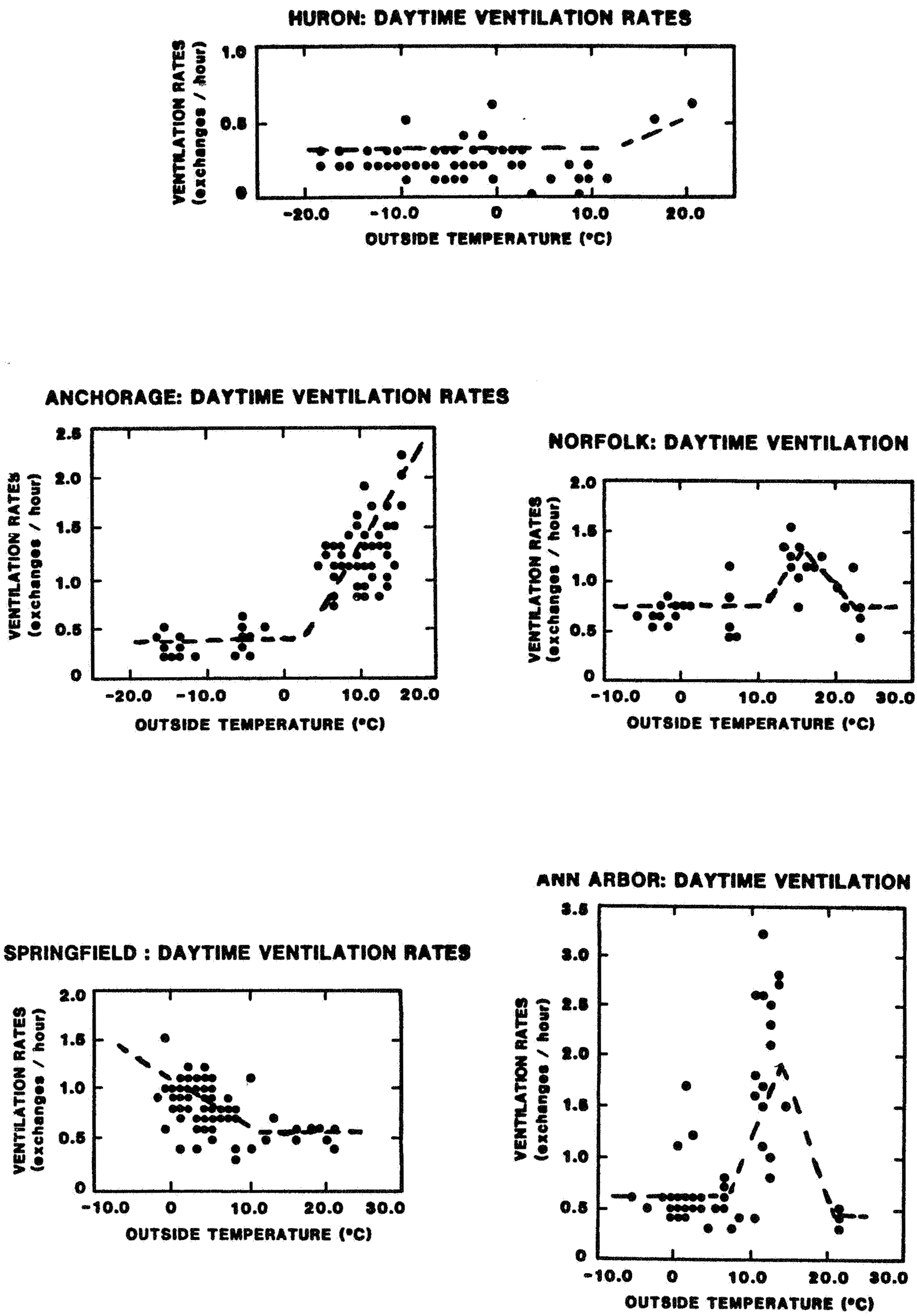


Figure 10. Ventilation Rates Versus Outdoor Temperature for Various Office Buildings

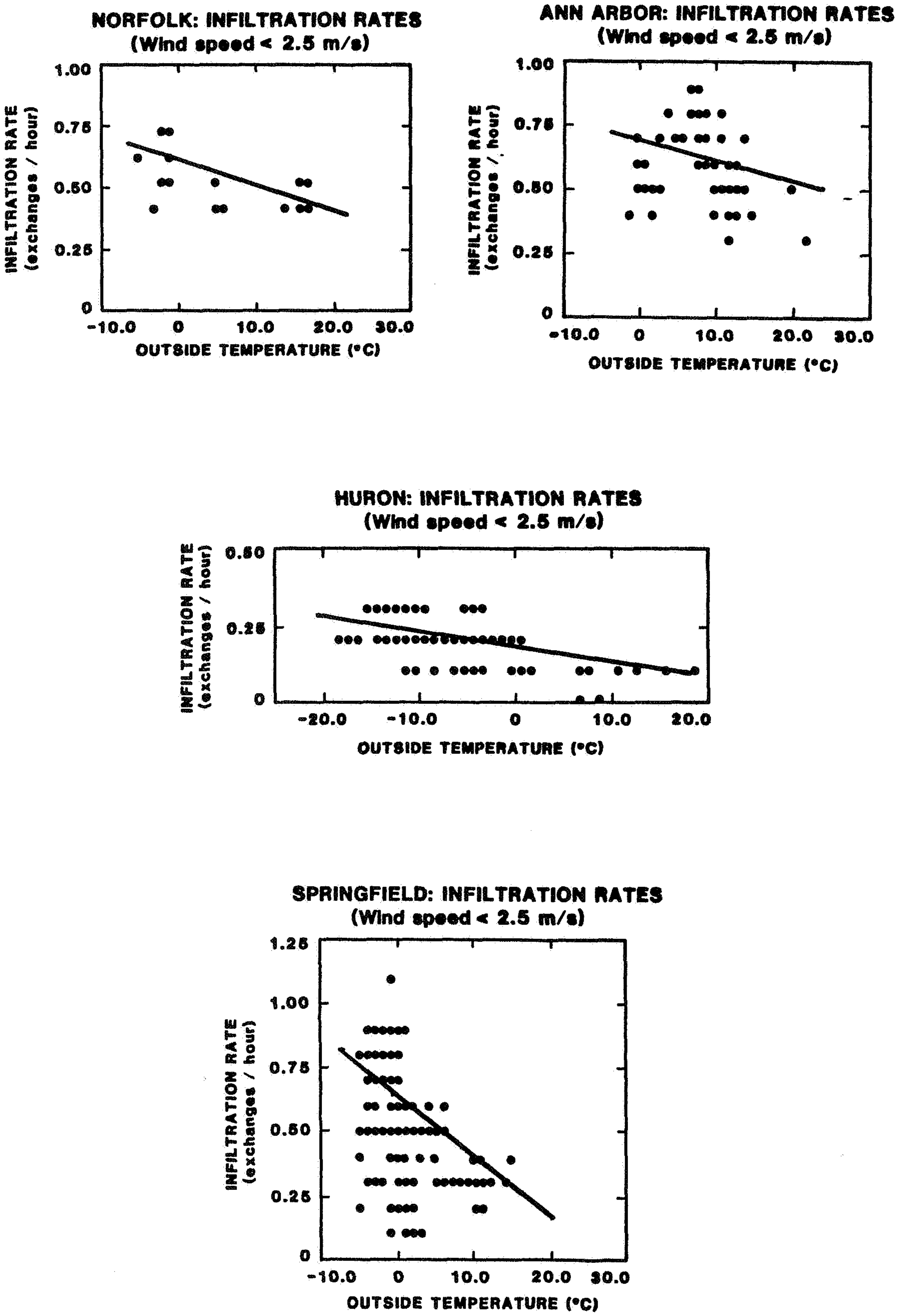


Figure 11. Infiltration Rates Versus Outdoor Temperature for Wind Speed Less Than 2.5 M/S

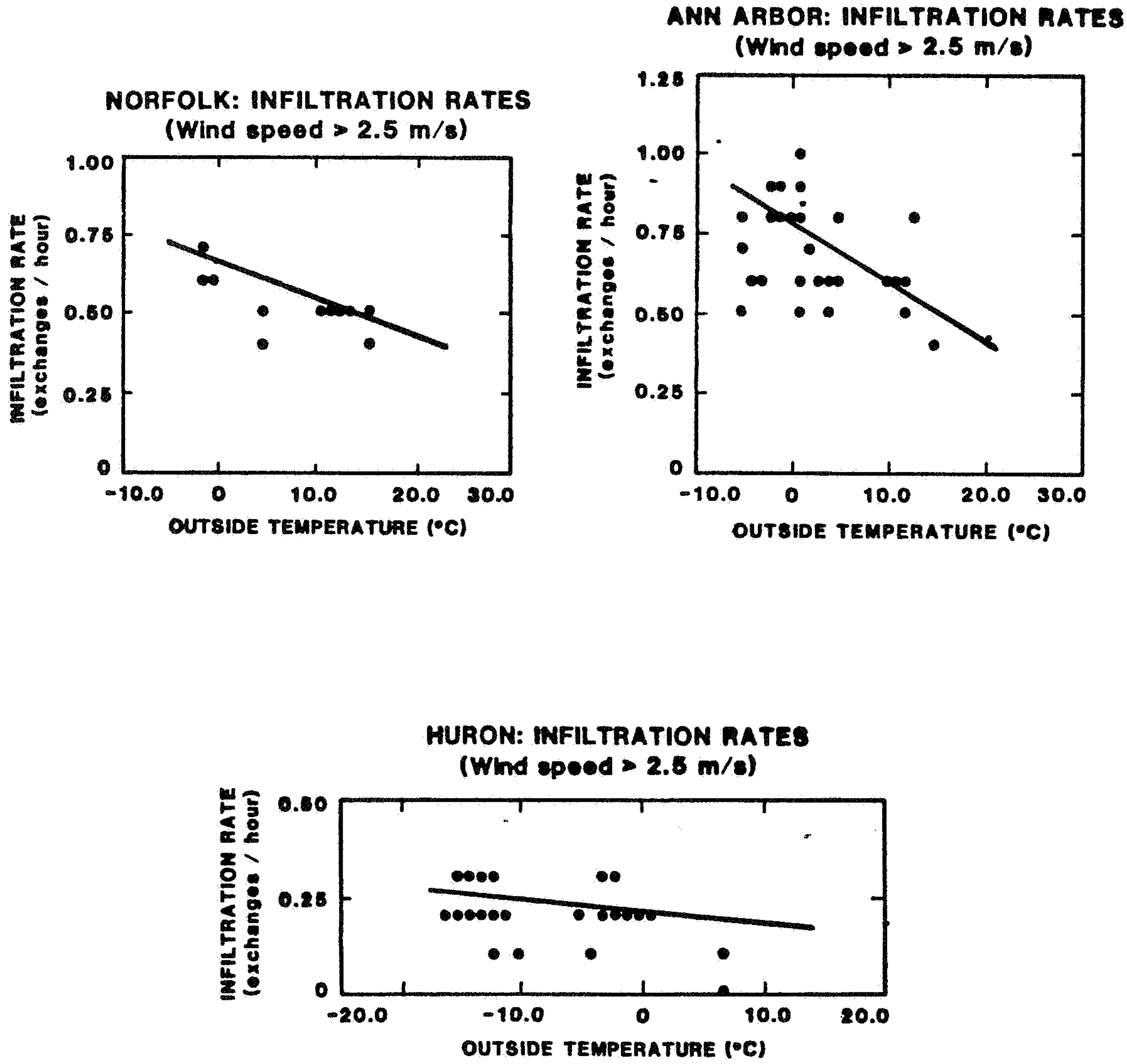


Figure 12. Infiltration Rates Versus Outdoor Temperature for Speed Greater Than 2.5 M/S

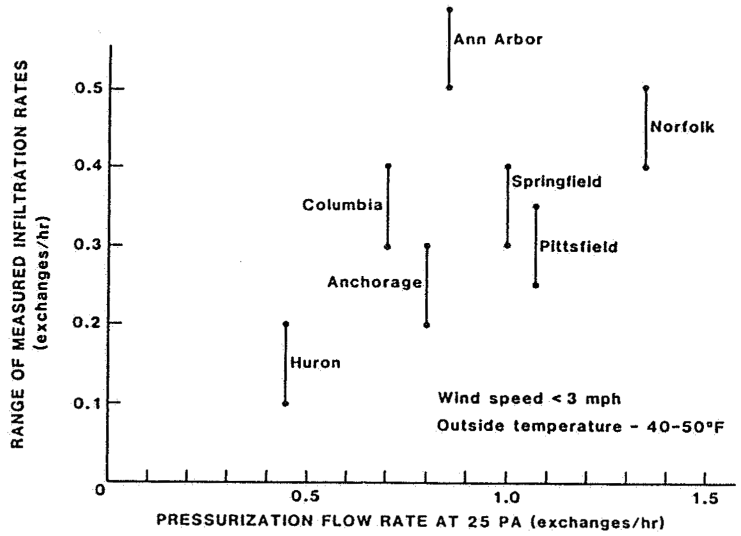


Figure 13. Correlation of Air Infiltration Rates Versus Induced Air Exchange Rates at 25 Pa

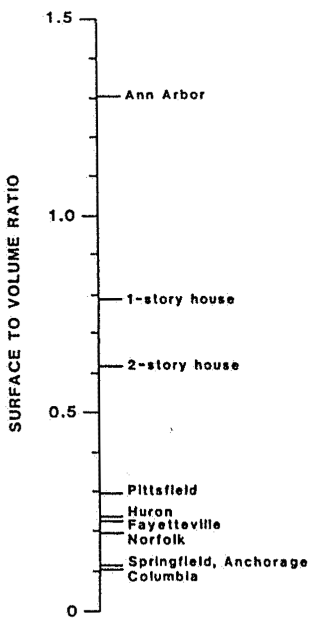


Figure 14.
Distribution of Surface to Volume Ratio Among Federal Offices and Residences

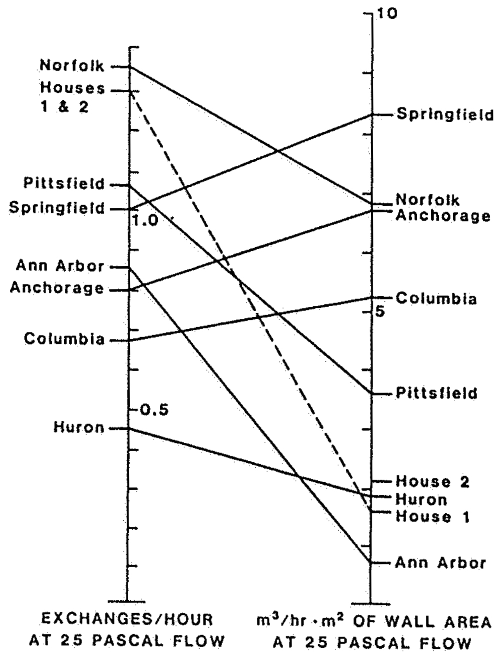
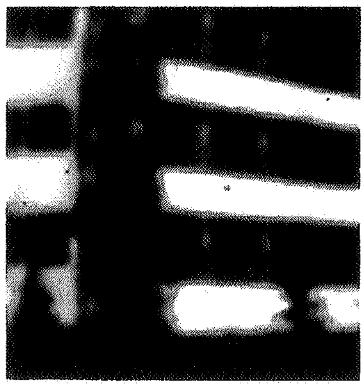
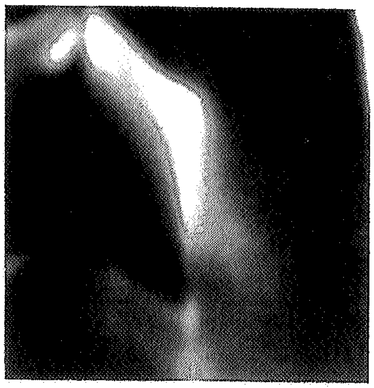


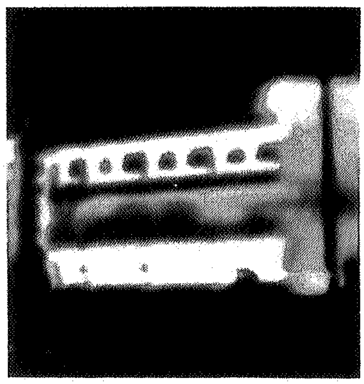
Figure 15.
Pressurization Test Results Comparision of Ranks



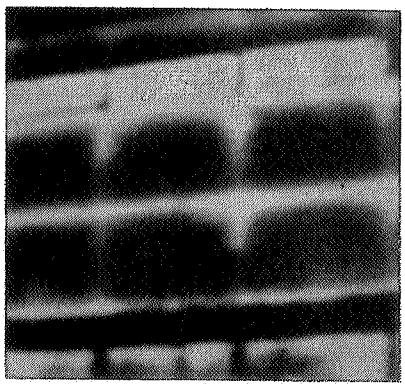
Anchorage - Air Leakage at Corner Columns



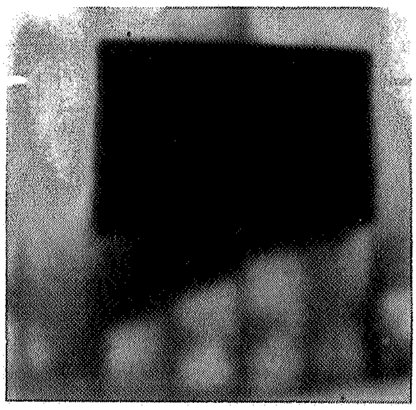
Huron - Air Leakage for Wall-Wall Corner



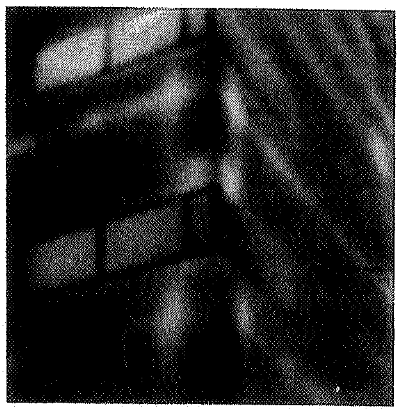
Pittsfield - Air Penetration in Wall



Ann Arbor - Air Penetration at Wall-Floor Joint



Columbia - Interior Air Penetration from Window



Springfield - Air Leakage Corner Column, Wall-Floor Joint and Window Frames

Figure 16. Sample Thermograms Showing Air Leakage Sites in Office Buildings

AIR INFILTRATION REDUCTION IN EXISTING BUILDINGS

4th AIC Conference, September 26-28 1983, Elm, Switzerland

PAPER 12

VENTILATION RATES AND INTERCELL AIRFLOW RATES IN A NATURALLY VENTILATED OFFICE BUILDING

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VENTILATION RATES AND INTERCELL AIRFLOW RATES IN A NATURALLY VENTILATED OFFICE BUILDING

by M D A E S Perera, R R Walker and O D Oglesby

SUMMARY

Ventilation rates and intercell airflow rates in a naturally ventilated office building have been determined using multiple tracer gases. To do this, the building was subdivided into three zones and each zone was then seeded individually with a different tracer gas. The time histories of the concentrations of all gases in each zone were then monitored using non-dispersive infrared gas analysers. The airflow rates were then calculated from the experimental data. A computer programme written in-house to predict the dispersion of a tracer gas in a multi-zoned environment was used to compare the predicted time histories of concentrations with those obtained from experiment.

Department of the Environment

July 1983

PD 125/83

EB208

VENTILATION RATES AND INTERCELL AIRFLOW RATES IN A NATURALLY VENTILATED OFFICE BUILDING

by M D A E S Perera, R R Walker and O D Oglesby

1. INTRODUCTION

In a programme of retrofit measures carried-out by the Property Services Agency to reduce fuel consumption in Government office buildings, it was found[1] that although significant savings were achieved over the programme as a whole, particular difficulty was found in reducing consumption in a number of high energy using buildings. A common feature of these was that occupants judged them to be generally cold and draughty, suggesting excessive ventilation and infiltration.

The following research programme was designed to explore this problem; in particular to,

(a) develop techniques to enable a better understanding of the ventilation of large complex buildings,

(b) identify the movement of air, and hence contaminants or heat, from one zone to another and,

(c) determine the effectiveness of remedial measures or to indicate zones where selected remedial measures will be cost-effective.

The main object of this paper is to give details of a multiple tracer technique which could be used to determine interzone airflows and infiltration rates in complex, multicelled buildings. To illustrate this, results are presented here from one set of measurements carried-out in a naturally ventilated office building.

2. EXPERIMENTAL DETAILS

A conventional two-storey office building (with a volume of 2153 m^3) at the Building Research Station, Garston was used. The building (Fig 1) is rectangular in plan (40 m x 11 m) and each storey is 2.44 m high. A stairwell region located near one end of the building allows access between each storey. For this experiment, the building was nominally divided into three zones; Zones G and F (each with 783 m^3 volume) incorporating the major portion of the ground floor and first floor respectively, and Zone S (587 m^3) encompassing the stairwell and the offices in the southern end of each of these two floors. During the experiment, the building was unoccupied but had its heating turned on to give an internal temperature of about 16°C.

During this particular experiment, the wind was blowing at a mean speed of 2 m/s from the SW. This wind speed at a height of 10 m was monitored at a nearby open site. The outside air temperature at this time was -1°C.

Three existing Leybold-Heraeus analysers, dedicated to measuring either one of SF_6, N_2O or CO_2, were used. For the future, a multicomponent infrared analyser will be used to determine concentration levels of the tracer gases. The tracer gases used in this experiment were determined by these analysers, but in future other gases such as Freons will be used.

The tracer gases were injected manually into each zone until a target concentration was reached. Zone G was seeded with N_2O to a concentration of approximately 200 ppm, Zone F with SF_6 to about 200 ppm and Zone S to 2000 ppm with CO_2. During injection, small desk-top fans were used to provide mixing within each zone. The doors to each office space were kept open throughout the experiment.

Single-point or blended multi-point samples were takes from each zone using equal-length 6 mm diameter polyethylene tubes. A sample line was also placed outside the test building in order to provide reference ambient concentrations of the test gases. All tubes were then brought back to individual solenoid valves which were under the control of an ITT Director microprocessor unit. Using this unit, each sample line was connected in turn to the three analysers and the concentrations of tracers present in each sample were recorded on cassettes. Figure 2 gives a schematic drawing of this system. The data recorded on these cassettes were later transcribed using an off-line computer.

3. THEORY

The theoretical basis for deriving ventilation rates and interzone airflow rates from concentration measurements of multiple tracer gases is given in detail in Reference 2. It is shown that in the 'decay' method, the conservation of tracer gas and of air can be written in the form

$$^{(l)}\{Y\} = [A].^{(l)}\{X\}$$

for any zone l where l=1,2,....,N and N is the number of zones.

The i^{th} and j^{th} elements of the column vectors $\{Y\}$ and $\{X\}$ are given respectively by

$$^{(l)}y_i = V_l \dot{C}_l^{(i)}$$

$$^{(l)}x_j = -S_l\delta_{lj} + Q_{jl}(1-\delta_{lj})$$

where δ_{ij} is the Kronecker delta and the a_{ij} element of the square matrix [A] is given by

$$a_{lj} = C_j^{(i)}$$

Thus, knowing

V_l	volume of zone l
$\dot{C}_l^{(i)}$	time derivative of the concentration of the i tracer in zone l
$C_j^{(i)}$	concentration of tracer i in zone j

the unknown flow quantities,

S_l	total outflow/inflow into zone l
Q_{jl}	flow from zone j to zone l

can be determined for any cell l.

4. RESULTS

Figure 3 shows the N_2O concentration as a function of time in the three zones. Similar results were derived for the other two gases giving in all a total of nine curves. Where appropriate, the outside background concentration levels have been subtracted from the raw data in plotting these results.

In order to determine the values for the interzone airflows, the mathematical procedure described above was used. For each of the nine data plots, a smoothed curve was drawn over a small portion of the experimental points. These smoothed curves were centred at time t=7.5 minutes and were drawn to cover a time range of about 5 minutes. Tangents were drawn at t=7.5 minutes and the gradients determined. Using the values of the gradients and the concentrations at these points, the interzone airflow values were determined. These are shown in Figure 4.a.

It will be noticed that some of the airflows are negative. Since the original definitions of these airflows as derived in Reference 2 preclude any physical meaning for negative interzone airflows, these results indicate that experimental errors, possibly arising from imperfect initial mixing have contributed to these negative values.

To avoid these negative airflow quantities, a method of analysis advocated by Penman and Rashid[3] has been used. Since the airflows are calculated from a set of simultaneous linear equations, the solutions can be constrained in the least-squares sense to have positive values. Using a computer programme given by Lawson and Hanson[4] the constrained solutions have been found and are shown in Figure 4.b.

5. DISCUSSION

To test the validity of these results, a computer programme, utilising the Runge-Kutta-Merson routine from the NAG library[5] was written. Here, knowing the interzone airflow quantities and the initial concentrations, the time histories of tracer concentrations in a multi-zone environment can be predicted.

The positive constrained values for the airflows calculated over the 5 minute period centred at time t=7.5 minutes of the experimental values were used as input to the computer programme. These, together with values of intitial tracer gas concentrations were then used to predict the dispersion of all the tracers in each zone during the 30 minutes period of measurement.

As an example, Figure 3 shows the predicted curves superimposed over the experimental data points obtained for the N_2O tracer. The matching between the experimental values and the predicted curves is seen to be good.

To ensure that no drastic change has occured in constraining the airflows to be positive, predicted curves using the initial solution which included negative values were plotted. These are shown as the full lines in Figure 5. For comparison, the predicted values of Figure 3 (i.e. solutions containing only positive constrained airflows) are drawn as broken lines in Figure 5. The comparison shows that there is only a marginal difference between the two solutions.

With regard to the performance of the building during this present experiment, the following results were obtained.

(a) The total fresh air infiltration rate for the whole building was 0.76 ach.

(b) The fresh air infiltration rate to the first floor zone was only 0.46 ach compared to values of 0.99 and 0.84 ach for the ground floor and stairwell zones respectively.

(c) The dominant route for the zonal interchange of air was from the stairwell to the first floor.

(d) There was negligible direct interchange of air between the ground and first floor zones.

(e) Only 15% of the fresh air entering the ground floor zone took part in any interzone mixing. The remaining 85% of fresh air is dispersed directly back to the outside.

6. CONCLUSIONS

A description has been given here of a multiple tracer gas technique which could be used to determine ventilation rates and air movement in complex, multicelled buildings. As an example of the use of this technique, results have been presented from one set of measurements made in a naturally ventilated office building. Further measurements in a controlled multi cellular test chamber operating under known and set conditions will enable this technique to be fully validated.

ACKNOWLEDGEMENTS

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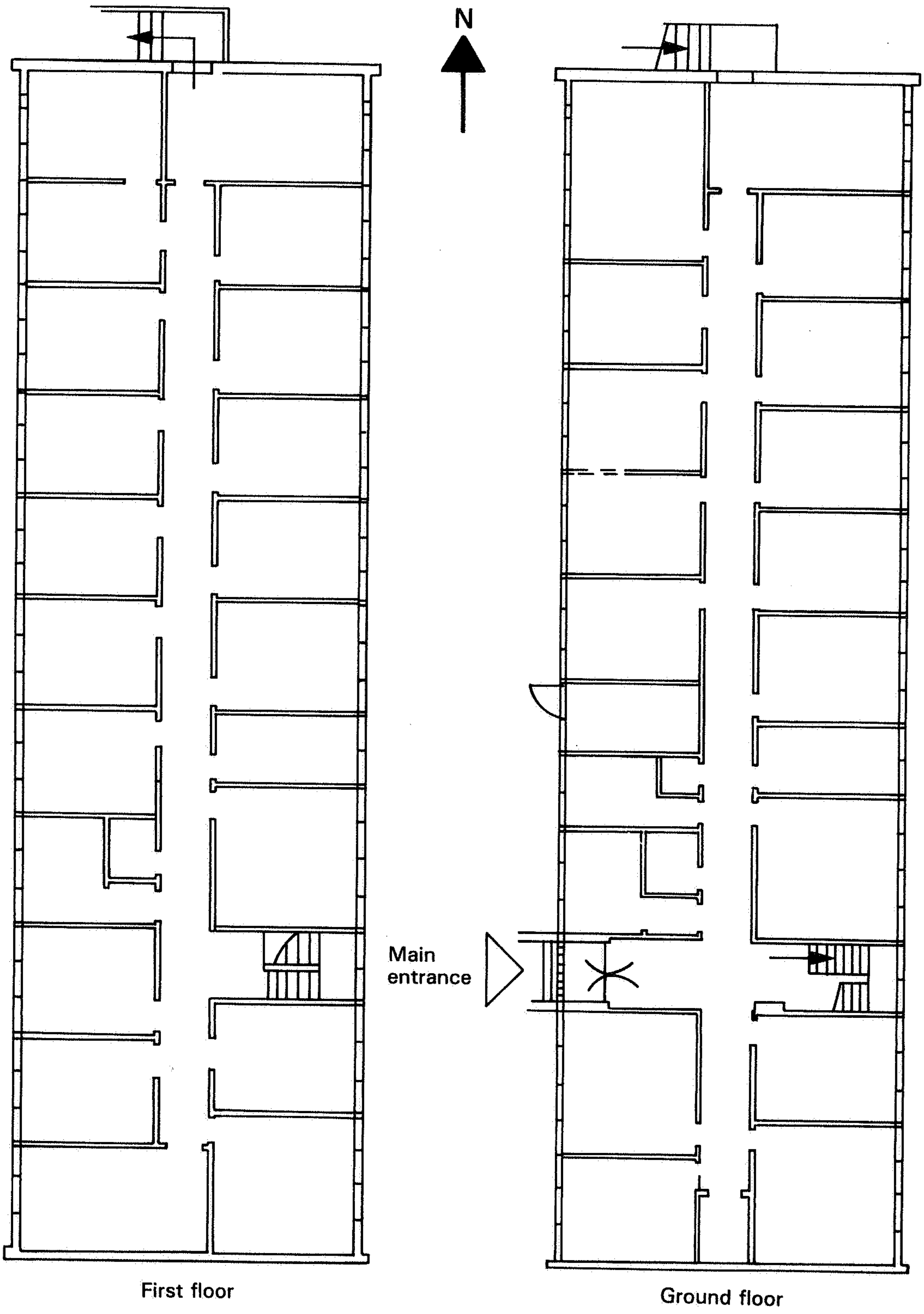

Figure 1 1:200 Plan view of building 10

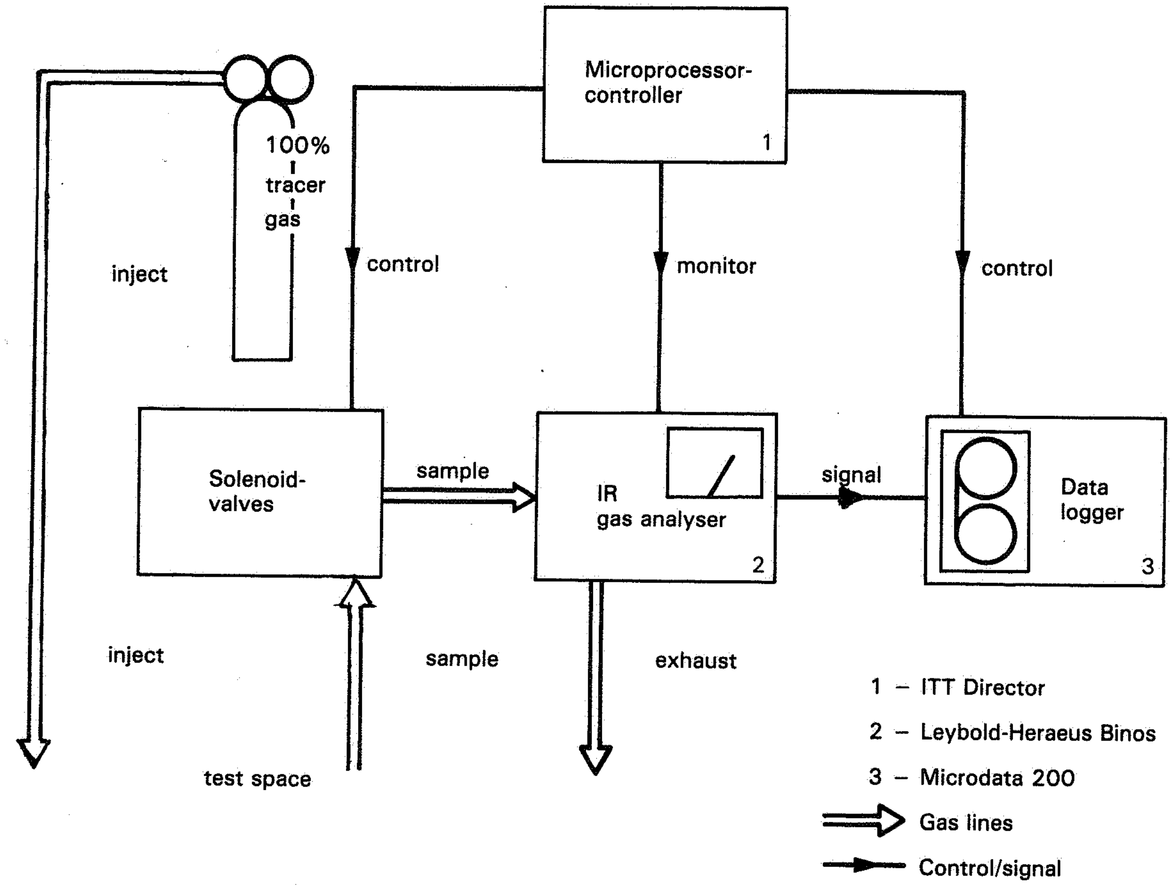

Figure 2 Microprocessor-controlled ventilation rate measuring system (Tracer gas decay)

AIR INFILTRATION REDUCTION IN EXISTING BUILDINGS

4th AIC Conference, September 26-28 1983, Elm, Switzerland

PAPER 13

RETROFIT-PLANNING-TOOLS FOR INSTITUTIONAL AND RESIDENTIAL BUILDINGS WITH USER INFLUENCED AIR INFILTRATION

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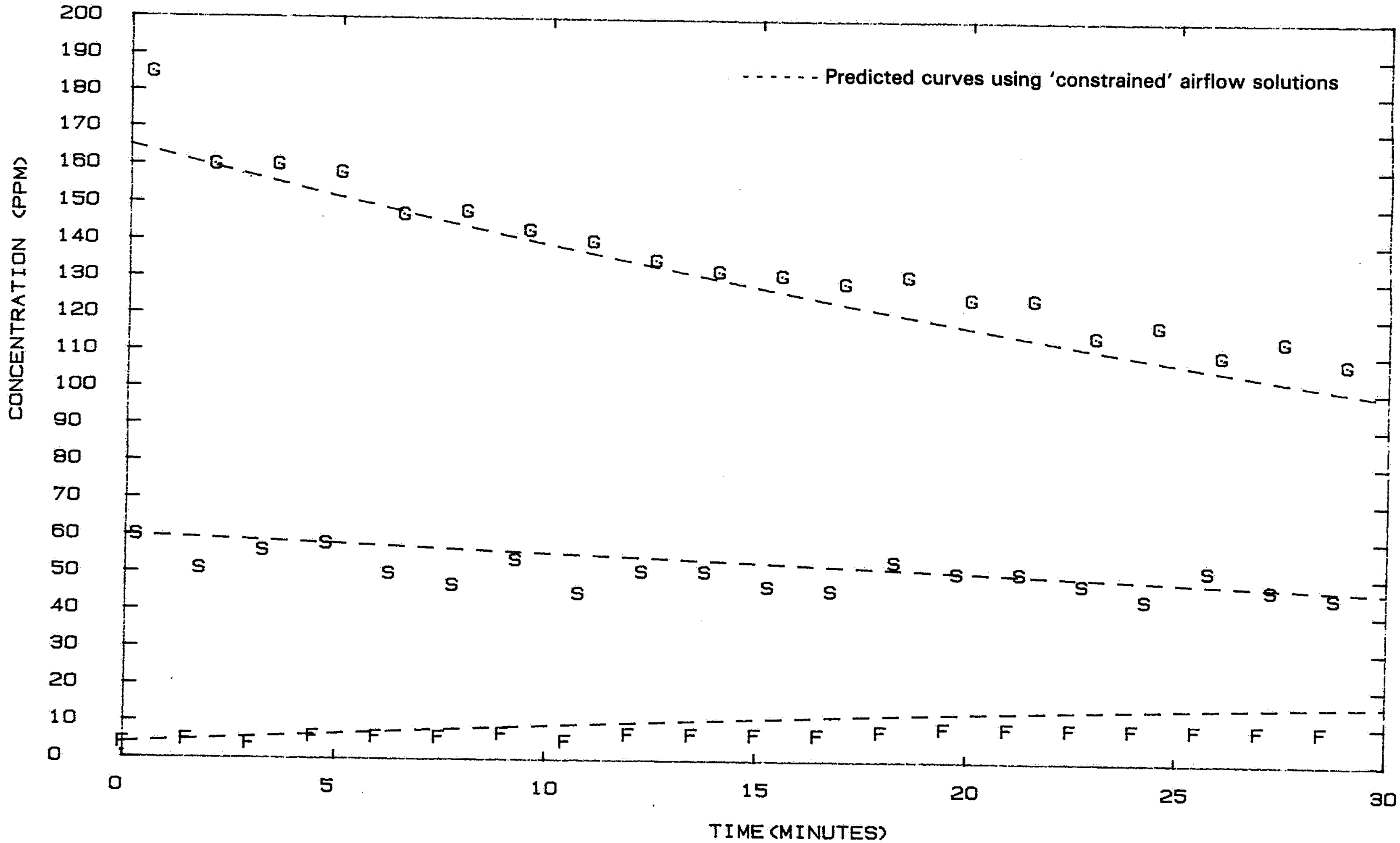
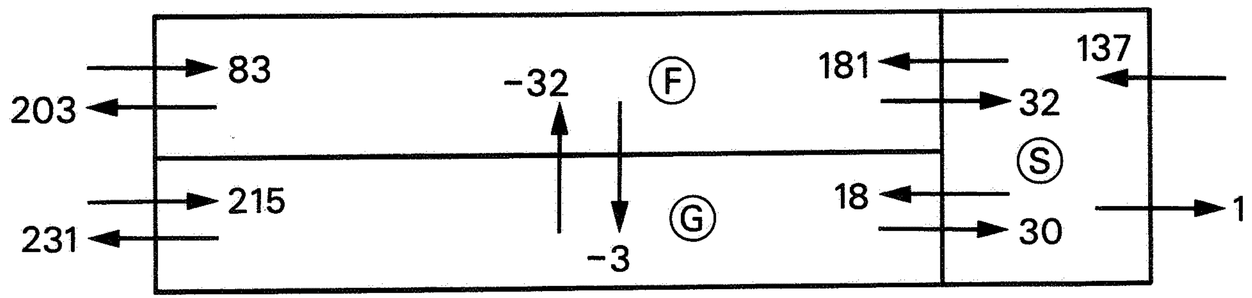
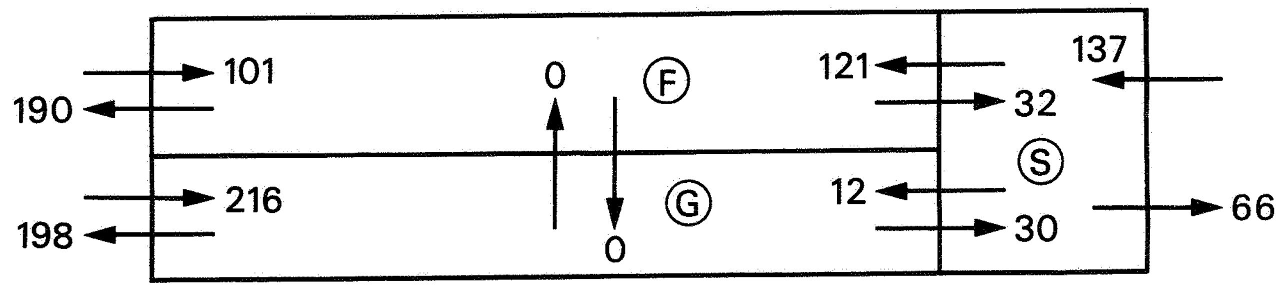


Figure 3 Building 10 – Nitrous oxide concentrations



'Unconstrained' solution



'Constrained' solution

Figure 4 Inter-zone airflows in litres/sec

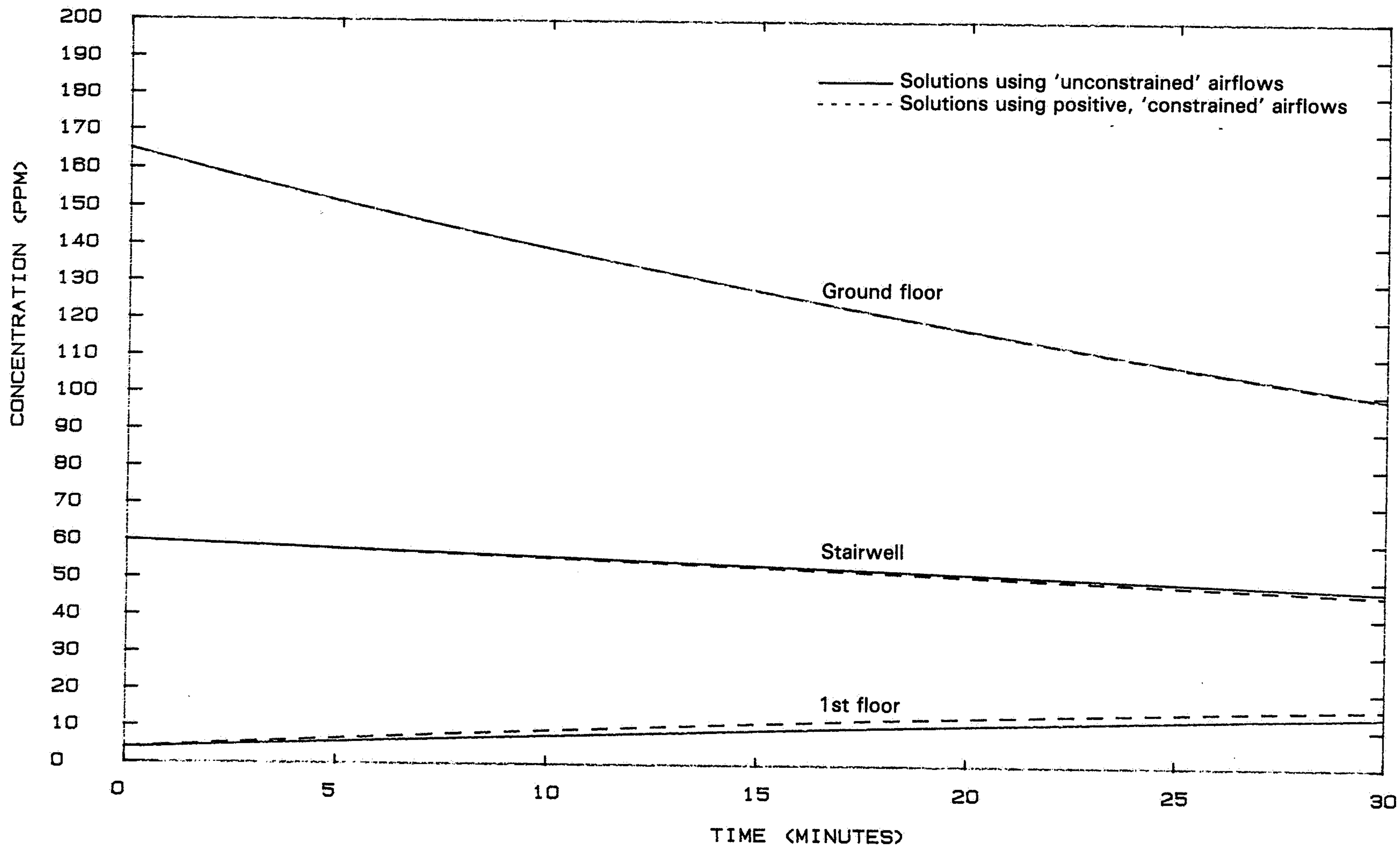


Figure 5 Predicted nitrous oxide concentrations

SYNOPSIS

The authors present a survey on the actual retrofit-planning methods in connection with the air change-situation in houses, how they are used by Swiss energy-consultants. Air exchange happens in Swiss and most other Central European houses by a superposition of infiltration, some single exhaust fans and window openings.
Inspite of refined analysis and planning methods, developed and published by research institutes, the actual planning situation by experts is poor, caused partly by cost effectivness-reasons and by a too small knowledge-transfer.
Main emphasis is given to a presentation of a new grafic method, which delivers values of mean air change rates, but also checks minimum and maximum values. Based on detailed calculation, this method demandes only few construction input data and preferably pressurisation values and window opening data.

1. INTRODUCTION, SCOPE

After discussions with a number of energy consultants, and also following on own experiences in this field we felt the existence of an uncertainity in connection with questions of air exchange in buildings. An example may explain this situation: an energy consultant may have some doubts about the thermal conductivity of some wall layers. But nervertheless he will be able to calculate the k-value of the wall within a precision of about ± 10 ÷ 20 %. Estimation on infiltration rates may - without additional measurement - well be within ± 50 ÷ 100 % of the true value.
There exists a worldwide activity on audit techniques for infiltration, on calculation methods about air exchange. But there is a poor knowledge transfer to the practicing consultants. As background for a better understanding a few highlights on typical Swiss (Central European) conditions in the institutional and residential sector are to be mentioned:

- large variety of constructions (especially in tightness)
- large stock of buildings to be retrofitted, small quantity of new units per year,
- climate and air pollution situation not demanding a mechanical ventilation in most cases,
- old habit of "window opening".

Many publications in foreign journals, as the AICHandbook [1], as Gertis [2] and others demonstrate the advantages of a controlled ventilation, preferably with heat recovery. Other authors as Blaich and Sell [3], Haltiner [4], Wegner [5] warn against the danger of an uncontrolled air exchange situation, which may cause humidity problems, odour - or poisoning problems. All these papers may well demonstrate the general situation or some special aspects. What the energy consultants really need is a cost effective auditing and planning method, taking into account these warnings, and which is applicable for the existing building stock. We think, that critical papers of Harryson [6] and of Krüger/Hausladen [7] show necessary steps to get these tools.

It is the scope of this paper, to display and critizise existing planning tools for the determination of the air exchange in houses, to explain new grafical tools, which are in a draft state and to show the necessity of reasonable building codes.

2. ACTUAL PLANNING TOOLS; USED BY SWISS CONSULTANTS

2.1 Problems of understanding

There are different reasons, e.g. an insufficient education in building physics, which cause difficulties in understanding infiltration phenomena. On the other hand these phenomena are more complex as others. Some of these problems are demonstrated:

- Air exchange in our houses occures not only due to a single action, as
  - natural infiltration (open and closed windows)
  - ventilation through shafts
  - mechanical ventilation,

  but due to their superposition. It is a pitty that many authors of papers do not point out the system, which they are describing.
- Similar complaints concern also publications and handbooks, which do not properly distinguish between
  - infiltration rates, valid for design conditions of the heating system,
  - mean infiltration with closed window conditions through a certain period,
  - mean infiltration in an occupied house through a certain period,
  - extreme infiltration, caused by special climate or user-conditions.

According the problem a specific date set is necessary.

A third mistake has to be mentioned:
Infiltration discussions or - calculations are too often based only on window and door gaps. We think, that after the TN 1 of AIC or after similar Swiss test results [8] it should be recognized, how important it is to judge on facade-leakage rates. Corresponding data are missing for most Swiss building types and also depending on aging or drying conditions. Some studies are made, which are listed below:

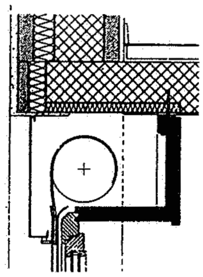
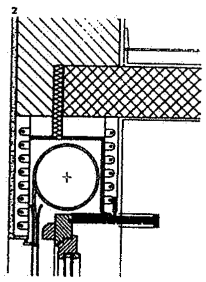
- Infiltration an leakage measurements of selected Swiss multifamily buildings including different construction types by Haerter and Steinemann, together with EMPA [9];
- A research project on the control of ventilation in Swiss timber construction buildings by Sell and Michel (EMPA, section Holz, Dübendorf)
- A report on the leakage of typical Swiss roller-blind-constructions and the corresponding handler (report EMPA Nr. 45160, 1982), (see fig. 1)
- A complementary work to the first project for additional types of buildings (through EMPA, H. Mühlebach/P. Hartmann and subcontractors).

Actual planning tools "air-change in residential buildings" (mean air changes)

Method	Advantage	Disadvantage	Possible errors	Practicability to judge retrofit errors
A "Estimation by observation" (of components)	quick, cheap, no tests	big errors, especially for consultants without any experience in testing of leakage		no
B Calculation of ventilation (losses) within energy balance	energy budget fits with this air changevalue	errors in a range of factor 2 well possible because of uncertainities in other parameters; errors smaller through combination with A		yes, in principle; problem of user reaction to changes
C Calculation of ventilation as sum of different effects (e.g. window doors ....)	well applicable to buildings with mainly mechanical ventilation	similar errors as method A, but higher effort to calculate	errors in range of factor 3 for tighter houses, factor 2 for leakly ones	yes, in principle, but dangerous to believe in these "calculated values"; user effects?
D Direct grafical determination of the air change, including a standard user influence	quick; experience of many research projects can be included in this tables	result should be cross-checked, to reach much higher accuracy as A÷C	factor 1.5 (÷2)	yes, generally

Fig.1 "Calculation values" for air leakage of roller blinds and handles

a) Leakage of the cage

Type of cage		sealing/tightness	leakage a [$m^3/h \cdot m \cdot Pa^{2/3}$]
inside of wall vertical service cover		good sealing no special sealing	0.015 0.10
integra-grated in wall/ ceiling; horizontal service-cover		good sealing no special sealing	0.03 0.15

b) Leakage of handle

Type	design / workmenship	Leakage [$m^3/h \cdot Pa^{2/3}$]
strap	- rather tight - rather leaky	0.08 0.02
handle	- tight plastic - enclosure for penetrating axle - metallic enclosure arround axle	0.045 0.19

2. TARGETS FOR RETROFITING OF BUILDINGS

In most cases retrofit actions at our buildings are combinating energy conservation measures with maintenance. Building codes or energy consultants set energy targets, building owners set financial targets or limits. Energy consultants, at least for residential buildings, rarely set air-change targets. Target values, as those of the Swedish Standard (cited in [10], pp 283) or in the new ASHRAE-Standard [11] slowly get introduced.
This unsifficient situation is not based on the lazyness of these consultants, but on the economical constraint. Building owners are not willing to pay more than about 500 - 1000 Swiss francs for a retrofit plan of a single family house or maybe a few thousand francs for a multifamily house. Therefore energy consultants are restricted to observations and empirical rules, which they cannot check. Only few experts are using any measurement equipment.

2.3 Measurement tools, actually used by consultants

(The following comments use the same structure as the corresponding table A 11.1 in [1])

There is no standard test procedure for checking existing buildings, which would be used nationwide. Only about half a dozen of Swiss experts posses more refined measurement tools.

Air change date would interest (condensation, energy, hygienic problems), especially long term tests. It may be, that cheaper systems with lower precision, which are under first tests, will promote these tests later. - Few consultants use pressurisation-equipments; but there is a big lack of target-values for this interesting reproducable procedure. - Some others use infrared cameras for a qualitative demonstration of ecessive infiltration. Inspite of these attempts most consultants use only the "observation method", paper-sheet-tests for windows or the smoke-pouncil-method for qualitative descriptions.
Exellent equipment and methods as presented e.g. by Lundin[12], Shaw [13] cannot be afforded.

2.4 Planning tools used by consultatns

A following table shows and judges existing planning tools. All 4 methods are quick and do not demand extensive measurements and observation. As consequence they may include errors in the range of a factor 2 to 3, as long as there is not a certain cross-check possibility.
It seems necessary to include some measurements for a more valide description of an actual exchange situation in a building and especially for any planning of retrofit - measures.

Fig. 2 Direct estimation method for mean air change rates, including "Standard users"

	Mean air change* $[h^{-1}]$ (during heating season including standard user influence)				
	single family house roof top apartment corner house of row	building shell tightness (window, wall, roof)		multi family house center house of row-houses	
Wind-class	Exposure	rather tight	rather leaky	Exposure	Wind-class
I or II		0.5	0.65	rather protected	I or II
	rather protected	0.6	0.8		
		0.65	0.8	exposed	
	exposed	0.8	1.0		
III or IV		0.65	0.8	rather protected	III or IV
	rather protected	0.8	1.0		
		0.8	1.1	exposed	
	exposed	1.0	1.4		

* Necessary multiplication factors for above values:

- rooms with shafts or open chimneys
  1.1 ÷ 1.4
  (leaky rooms) (tight rooms)
- open high rooms with a rather leaky roof : 1.3

One example may explain this situation:
a rule of thumb says, that the factor
n_B / n_o = air-change, occupied / air change, closed windows is about 2 ÷ 4. For a large residential block in a windy situation we checked this rule and got a factor of about 1.2 · 1.3. This happend, because of a very resticitve heating set-point and the fact, that it seems dangerous to leave windows open during any absence because of wind and rain-damages.

3. OTHER, NEW TOOLS

3.1 New methods and their practicability

Energy consultants need, as mentionned before, better tools, which

1) start with a reasonable detection of the air exchange conditions of a building,
2) set reasonable ventilation targets (mean, minimum, maximum values),
3) show different concepts to reach such targets,
4) and finally present tools to control the results of such retrofit actions.

These tools have to fulfill different conditions to be applicable for Swiss conditions:
Measurement methods have to be as simple and quick as possible, with well reproductible results;
By the fact, there is an interest to conserve energy in connection with ventilation without installing mechanical ventilation in all houses, such recomondations/laws would be more complicated as e.g. Swedish standards.
Pressurisation tests seem to be much more practical than tracer-gas tests for audit purposes. Target values considering wind class, exposure, use, building height and other parameters are missing up to now. Cheaper air change measurements sets may interest nevertheless.
Calculation methods for air change rates are available for consultants. Nevertheless we think, that grafical methods benefit of it's visualisation capacity; calculation models are exellent tools for research purposes.
Two concepts to control ventilation-rates in residential and institutional buildings made progress:

- The possibilities to controll ventilation by the occupants will be more efficient, if sensors indicate the necessity of additional air change (humidity -sensors, CO_2-sensors). - A recent report by Voss [16] gives a good background on the user behaviour; Steinert and Draeger [17] investigated the limits of humidity to prevent surface-condensation in corners, depending on the wall construction.

- If there should be higher safety in connection with the prevention of condensation and hygienic problems some type of additional mechanical ventilation is necessary also in cases of retrofitting.

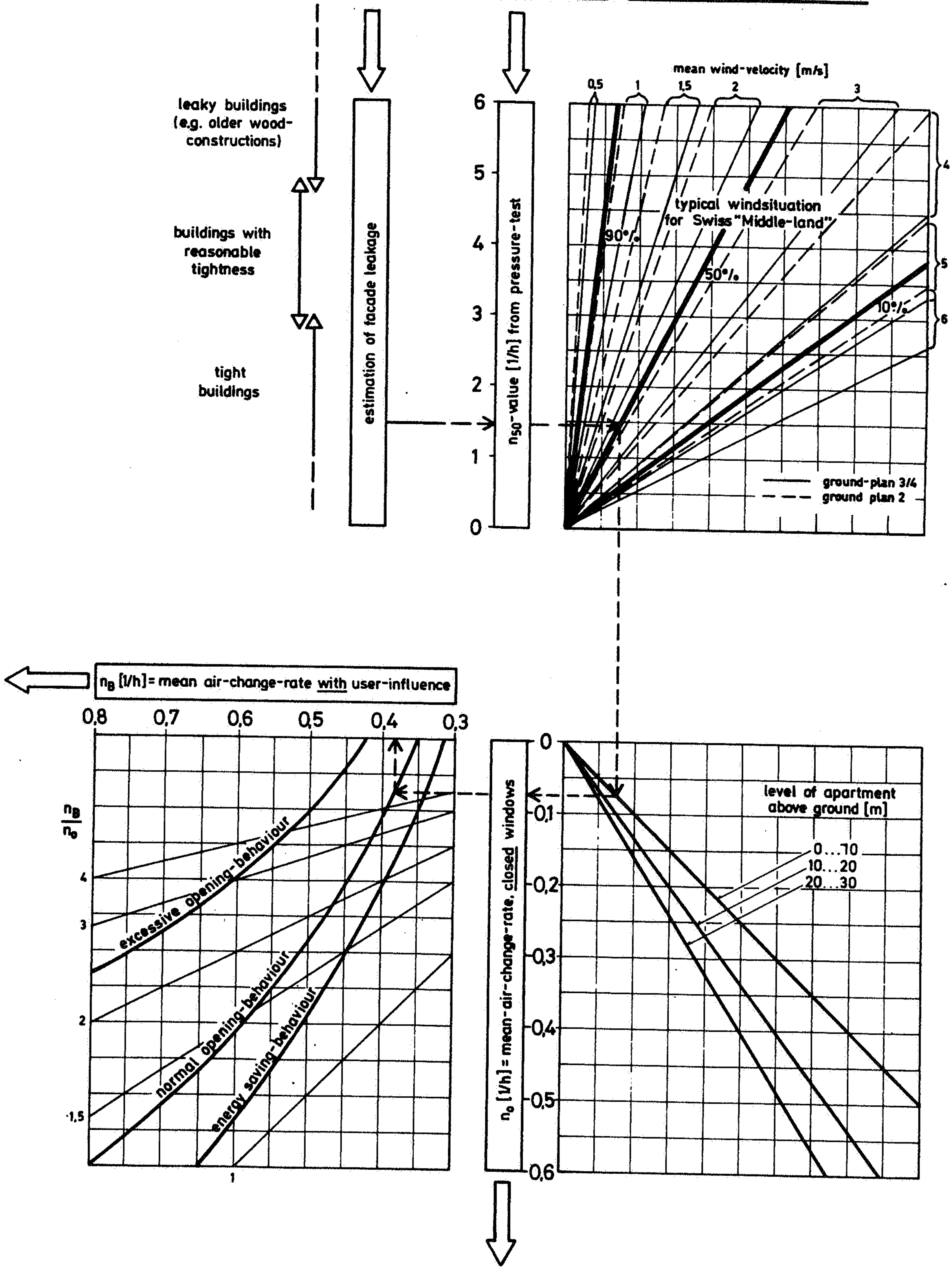
3.3 Grafical method to judge the air-exchange in residential builidings

The following tables are based on a calculation model, developped by Haerter, Steinemann [18]). Necessary input data for wind conditions have been developped by T. Baumgartner in connection with the Swiss design standard for heating plants. User factors, which are introduced into the calculation of the mean "occupied" air-changes, have their origine in Voss' report [16] and many observations of EMPA researchers [15].

The scope of this table, which is yet in draft form for one wind zone in fig.3, lies in the determination of the mean air change-rate. Depending on the reliability of the input data (building-shell leakage, user behaviour, exposure of a building within a wind zone) the result will have its accuracy.
Besides a mean air change, which is needed for the calculation of the mean winter energy losses, the table allows to check minimum wind conditions (condensation, maybe air contamination problems e.g. by formaldehyd) and maximum wind conditions (comfort problems).
As "extreme" conditions we have chosen the wind speeds, which is no more reached during 10 % of time, respectively which is exeeded during 10 % of time.

Fig. 3

Grafical estimation of mean air-change-rates in residential buildings (including extreme values)



Comments to figure 3 and 3a

- Symbols: n_{50} $[h^{-1}]$ = air-change $[h^{-1}]$ for a pressure difference of 50 Pa

  a_F = leakage of windows per meter of gap, calculated for 1 Pa $[m^3/h \cdot m \cdot Pa^{2/3}]$

  a_{RK} = leakage of roller-blind-cage per meter of cage width $[m^3/h \cdot m \cdot Pa^{2/3}]$

  ω = specific gap length for a window $[m/m^2$ of area$]$

  = $\ell \cdot A_F$; frequent value: 4 m/m^2

  ℓ = gap-length for a window [m]

  A_F = window area $[m^2]$

- Definitions

  ground plan 2: unit/dwelling with windows in (-- linie) 2 facades

  ground plan 3/4: (—— line) unit/dwelling with windows in 3 or 4 facades

  90 % line : for a certain wind zone this wind speed is not reached during 10 % of time; proposed value to check "minimum wind situation" with closed windows.

  10 % line : for a certain wind zone this wind speed is exeeded during 10 % of time; proposed value to check comfort conditions (drafts).

  User opening behaviour lines: these lines follow observations and recent experiments;

Limitations

- Extraordinary exposures of buildings should be taken into account by some extrapolation in the 2nd quadrant or by a change of wind class.
- All tables are designed for buildings with primarly natural air infiltration. For buildings with primarly mechanical systems these tables are not applicable.
  In cases with a small additional ventilator (e.g. in an internal toilet), this fan delivers a minimum air change in "closed conditions".
- Open chimneys and shafts may increase the air exchange remarkably. It is difficult to estimate this effects on existing Swiss experiments; corresponding experiments are made now.
  Extrem draft effects are not taken into account.

Fig.3a Estimation for buildings with primarly window infiltration (variation of fig. 3)

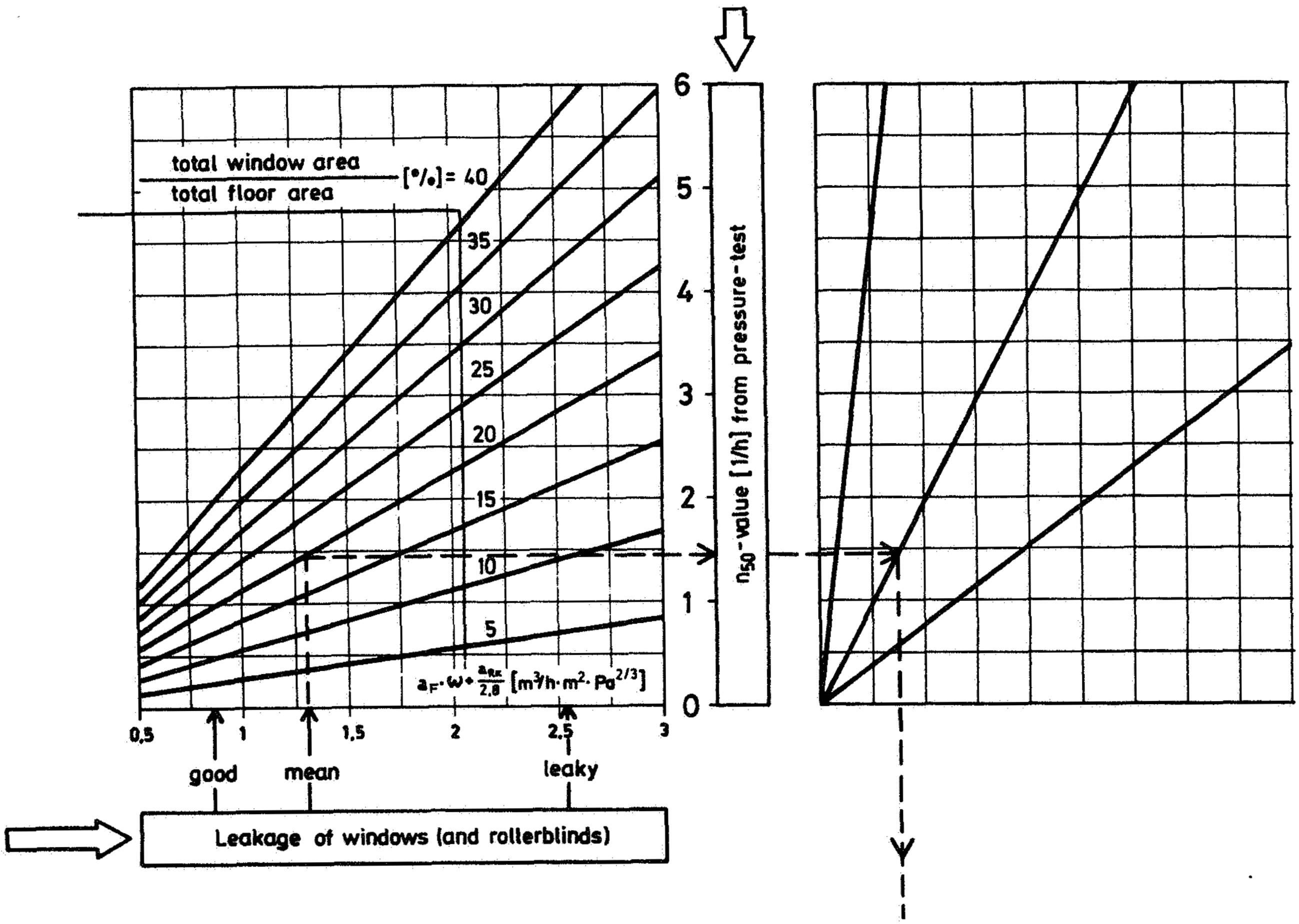


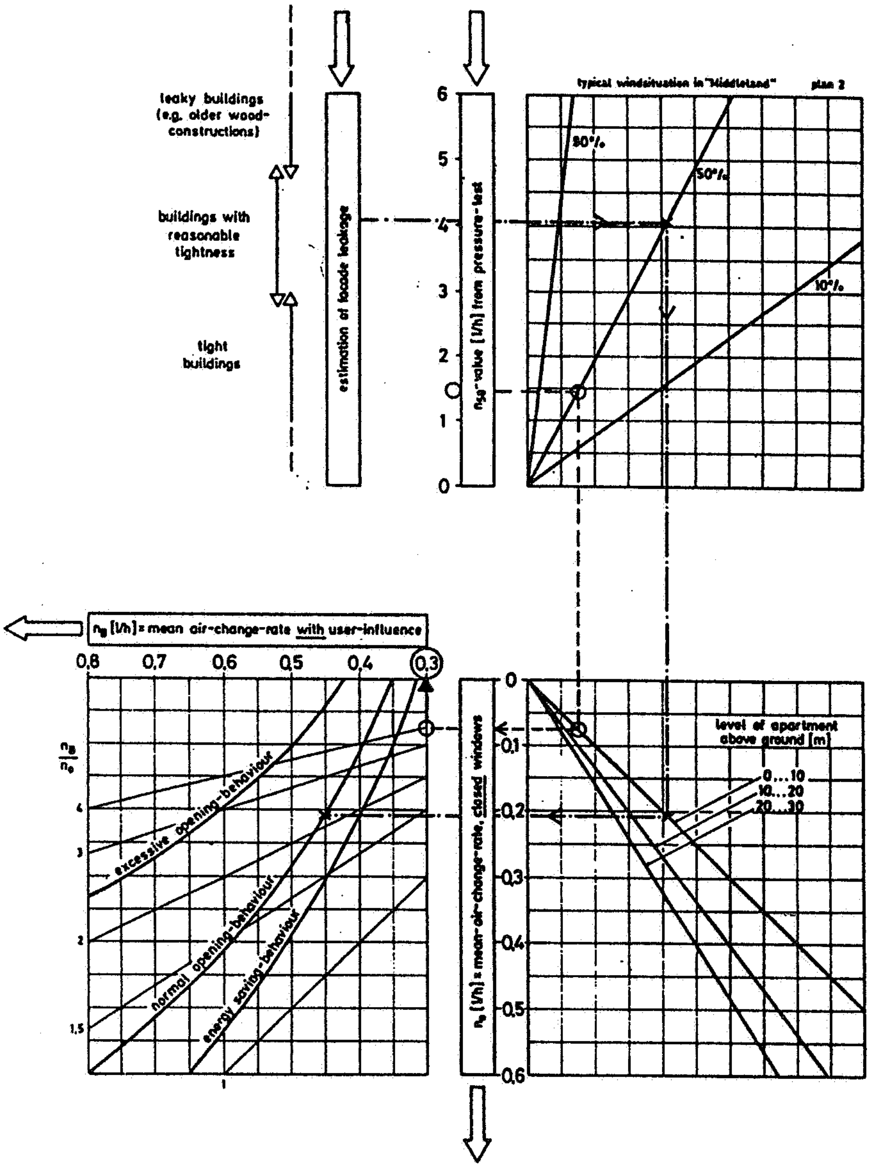
Figure 3a is adjusted to the situation, where infiltration primarly happens through windows, doors and maybe roller blind cages. The upper left corner of the figure 4 is replaced through a diagram, whereby window and roller-blind lekage data, the ratio of window area and floor area lead to an overall leakage.
Finally we explain the procedure of this estimation of air change for two examples in figure 4 :

Example 1 (x) without measured input data :

A consultant would like to estimate an actual air exchange rate, based on a short observation of a single-family-house (timber construction, no special complains about drafts). His estimation of leakage leads to the line of mean wind speed in the 2nd quadrant (middle land, normal exposure of the building).

The 10 m - line in the 3rd quadrant delivers a mean air change rate for closed conditions of 0.21 h^{-1}. The absence of indications on the user behaviour gives a vague indication of a real air change between 0.4 and 0.62 h^{-1} with a good probability for about 0.45 - 0.5 h^{-1}. A check of the "extreme lines" shows, that for low wind conditions and absence of the inhabitants there maybe an air change of only about 0.05 h^{-1}, in strong situations of > 0.5 h^{-1} (with preferably closed windows).

Fig. 4   2 Examples of air-change estimation



Example 2 (●)

In a second case this expert gets the possibility to measure the real building-leakage and the user-behaviour. Introducing these two values

- $n_{50} = 1,4\ h^{-1}$
- rare window openings

he is able to estimate the infiltration rates much closer.

4. CONCLUSIONS

As a consequence of the insufficient level of knowledge and an insufficient use of planning tools to reach air-change targets in retrofited buildings different actions are necessary:

- The establishment of audit-/measurement standards for air exchange (planned by Schindler-Haerter and EMPA as draft proposals)
- Additional research projects as experimental studies on the behaviour of advanced ventilation concepts for different building types, e.g.
  - for residential buildings
    - user controlled ventilation (with indicators)
    - user controlled ventilation with "add-on" mechanical systems
    - mechanical systems with heat recovery
  - for school buildings
    - user (teacher) controlled systems
    - mechanical systems with heat recovery
  - for office buildings
    - simple mechanical systems
      (research project ongoing by Sulzer, Winterthur)
- An establishment of target values for air exchange, which should be transformed to easy controllable values, e.g. leakage rates at 50 Pa or preferably lower pressures.

Fig. 5 gives details, how existing knowledge, combined with additional results from ongoing research could lead to target values and additional proposals for the application of certain ventilation control methods.

Figure 3 shows these possibilities graphically:
e.g. if there is a target value of 0.25 air changes in a small residential building (closed windows), this would be guaranteed by a building shell with a n_{50}-value of 5 h^{-1}. In this house there will happen minimum air changes of 0.05 h^{-1} and maximum values in the range of 1 h^{-1}. Depending on comfort demands, this situation may be unsatisfying.

It may be interesting to see, how important it is, to control certain target values in the buildings. Etheridge [17] shows the influence of workmenship in the leakage of nominally identical houses; some own tests on windows [8] show yet a wider spread of their leakage.
Coming target values should therefore be given with upper and lower limits of deviation; corresponding rules should fix the method and period of control (important e.g. for timber constructions).
These explanations show, that energy conservation efforts in connection with air change are not yet systematic. Many experiments demonstrate that not only constructional changes, but also other means as individual heat metering or a tight heating regime will promote these effects.

Figure 5 : Concept of building regulations to achieve controlled ventilation

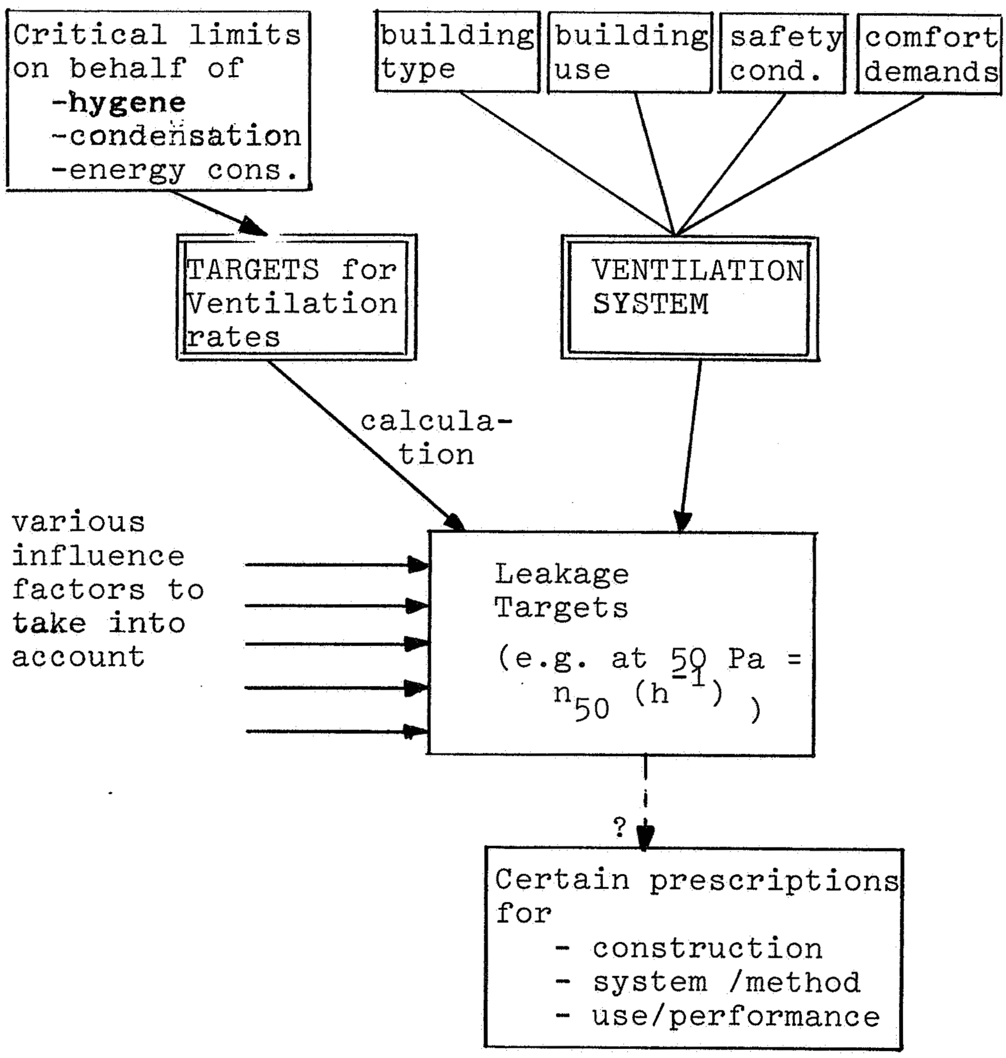
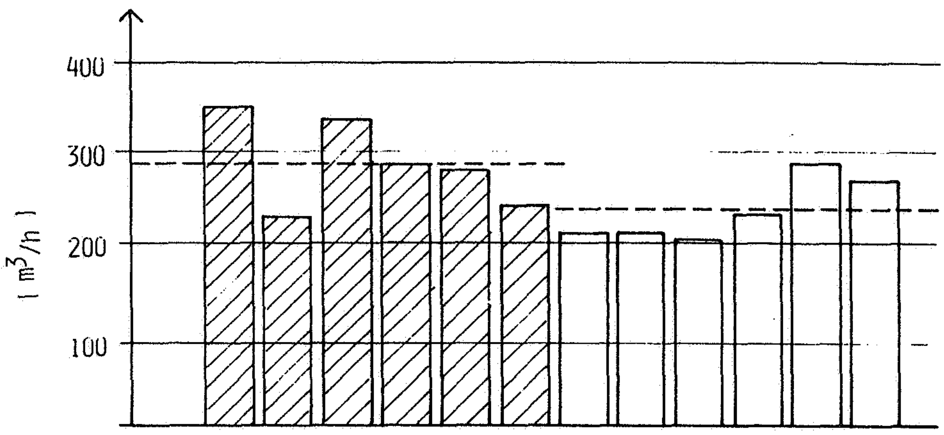


Figure 6 Dispersion of leakage for identical constructions

a) Leakage of nominally identical dwellings, 6 of them unoccupied (cited from Etheridge [18])



Occupied dwellings

n_{50} = 289 m³/h

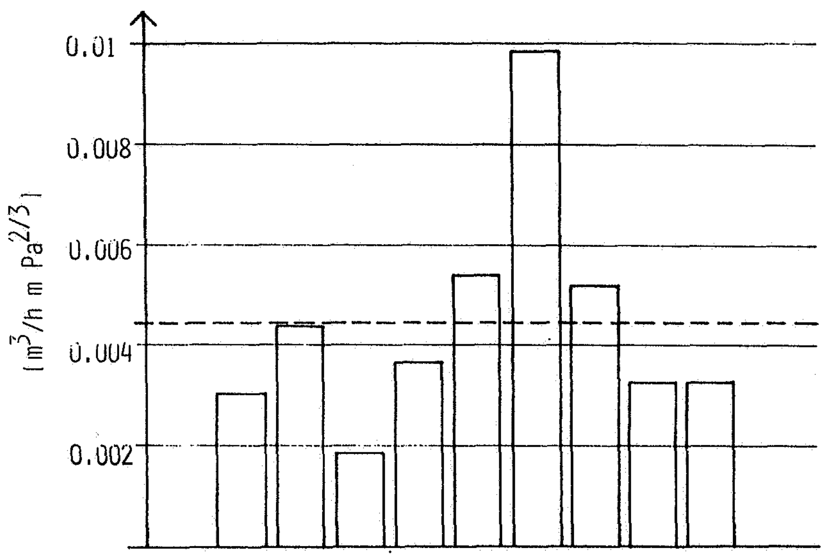
σ = 43.6 m³/h ≙ 15 %

unoccupied dwellings

n_{50} = 240 m³/h

σ = 31.5 m³/h ≙ 13 %

b) Leakage of windows with identical construction, but different size (see 8)



$\bar{a}$ = 0.045 m³/h·m·Pa²³

σ = 0.023 m³/h·m·Pa²³ ≙ 51 %

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Attachment 1

OBSERVERFORM "WINDOW OPENINGS" in Residential Buildings

1 RULES / ADVICES

- Control - Time (day/week) to chose ....
- "Weighting factors" for windows

closed	0	point
small opening	10	points
rather open	20	points
wide open	50	points

- To chose 100 windows; to seperate out first all closed windows to treat than all openings.

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2 GENERAL DATA

- Location of building:
- Observed wall(s):
- Floors of observed windows:
- Heating system, type ...
- Control of set point of heating by:.....
- Thermostatic valves for radiators yes/no ?

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3 ACTUAL OBSERVATIONS

3.1 Time / day of week:

3.2 Weather:

- Wind : leafs quiet // little moving // branches moved // strong wind // storm
- Air temperature outside: .... °C
- Sun (before / now):
- Indications on room temperatures inside
  living room ... °C / sleeping room ... °C

3.3 Frequently open windows (certain rooms ?): ......
Nr. of probably "fixed" open windows (longterm openings) .....

3.4 Window openings: no. of "points" out of 100 windows =========

AIR INFILTRATION REDUCTION IN EXISTING BUILDINGS

4th AIC Conference, September 26-28 1983, Elm, Switzerland

PAPER 14

AIR INFILTRATION IN NEW ZEALAND HOUSES

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Contents

SUMMARY

The paper reviews air infiltration studies in New Zealand. Tighter houses have evolved over the years through changes in building methods and materials, rather than through a deliberate attempt to reduce air infiltration. We find that some of the tighter houses can be less forgiving of 'windows closed' living styles and dampness problems can develop. At the loose extreme, high heating costs or a reduced standard of thermal comfort are evident.

The air tightness of 40 houses was investigated together with the leakage resistances of a range of building components and bulk sheathing materials. A comparison with houses in other countries shows that comparitively tight houses can arise from simple construction methods not employing vapour barriers.

Air infiltration rates as a function of windspeed are given for a subset of 4 of the 40 houses. Two simplified models were used to calculate infiltration rates that agree with experiment within the limits of our ability to assign wind exposure factors to the building site.

1. INTRODUCTION

There are two important air infiltration related problems in New Zealand houses, these are

1) Control of indoor moisture

2) Winter space heat loss.

The first ranks as the most common reason for unsatisfactory house performance in the country. It is prominent mainly because New Zealand has a warm maritime climate which limits the moisture pick up capacity of ventilation air. During much of the winter, moisture can be controlled adequately by opening windows but in colder periods or for reasons of security when houses are closed up as tight as possible, surface dampness and mildew can develope.

1.1 Control of Indoor Moisture

Dampness problems fall into two classes, those occurring in the living space and those where moisture accumulates within the structure. Both are considered to depend on air leakage to a large extent and both are currently being studied at the Building Research Association.

A survey (1972), of the incidence of dampness in the living spaces of New Zealand houses[3] concluded that:

> "The incidence of mildew growth and surface dampness in New Zealand housing is very high (45%). The most common problem reported is mildew in wardrobes (25%) followed by mildew on bedroom walls (20%), mildew on other walls (11%), visible dampness on bedroom walls (9-10%). In about 20% of all homes dampness problems are serious".

Since this survey result, some measures to control condensation have become more widespread. These include:

1) A uniform standard of insulation in walls, ceilings and foor which helps raise the indoor dew point and wall surface temperatures to discourage condensation.

2) Ventilation in high moisture release areas using fan extraction hoods or window mounted extract fans.

3) Single glass windows with a catch and drain channel to allow condensation to escape outside.

Further measures and more widespread use of 2) and 3) may become necessary to ensure adequate control of moisture. So far no assessment of other options, their suitability and cost has yet been made.

1.2 Winter Space Heat Loss

Standards for thermally insulating walls, ceiling and floors of houses are defined in New Zealand Standard NZS 4218P[1]. With the conductance of walls, ceiling and floor reduced to the extent shown in Fig 1, this leaves heat loss through single glass windows and air infiltration unattended. Until recently, the size of air infiltration in houses with windows and doors closed was unknown. Now that it is believed to lie in the region of 1 ac/h (air change per hour) with wide variation between houses it is evident that air infiltration can be the single largest source of heat loss.

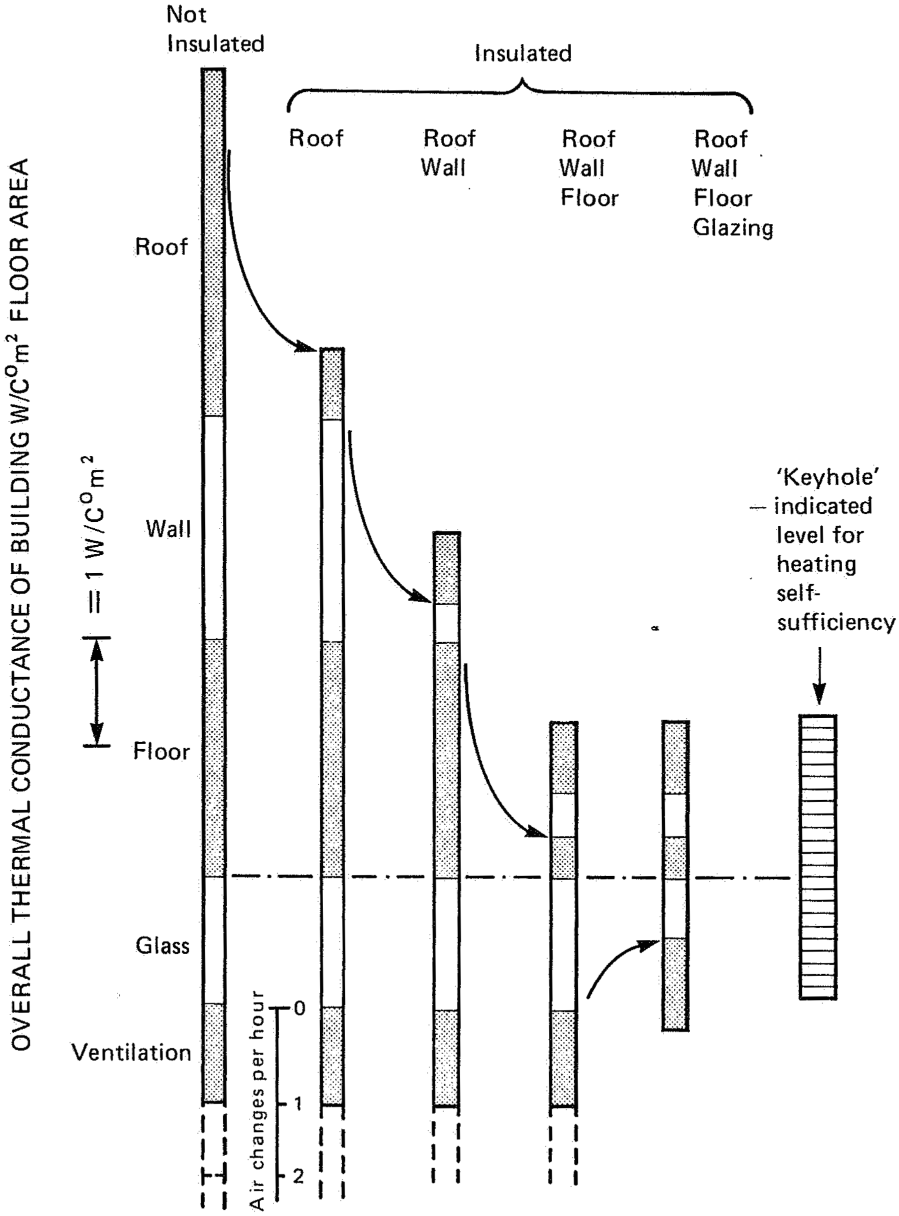

FIG. 1 ILLUSTRATING THE 'KEYHOLE' EFFECT AND THE EFFECT OF A PROGRESSIVE INSULATION PROGRAM

Guidance on low energy house design Trethowen and Bassett[2] has shown that space heating needs could be satisfied by solar heat gains and heat released by appliances and occupants. The size of this incidental heat is represented approximately in Fig 1 as a 'keyhole' through which the building conductance would have to fit in order to be self-sufficient of space heat much of the time. A general tightening of houses may save energy but the dangers of moisture condensation and surface mildew problems mean that ventilation would have to be more tightly controlled, either by the home occupier or by a ventilation system.

2. HOUSE AIRTIGHTNESS

2.1 A Survey of 40 Houses

A survey of house air tightness was completed in 1982 by Bassett[7]. It used the fan pressurization method to measure the air leakage characteristics of 40 houses of different age and construction type in Wellington city.

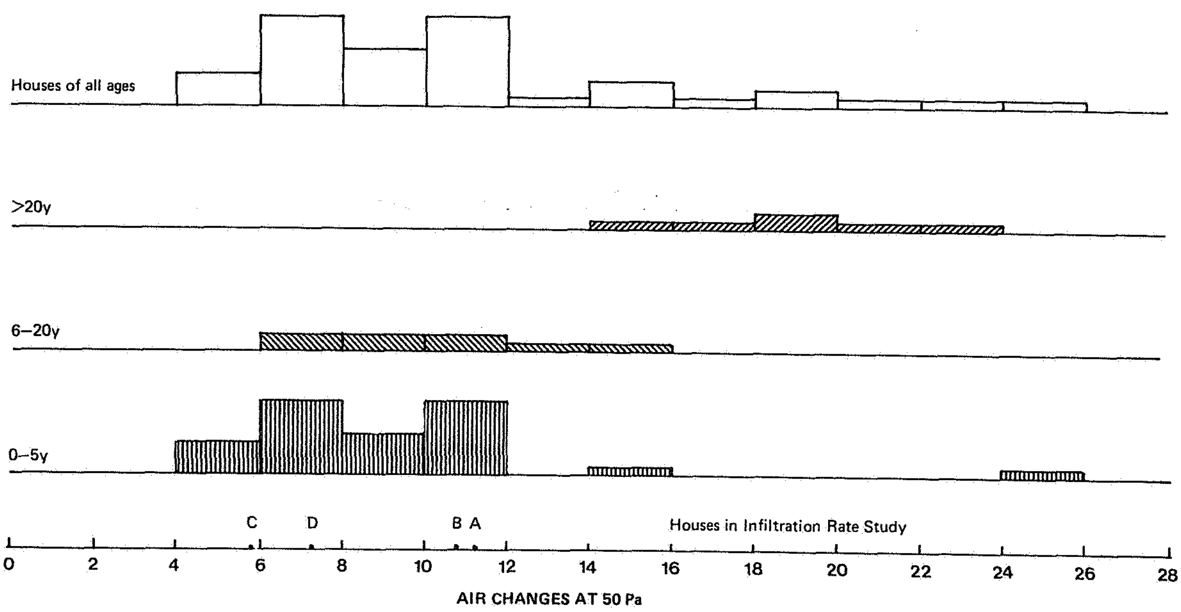

FIGURE 2: HISTOGRAM OF AIR CHANGE RATES @ 50 Pa FOR 40 NEW ZEALAND HOUSES

A histogram of house air tightness expressed in air changes/hour (ac/h) is given in Fig 2. The houses are divided into three age classes, chosen to approximately seperate insulated houses at the new end and houses with strip flooring at the old end. Interior strip wall lining has not been used for many years and the houses remaining with the original scrim and sarking are a small and decreasing percentage of the housing stock.

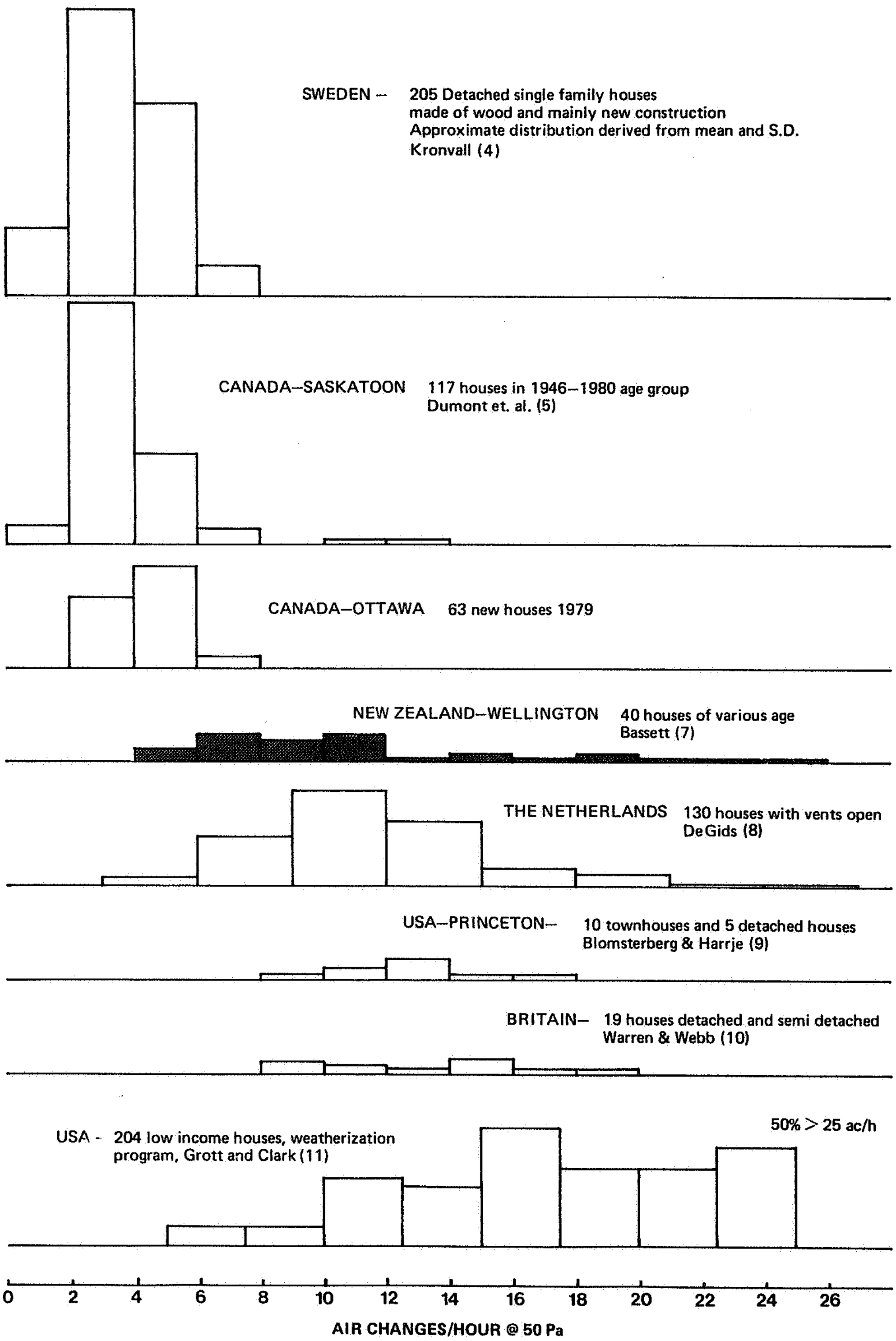

FIGURE 3: RELATIVE AIR TIGHTNESS OF HOUSES

Most results lie in the range 4 to 26 ac/h with 75% between 4 and 12 ac/h. Subdividing by age group shows the (0-5)y and (6-20)y groups to be indistinguishable but that the (21+)y age group represented by 6 houses was less air tight at 16-24 ac/h.

2.2 An International Comparison

House air tightness results are available for a number of countries. A selection of this data appears in Fig 3 and while not exactly equivalent in terms of age selection etc, it does immediately confirm that houses in cold climates are tighter on average than those in more mild climates. More importantly however, it shows that a large block of New Zealand houses less than 5 years old fall within the 0-8 ac/h range occupied by conventional houses in Canada and Sweden. This result has contested the view held within New Zealand that the typical house was exceedingly loose by international standards.

There are no special reasons for expecting to see air tight houses. Since vapour barriers have not been found necessary to control cavity moisture they make no contribution to air tightness. Neither are gaskets used in joints or special control of tolerances of timber frame joints to be found. However, in recent years there has been wider use of sheet lining materials both internally and externally together with prelaid particle board or slab on grade floors. We also noted that the tightest houses were architecturally quite simple.

2.3 Air tightness and Design Complexity

Two houses in the (0-5)y age group were quite leaky and it was noted they both had an unusually complicated shape. This raises the possibility that some design details influence air tightness in a way that can be identified and used at the stage buildings are designed.

In Fig 4 we attempt to show how the leakage rate at 50 Pa per m^2 shell area depends on shell complexity. As a measure of the latter, we added together the perimeter length of top and bottom plate together with vertical lengths of exterior corners and the boundaries of changes of ceiling pitch. This total has been divided by shell area to give a notional measure of shell complexity. Fig 4 shows this variable plotted against the leakage rate at 50 Pa divided once again by shell area. Leakage around doors, windows and through vents and chimneys has also been subtracted to ensure the leakage rate is as shape specific as possible.

Fig 4 suggests a subdivision of houses into the following four groups:

1. Average tightness and average shell complexity — 23 houses
2. Below average tightness and average shell complexity — 0 houses
3. Below average tightness and above average shell complexity — 5 houses
4. Average tightness and above average shell complexity — 3 houses

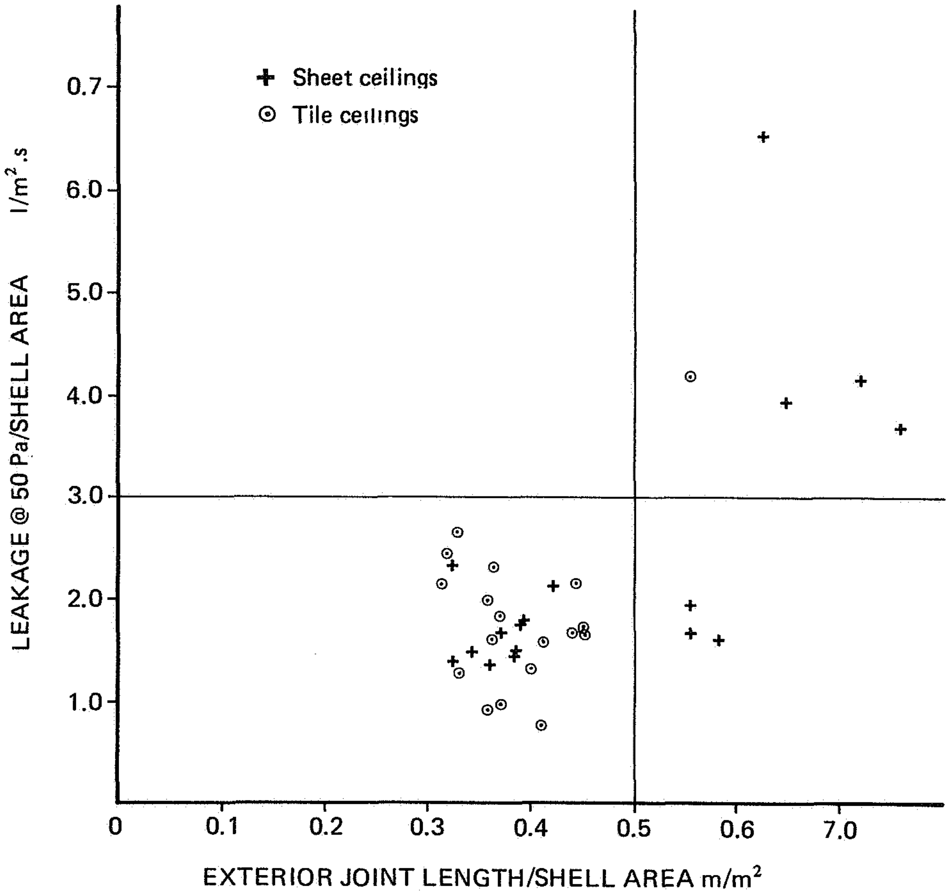

FIG 4 : MEASURE OF BUILDING SHELL COMPLEXITY AGAINST LEAKAGE/SHELL AREA @ 50 Pa

It seems that while some houses of complicated shape can be less air tight than average, this is not always the case. There are eight houses of above average shell complexity. Five have higher than average leakage rates but the other three are about average. It can however be said that there is a high degree of association between shape and tightness since there are no examples of average houses with high leakage rates.

2.4 Air Leakage through Solid Materials

Diffusion of air through the solid components of a building such as its walls, floor and ceiling warrants investigation because these areas are orders of magnitude larger than the size of cracks and joints. It is possible that diffusion through materials of quite high resistance could be important. Air diffusion resistance measurements were made in the laboratory for a range of interior and exterior lining materials. A summary of the results are given in Table I together with a brief physical description of each material. Of immediate note is the single order of magnitude resolution of the diffusion resistances. Although the accuracy of the experiment is rather better than this, there were often wide differences between wall board samples manufactured in different batches. The resolution of the data reflects these differences, as well as being quite adequate for the present purpose.

TABLE I

BULK AIR FLOW RESISTANCE OF COMMON BUILDING MATERIALS

LOCATION	DESCRIPTION	APPLIED COATING	DENSITY (Kg/m^3)	THICKNESS (mm)	ORDER OF MAGNITUDE RESISTANCE MNs/m^3
Floor	Flooring grade wood chip board	Unpainted	700	20	10
	Flooring grade wood chip board	Varnish paint system			10^4
Exterior walls	Exterior grade plywood	Unpainted	900	4	10
	Asbestos cement board	Unpainted	1500	6	10
Interior wall and ceiling	Paper coated gypsum plaster board	Unpainted	750	9.5	10
	Paper coated gypsum plaster board	Alkyd paint system			$>10^7$
	Paper coated gypsum plaster board	Acrylic paint system			10^5
	Paper coated gypsum plaster board	Vinyl wall paper			10^3
	Interior grade wood chip board low density	Unpainted	600	10	1
		Acrylic paint system			10^5
	Low density wood fibreboard	Prepainted	330	13	1
	High density wood fibreboard	Unpainted	1130	5	10
	High density wood fibreboard	Acrylic paint system			10^4
	High density wood fibreboard	Varnish paint system			10^6
	High density wood fibreboard	Alkyd paint system			$>10^7$
	Glass fibre reinforced gypsum plaster board	Unpainted	910	8	1
	Melamine formaldehyde laminate for wet areas		1130	5	$>10^7$

AIR FLOW RESISTANCE OF TILE OR BOARD MATERIALS INCLUDING JOINTS

LOCATION	DESCRIPTION	APPLIED COATING	DENSITY (Kg/m^3)	THICKNESS (mm)	ORDER OF MAGNITUDE RESISTANCE MNs/m^3
Exterior walls	Lapped weatherboards	Alkyd paint system		18	10^{-1}
	Rusticated weatherboards	Unpainted		18	10^{-2}
Ceiling	Low density wood fibreboard ceiling tiles	Prepainted		13	10^{-1}

The air flow resistance is defined by equation 1

$$R = \frac{A\,\Delta P}{Q}\ 10^{-6} \qquad \frac{MNs}{m^3} \qquad (1)$$

where R is the leakage resistance in MNs/m^3
A is the area of material in m^2
Q is the volume flow rate of air in m^3/s
ΔP is the air pressure difference across the material in N/m^2

As an aid to interpreting Table 1, a reference air flow resistance can be calculated to give a volume flow rate of 2×10^{-5} $m^3/m^2.s$ @ 50 Pa. This is about 1% of the average leakage rate/m^2 of shell area for New Zealand houses less than five years old.

$$R(1\%) = 2.5 \quad MNs/m^3$$

A quick scan of the air flow resistances for solid materials in Table 1, shows that only unpainted lining materials are likely to contribute significantly to measured leakage rates. The normal practice of interior decorating by painting greatly increases the air flow resistance to the point where air leakage can be considered insignificant.

Samples painted with an alkyd paint system proved to be tighter than our equipment could measure and a lower limit is recorded in Table 1. Water vapour diffusion and errors in measuring temperature and pressure changes have determined this lower limit.

Board or tile materials with joints included in the leakage measurement have lower air flow resistances. However, of the three examples in Table 1, the two outdoor sheathing materials are likely to be fixed in series with a much higher resistance interior lining. This leaves the ceiling tile system as the only lining material in wide use with significant joint system leakage. In a house with average leakage characteristics and a low density wood fibre tile ceiling, leakage through joints in the ceiling could contribute 10% of air leakage under air tightness test. Further reference can be made to Fig 4 where houses are separated into those with tile ceilings and those with sheet ceilings. In the average tightness average complexity classification there is no significant difference that can be attributed to ceiling type. A 10% difference if present would be significant at the 80% level.

2.5 Other Leakage Openings

Measurement of air leakage through building components has progressed to the point where we have data for the following

1) Windows - leakage between frame and sash

2) Doors - leakage between door and frame

3) Chimneys and heating appliance flues

4) Fitting of plumbing supply and waste pipes

Leakage openings yet to be studied include the joint at the top and bottom plate and the fitting of window and door components to the wall lining.

2.5.1 Windows and Doors

Windows and door leakage measurements were completed using the technique of masking joints and remeasuring the total house leakage rate. Windows and doors of all types were masked together and statistical methods used to resolve differences attributed to joinery type. The most important difference is that between aluminium and wood framed joinery with the following leakage rate and 95% confidence interval applying at 50 Pa pressure difference.

Window and Door Joinery Type	Leakage/m @ 50 Pa l/s.m
Aluminium extrusion	0.5 ± 0.5
Wood moulding	4 ± 1

The current New Zealand Specification for performance of Windows[12] defines three grades of leakage. When converted to a leakage rate at 50 Pa they are as follows:

Grade A	0.3 l/s.m
Grade B	1.0
Grade C	2.0

On the basis of the survey results, the average contribution of windows and doors to leakage in a house less than 5 years old is 17% and for houses older than this it is 23%. These values were worked out on the basis of 100m² floor area together with the average proportions of timber and aluminium joinery found in the 40 house survey houses. These leakage proportions can be compared with 15 to 24% measured by Tamura[13] in Canada and 40% measured by McIntyre and Newman[14] in a single house in the U.K.

2.5.2 Towards Improved Air Tightness - Location of Major Leaks

While a house is under air tightness test, it is a relatively simple matter to look for major leaks by detecting draughts. On a number of occasions leakage openings discovered this way were blocked and a new tightness test performed to measure the improvement. It is helpful to compare the size of some of these leaks with chimneys and other common vents, and with the house envelope leakage using the equivalent leakage area (Aeq) concept. These are given in Table 2.

Table 2

		Aeq m^2	Relative Size
1.	Average 100 m^2 house in survey sample	0.113	100%
2.	Brick chimney and open fire place	0.022	19%

3.	Cracks around openable doors and windows	0.019	17%
4.	Electrical switch board detail, one case	0.009	8%
5.	100 mm flue and freestanding fireplace with all dampers open	0.008	7%
6.	Bath toe space detail, average of 3 cases	0.007	6%

Of immediate note is the relatively small Aeq of chimneys and workmanship details compared with the envelope equivalent leakage area. It was found to be quite difficult to make major improvements to houses in this test sample within the practical constraints of taping over accessible cracks. For example, blocking the cracks around openable windows and doors to simulate a weatherstripping operation reduced the overall leakage by between 17 and 23%. This indicates that a large variety of leakage openings contribute to the total and that the location and size of many of these are not yet known for N.Z. houses.

3. AIR INFILTRATION RATES PREDICTED AND MEASURED

3.1 Infiltration Rate Measurements for Four Houses

Air infiltration rate, wind speed and temperature measurements are available for four of the houses in the air tightness survey. The measurements were made by Clarkson[15] using the tracer gas decay method and SF_6 as a tracer material. On site wind speed measurements were made above roof height and were similar in strength to wind speeds measured at a meteorological station less than 10 km away. The work was completed in the summer when indoor/outdoor temperature differences were less than 3°C.

Three of the houses (A, B and C) are similar in type, size and sheathing materials. They are detached single storey houses with about 100 m² floor area, suspended particle board floors and similar interior lining materials. House D is semidetached with a concrete block party wall. It is split level, has a basement underneath and a skillion roof lined with particle board.

Air tightness data for the four houses is marked on Fig 2 and Fig 4. House C is rather tighter than A, B and D which in terms of leakage rate at 50 Pa/Shell surface area are quite similar.

Air infiltration rates at three wind speeds between 2 and 10 m/s were found within experimental error to form a linear relationship with windspeed. A series of 16 measurements had been made in two similarly sited houses and found to be largely independent of wind direction which at house level generally bore no relation to wind directions measured in the free air stream. The following values of air changes/km of wind run were recorded.

Table 3

HOUSE	Air Changes/km wind run
A	0.053
B	0.045
C	0.012
D	0.020

3.2 Infiltration Rate Predictive Models

The application of two infiltration rate prediction models has been investigated. One was developed at Lawrence Berkeley Laboratory in California by Sherman et al[16] and has a strongly analytical basis. The second was developed by Shaw[17] based on a correlation of measurements made in Canadian houses.

3.2.1 The LBL Model

The basic form of the air infiltration model is:

$$Q = L\sqrt{fs^2 \Delta T + fw^2 V^2}$$

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 ($m/s/K^{\frac{1}{2}}$)
v	is the wind speed (m/s)
f_w	is the wind parameter

The various constants were calculated and appear in Table 4. As indicated by the authors, the stack and wind parameters are relatively insensitive to uncertainties about the distribution of leakage openings. The critical choice is the generalized shielding coefficient used in calculating the wind parameter fw from building and weather station site information. It accounts for shielding around the building by other structures and topographical features. The following two shielding classes were assumed for results shown in Fig 5 and Table 4.

Shielding Class	C^I	Description
III	0.24	Some obstructions within two house heights
IV	0.18	Obstructions around most of perimeter

TABLE 4

BUILDING	L m^2	fs	fw	C^I
A	0.070	0.13	0.17	0.24
			0.13	0.18
B	0.089	0.13	0.17	0.24
			0.13	0.18
C	0.027	0.13	0.18	0.24
			0.14	0.18
D	0.029	0.16	0.15	0.24
			0.11	0.18

With low indoor/outdoor temperature differences and wind speeds above 2 m/s the predicted leakage rate is a linear function of wind speed. Calculated values of air changes/km wind run are compared with measured date in Fig 5.

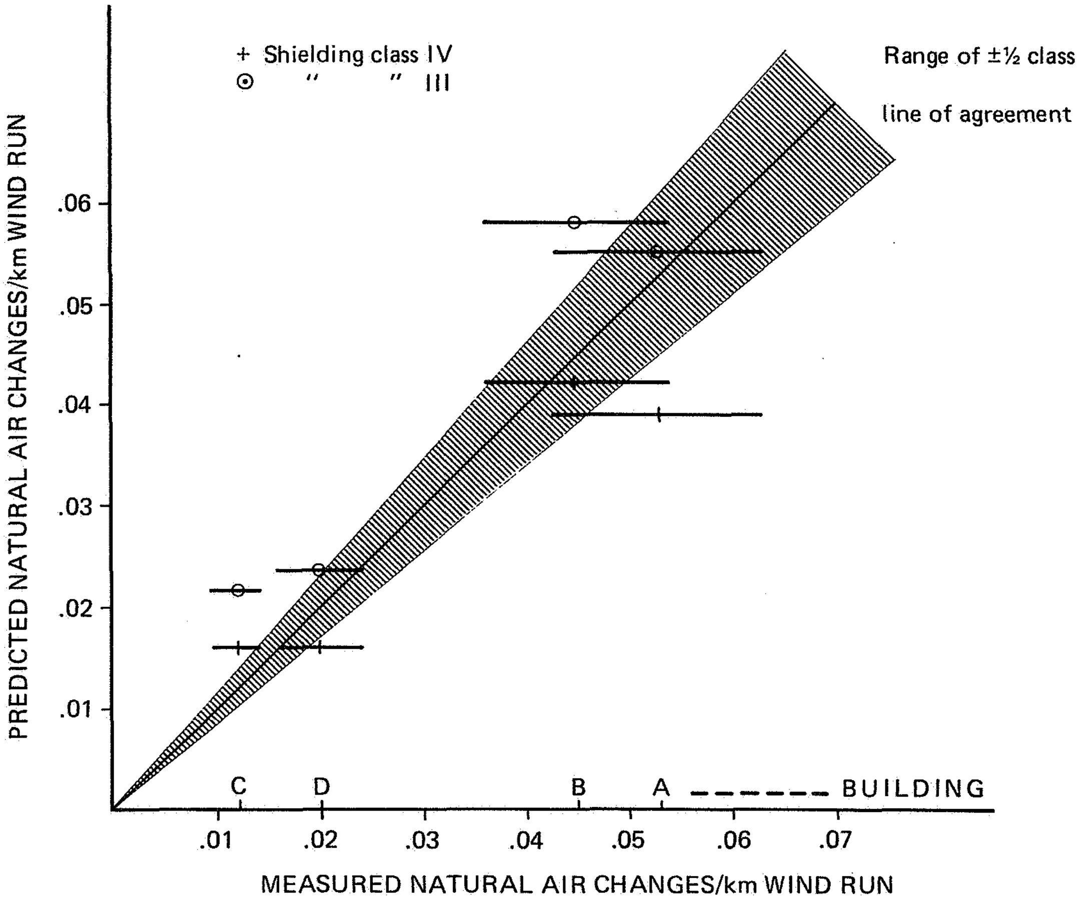

Fig 5 : CORRELATION OF INFILTRATION RATE PREDICTIONS USING 'LBL' MODEL WITH EXPERIMENT

Fig 5 indicates reasonable agreement between predicted and measured air change/km wind run but that we may have to learn more about choosing appropriate shielding classes.

3.2.2 The Shaw Model

This model identifies three climate regimes based on wind speed and indoor/outdoor temperature. Our data falls into regime II where the dominant driving force is wind pressure. In this case the air change rate can be calculated from wind speed, building air tightness coefficient and exponent with an option of either high or low wind exposure.

As before with the LBL model, the predicted air change rate is more strongly influenced by the choice of shielding factor than experimental errors in the building air leakage characteristics. We simple chose the mean of the extreme shielded and exposed cases and calculated air change rates for wind speeds between 2 and 10 m/s. While not exactly linear in wind speed, little error is incurred in representing the predictions in terms of ac/km wind run as before. The results appear in Fig 6.

Uncertainty in the shielding factor can not easily be indicated but results generally agree with experiment within the range of shielded to exposed site exposure.

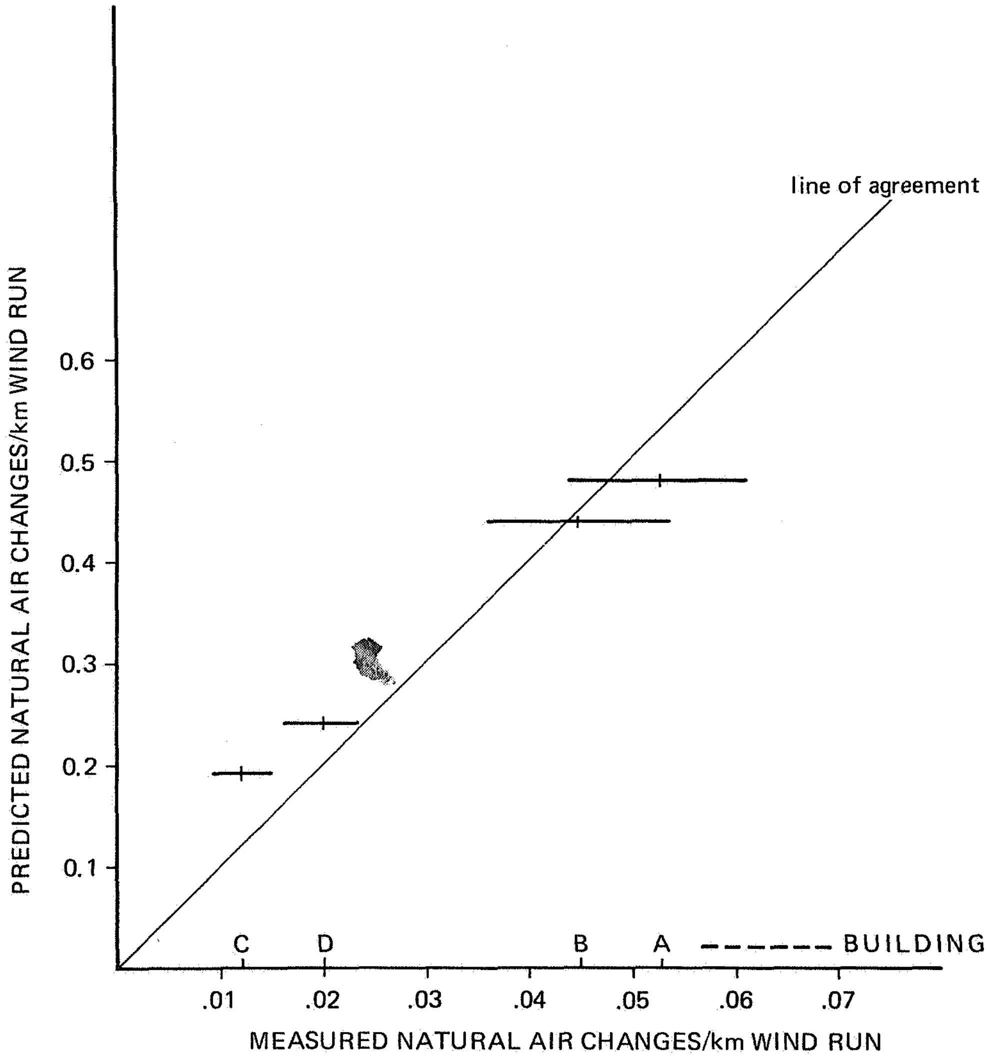

Fig 6 : CORRELATION OF INFILTRATION RATE PREDICTIONS USING SHAW MODEL WITH EXPERIMENT

4. CONCLUSIONS

The following conclusions arise from house, component and material air tightness tests.

For a sample of 40 houses of timber frame construction clad mostly with woodbased sheet materials.

1. Houses in the age groups (0-5)y and (6-20)y were not significantly different in terms of air tightness. The mean air change rate @ 50 Pa being 9 ac/h $\pm$ SD 3 ac/h. The greater-than 20y age group represented by 6 houses were less air tight with a mean air change rate @ 50 Pa of 19 $\pm$ SD 3 ac/h.

2. Air leakage around openable doors and windows made up 17% of the average envelope leakage in houses less than 5 years old and 23% in houses older than this.

3. The air tightness test was found to have limited application in locating leakage openings for weather stripping attention because leaks were typically many and widely spaced rather than few in number and easily accessible.

A survey of material leakage resistances showed:

4. That leakage through solid interior lining materials should contribute less than a few per cent to air tightness test results, and much less when painted.

5. Joints around low density fibre board ceiling tiles were expected to add 10% to house leakage rates but no evidence of this was detected in house air tightness tests.

Preliminary attempts at natural infiltration prediction show:

6. That wind speed and air tightness dependence agrees with experiment to the limit of our ability to assign wind exposure factors to the building site.

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AIR INFILTRATION REDUCTION IN EXISTING BUILDINGS

4th AIC Conference, September 26-28 1983, Elm, Switzerland

PAPER 15

AIR-TIGHTNESS OF RESIDENTIAL BUILDINGS IN JAPAN

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SYNOPSIS

The air-tightness of various types of 25 residential units was measured in detail by the fan pressurization technique. The residences included nine detached houses and 16 apartment units. In this study, the relationship between the pressure difference across the building envelope and the volumetric flow rate of air is shown as well as the ratio of the effective leakage area of one building element to the total leakage area. Secondly, the air-tightness of various types of houses in different countries is compared using the value of the effective leakage area per floor area when the pressure difference across the envelope is 10 Pa. This comparison gave the important information as to the air-tightness target in Japanese houses. Additionally, in the three apartment units which had different leakage areas, the decrease in indoor pressure compared to outside pressure and the extracted volumetric flow rate of air were measured in relation to the diameter of the duct for intaking outdoor air. Lastly, the important points in the design of ventilation systems for an air-tight house are considered.

LIST OF SYMBOLS

Δp	:	Pressure difference between the inside and the outside of building, Pa
Δp_o	:	Reference pressure difference, Pa
Q	:	Volumetric air flow rate through leakage, m^3/h or m^3/s
Q_o	:	Q for $\Delta p=\Delta p_o$, m^3/h or m^3/s
Q'	:	Q per unit floor area, m^3/hm^2
Q'_o	:	Q' for $\Delta p=\Delta p_o$, m^3/hm^2
Q_l	:	Volumetric air flow rate per unit length of window crackage, m^3/hm
Q_{lo}	:	Q_l for $\Delta p=\Delta p_o$, m^3/hm
n	:	Flow exponent
ρ	:	Air density, kg/m^3
A	:	Orifice area or effective leakage area, m^2 or cm^2
A_o	:	Effective leakage area for $\Delta p=\Delta p_o$, m^2 or cm^2
A'_o	:	Specific leakage area, that is A_o per unit floor area, cm^2/m^2
F	:	Floor area, m^2

1. SURVEY OF THE RESEARCH DONE ON AIR-TIGHTNESS OF HOUSES IN JAPAN

1.1 Abstract of research in Japan

Sixty years ago, Nomura[1](1924) and Ohtani[2](1928) measured, for the first time, the area of the crackages in the room envelope by means of a scale, and investigated the effect of the amount of such crackages on air infiltration. Watanabe[3](1951) indicated, on basis of the above results, that the leakage areas in the room envelope of conventional wooden houses constructed roughly, normally and strictly were, more than 90 cm^2, 50 to 60 cm^2 and less than 30 cm^2 per cubic metre of the room volume, respectively. Also, he showed that the leakage area in the room envelope of a concrete house was 10 to 15 cm^2 per cubic metre.

Maeda and Ishihara[4](1961) measured the air-tightness of building elements in concrete apartments using the fan pressurization technique. It was the first time the fan pressurization technique was used. This study was followed by Narasaki et al.[5](1974), Murakami, Yoshino et al.[6,7,8,9](1975-), Asano[10,11](1979), Aratani et al.[12](1980) and Kamata et al.[13,14](1981-), all of whom measured the air tightness of various types of houses by the fan pressurization method.

Recently, Yoshino et al.[15,16](1982-) and Kamata et al.[14,17](1982-) investigated the relationship between the air-tightness of a house and air infiltration by field measurements.

1.2 Measurement techniques of air-tightness

The air-tightness of a whole house or one room was measured by fan pressurization and/or depressurization. In general, the volumetric flow rate through the fan at depressurization is a little smaller than the flow rate at pressurization, because when the room is depressed the space of crackage is forced to become narrower by the pressure exerted on the outer surface of the wall. Kato et al.[13](1981) showed, by the investigation of a small test house, that when the pressure difference was 10 Pa, the volumetric flow rate in the case of depressurization was 60 to 80 % of that in the case of pressurization. Yoshino et al.[9](1981) also demonstrated, by the measurement of the air-tightness of one room, that the volumetric flow rate in the case of depressurization was 80 % of that of pressurization. But, Kamata et al.[14](1982) and Yoshino et al.[9](1981) reported that no significant different in volumetric flow rate was found between the pressurization and the depressurization methods when applied to a typical wooden house.

The air-tightness of a particular building element was estimated by Murakami, Yoshino et al.[6](1975) in terms of the volumetric flow rate difference of air pushed into the shelter before and after removing tapes and/or vinyl sheets which covered that element. Maeda and Nakazawa[18](1965) proposed a measurement technique in which a covering sheet supported by wires was attached to window and air pushed into the space between the window and the cover by a small fan. Kamata et al.[14] (1982) measured the leakage area of building elements using Blomsterberg's technique[19], which he modified to apply to Japanese houses.

1.3 Indication of air-tightness of house

Air-tightness is indicated by the effective leakage area, which can be calculated on the basis of the relationship between the pressure difference and the volumetric flow rate of air. In the case of an orifice plate, the relationship between the pressure difference across the plate and the air flow is

$$\Delta p = \frac{\rho}{2}\left(\frac{Q}{A}\right)^2 \quad \text{----------------} \quad (1)$$

Therefore, the effective orifice area is obtained by

$$A = \sqrt{\frac{\rho}{2}/\Delta p}\cdot Q \quad \text{----------------} \quad (2)$$

In the case of the leakage of building envelope, the relationship between Δp and Q is expressed by

$$Q = Q_o\left(\frac{\Delta p}{\Delta p_o}\right)^{\frac{1}{n}} \quad \text{----------------} \quad (3)$$

Q_o takes the value of the flow rate Q for $\Delta p = \Delta p_o$. n is flow exponent, which varies from 1.0(laminar flow) to 2.0(turbulent flow).

If Equation(3) is introduced into Equation(2), the effective orifice area (effective leakage area) is calculated by

$$A = \sqrt{\frac{\rho}{2}/\Delta p}\cdot Q_o\left(\frac{\Delta p}{\Delta p_o}\right)^{\frac{1}{n}} \quad \text{-----------} \quad (4)$$

If $\Delta p = \Delta p_o$, Equation(4) is rewritten simply as

$$A_o = \sqrt{\frac{\rho}{2}}\cdot Q_o(\Delta p_o)^{-0.5} \quad \text{-----------} \quad (5)$$

Q_o depends on the value of Δp_o. So, it is significant how the value of Δp_o is selected. In Japan, Δp_o is given as 9.8 Pa (1 mmAq). Tamura[20], Hildon[21] and Grimsrud et al.[22] gave Δp_o as 74.7 Pa(0.3 inchH_2O), 50 Pa and 4 Pa, respectively. In consideration of the pressure range exerted upon the building surface in a natural environment and ease of the measuring by the fan pressurization technique, it is better to select 10 Pa(≒1 mmAq) as the reference pressure difference.

2. MEASUREMENT OF THE AIR-TIGHTNESS OF HOUSES

2.1 Description of measured houses

Table 1 shows the description of measured houses including 8 detached houses, 4 terrace houses and 13 apartments. Some detached

Table 1 Description of measured houses

	Location	Houses		Floor area, m^2	SLA* cm^2/m^2	Date of measurement
Detached houses	Ibaraki pref.	①Wooden prefab. house(One story, 3BR+LR)		96	15.1	1975.2.1-5
	Tokyo	②Concrete prefab. house(Two stories, 4BR+LR)		101	5.8	1975.11.18-23
	Sendai-shi	Conventional wooden houses	③A-1(Two stories, 3BR+LR) A Co.	99	10.5	1981.8.3-6
			④A-2(Two stories, 3BR+LR) A Co.	89	10.0	
			⑤B-1(Two stories, 4BR) B Co.	98	11.7	
			⑥C-1(Two stories, 5BR) C Co.	88	20.8	
			⑦C-2(Two stories, 3BR+LR) C Co.	81	21.9	
			⑧C-3(Two stories, 4BR) C Co.	81	22.6	
Multi-family houses	Tokyo	⑨Concrete prefab. house(Semi-det. 4BR+LR)		104	11.8	1975.1.21-29
	Hachiohji-shi, Tokyo	⑩ KEP-Experimental house(Mid floor, 4BR+LR)		89.0	6.0	1976.3.28-31
		⑪ KEP-Experimental house(Mid floor, 2BR+LR)		70.0	7.5	
	Tokyo and the suburbs	Housing estat-A (apartments have acoustic insulated windows)	⑫ A-1(3rd flr. end flat. 3BR)	67.0	2.4	1980.7.14-19
			⑬ A-2(3rd flr. mid flat. 3BR)	65.8	3.0	
			⑭ A-3(3rd flr. mid flat. 3BR+LR)	63.4	2.8	
			⑮ A-4(3rd flr. mid flat. 3BR)	63.4	2.2	
			⑯ A-5(3rd flr. mid flat. 3BR)	64.3	1.7	
		Hous.Est.-B	⑰ B-1(5th flr. mid flat. 3BR)** ***	46.3	8.7	1980.7.22
		Hous.Est.-C	⑱ C-1(4th flr. mid flat. 3BR)***	54.4	3.4	1980.7.24
		Housing estate-D	⑲ D-1(1st flr. end flat. 3BR+LR)	73.6	3.8	1980.7.28-31
			⑳ D-2(2nd flr. mid flat. 3BR+LR)	73.6	3.8	
			㉑ D-3(2nd flr. mid flat. 3BR+LR)	73.6	3.8	
		Housing estate-E	㉒ E-1(End terr. 4BR+LR)	93.0	5.7	1980.8.4-9
			㉓ E-2(Mid terr. 3BR+LR)	93.0	7.8	
			㉔ E-3(End terr. 3BR+LR)	93.0	6.6	
			㉕ F-1(2nd flr. 4BR+LR)	98.2	2.2	

*Specific Leakage Area **Steel frame windows ***Measured after occupation

houses are constructed by the conventional method, others are prefabricated. Measurements were made before the houses were occupied, except for Houses #17 and #18 which were measured several years after occupation. Houses #12 to #16 in housing estate A had acoustic insulated windows.

2.2 Measurement techniques

The measurement of the air-tightness was made using the fan pressurization technique. The tightness of the building elements was estimated by the volumetric flow rate difference before and after removing the vinyl sheet which covered that element. Measurements were carried out under low wind speed conditions.

2.3 Results of measurements

2.3.1 Tightness of a whole house

Fig.1 and Fig.2 show the relationship between the pressure difference across the shelter and the volumetric flow rate per unit floor area. Multi-family houses are generally more air-tight than detached houses. Among detached houses, House #2, built with concrete, is significantly more air-tight than other houses. Conventional wooden houses, Houses #6 to #8, are rather leaky. Detached houses have the value Q_0' of 8 to 33 m^3/hm^2 and the value n of 1.1 to 1.9. Among multi-family houses, Houses #12 to #16 which had acoustic insulated windows are relatively air-tight. Multi-family houses have Q_0' of 2.5 to 20 m^3/hm^2 and n of 1.3 to 3.3. The value of n is 1.0 to 2.0 theoretically. But three of n values calculated by regression analysis are more than 2.0. This may be due to the fact, when the pressure difference was low, Δp and Q were not always precisely measured because of the wind effect.

2.3.2 Air-tightness of one to two rooms

Fig.3 shows the results of measuring the air-tightness of one or two rooms. No difference in air-tightness was found between detached houses and multi-family houses. The room of House #8 is leaky because the rooms are divided by "Fusuma", traditional Japanese sliding doors.

2.3.3 Air-tightness of building elements

Fig.4 shows the air-tightness of the building elements of House #9. Fig.5 shows the same information for House #2. Houses #9 and #2 are typical examples of leaky and air-tight houses.

Before the measurements were taken in a room, each element was covered over with a vinyl sheet until the whole inner surface of the room was covered over. We then confirmed that the room was almost perfectly air-tight. Then, every time a vinyl sheet was removed from a particular element, the relationship between the pressure difference across the shelter and the volumetric flow rate was measured. For a whole house, the measurements were taken, after visible openings such as crackages of windows and doors, ventilation inlets, and openings for pipes were sealed with tape and vinyl sheets.

(1) House #9

a) Main bedroom

Even when the whole inner surface of the room was covered over with vinyl sheets, a slight air flow was measured when the room was pressured, which means the room was not perfectly air-tight. Whenever a vinyl sheet was removed, the value Q increased. The data of Fig.5 indicates the followings:

i) The wall itself has no leakage, but the ceiling, the interface between the ceiling and the wall, and the interface between the floor and the wall have significant leaks. It is surprising that the volumetric flow rate Q_0 through such leaks is three times that of Q_0 through the crackages of windows.

ii) Unexpectedly, Q_0 through the crackage of windows is about one-fifth of Q_0 through all leakages in the room.

b) The whole house

House #9 has a Q of about 600 m^3/h at Δp=5 Pa when all visible leaks are sealed. Even if the openable ventilation inlets provided in the window frame were open, the increasing fragment of Q is only 10 % of Q through the crackage of windows. It can be said that such inlets are not used for ventilation at all.

(2) House #2

a) Main bedroom

There was no leakage in the wall, ceiling, floor and the interface between them except for the crackages of windows and doors, and ventilation inlets. The value Q_0 through the ventilation inlets is half that of Q_0 through the crackage of windows.

b) The whole house

The value of Q for Δp=5 Pa when all visible leaks are sealed is a quarter that of House #9. Both Houses #2 and #9 are prefabricated with concrete panels. But a significant difference in tightness is found between the two houses. This differnce is most likely due to the difference in the quality of workmanship, judging from the close observation of the building and the report of builders.

2.3.4 Comparison between the catalog data and the field measurement results of the air-tightness of windows

Fig.6 shows the measurement results for Houses #1, #2 and #10 and their catalog data. The volumetric flow rate per unit length, Q_{lo}, obtained by the field measurement of Houses #1, #10 and #2 are, 1 to 1.5 times, 4 times and 6 times values of their catalog data. This may be due to unskilled construction. In order to realize the expected air tightness of windows, skilled construction is necessary.

2.4 Effective leakage area of building elements

The effective leakage area of a particular element, A_0, can be obtained by calculating the difference in the effective area before and after removing the vinyl sheet which covers the element. Table 2 shows the A_0 of the building elements of Houses #12, #19 and #22 all of which are apartments. The background leakage areas of Houses #12, #19 and #22 are, 40.3 cm^2, 28.1 cm^2 and 126.0 cm^2, respectively. The background leakage area of House #22 is 25% of all of the leakage area of the envelope. The acoustic insulated

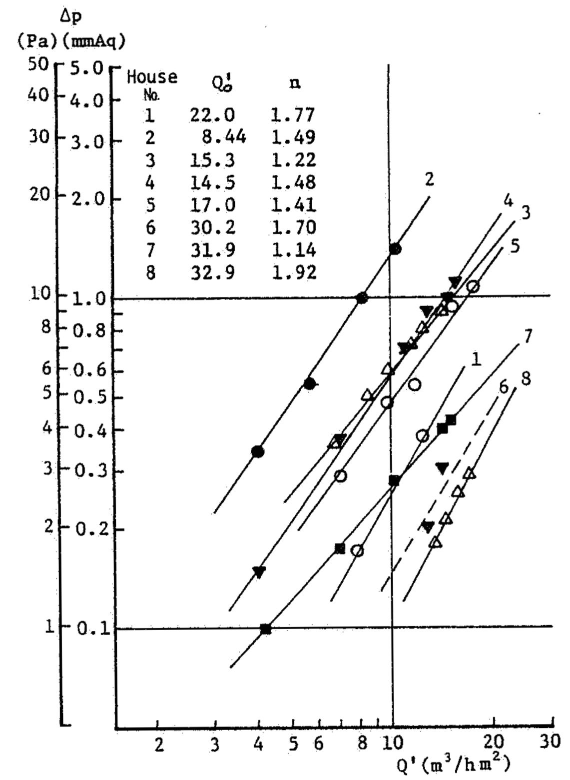

Fig. 1
Pressure difference and leakage flow rate for detached houses

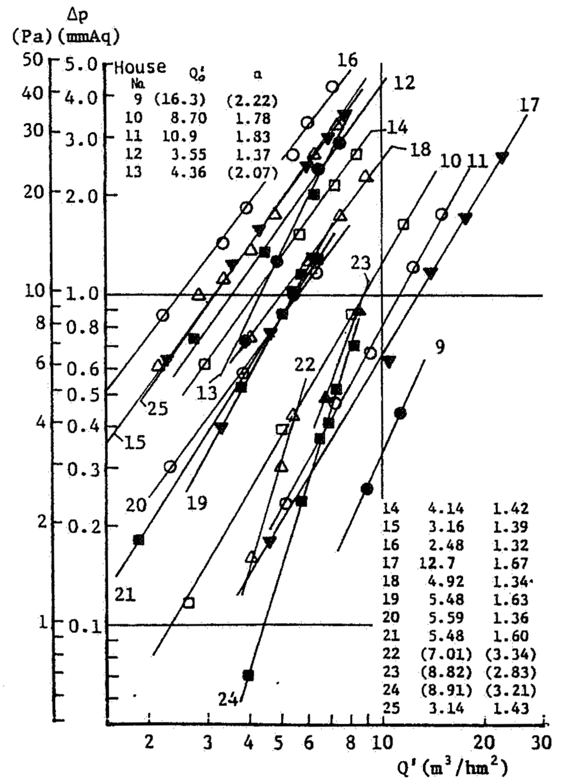

Fig. 2
Pressure difference and leakage flow rate for multi-family houses

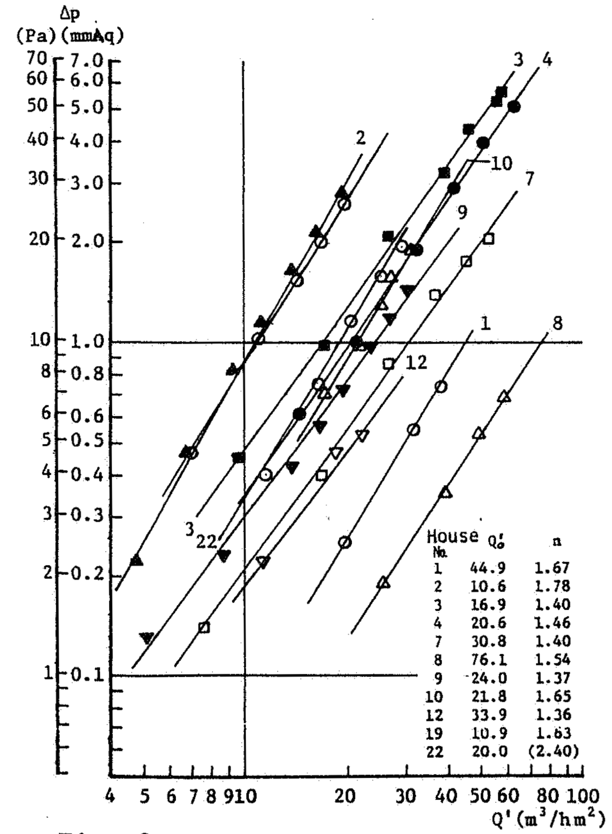

Fig. 3
Pressure difference and leakage flow rate for one or two rooms

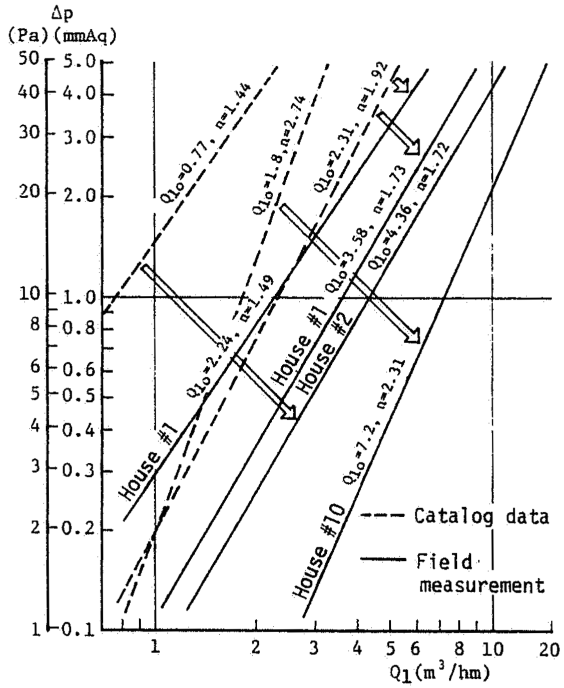

Fig.6
Measurement results and catalog data of window tightness

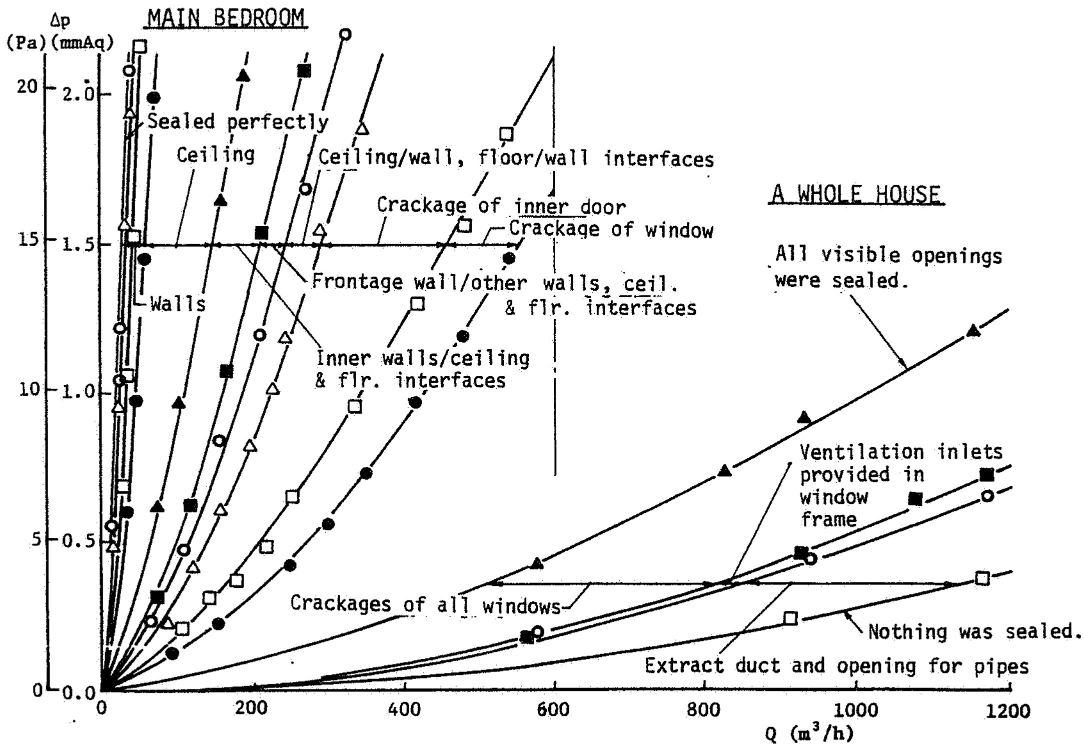

Fig. 4 Pressure difference and leakage flow rate for building elements of House #9

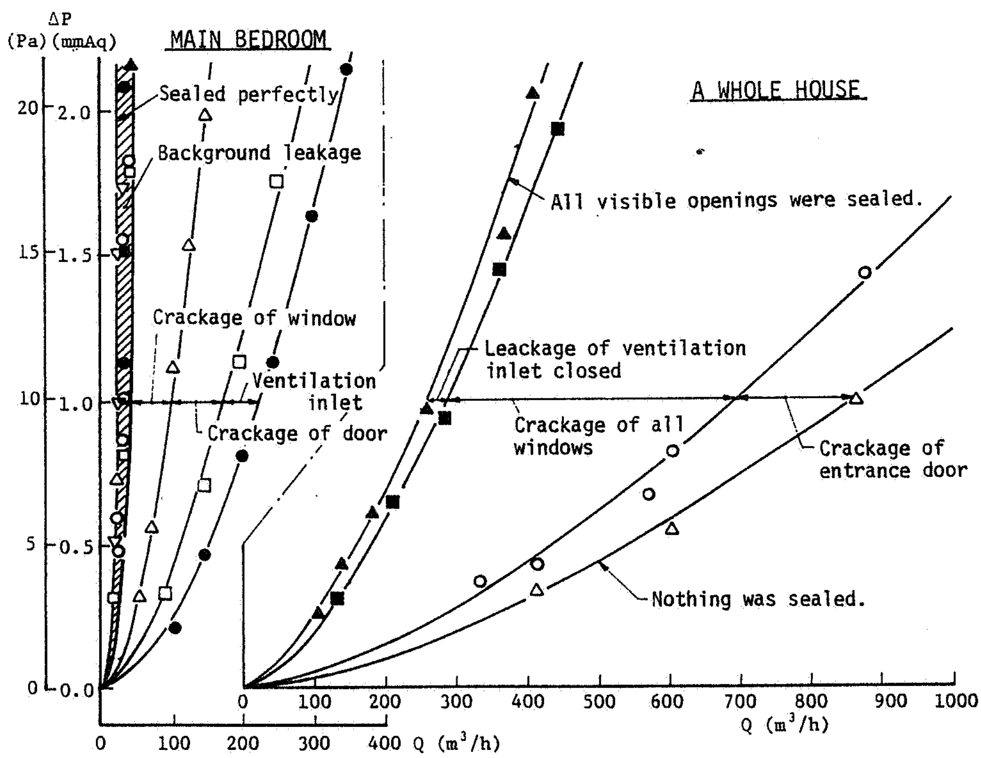

Fig. 5 Pressure difference and leakage flow rate for building elements of House #2

Table 2 Effective leakage areas of building elements

Leakages \ Houses	#12 (had acoustic window)		#19		#22 (Seme-detached)	
Bachground leakage area	40.3cm²	(24.6%)	28.1cm²	(10.1%)	126.0cm²	(25.9%)
Electric outlets	4.7	(2.9)	0.9	(0.3)	9.2	(1.9)
Leakage of venti. inlet closed	-	-	-	-	11.5	(2.4)
Cover in ceiling of closet for inspection	-	-	-	-	21.7	(4.5)
Ventilation inlet in kitchen	4.7*1	(2.9)	0*2	(0.0)	0*2	(0.0)
Window crackage	18.4*4	(11.3)	92.0	(33.2)	123.4	(25.4)
Closed venti. inlet in bath	13.9	(8.5)	-	-	-	-
Entrance door	37.9*3	(23.2)	106.2	(38.3)	0	(0.0)
Venti. inlet in entrance door	-	-	-	-	194.1	(39.9)
Leakage of kitchen fan	34.0	(20.8)	36.2	(13.0)	0	(0.0)
Vent. outlet in bathroom	9.6	(5.9)	14.1	(5.1)	-	-
Total	163.5	(100.0)	277.5	(100.0)	485.9	(100.0)

*1 The inlet was open. *2 The inlet was closed. *3 Had the post box.

windows of House #12 have an A_0 of 18.4 cm^2, which is 11 % of the entire leakage area of the envelope. That particular window is far tighter than the normal windows of other houses. The greatest leakage areas were the background leakage(24.6%) in House #12, the crackage of the entrance door(38.3%) in House #19 and the openings for ventilation provided in the entrance wall(39.9%) in House #22.

3. INTERNATIONAL COMPARISON OF THE AIR-TIGHTNESS OF VARIOUS HOUSES

It has been proposed for the purpose of international comparisons that the air-tightness of a house be given as the ratio of the effective leakage area to unit floor area for Δp=10 Pa, which Grimsrud et al.[37] called "Specific leakage area". Specific leakage are A_0' can be calculated by

$$A_0' = \frac{Q_0}{F}\sqrt{\frac{\rho}{2}}(\Delta p_0)^{-0.5} \quad \text{-----------} \quad (6)$$

Fig.7 shows the specific leakage areas of various houses in different countries. If the original data of air-tightness were not shown as Q_0 or A_0 for Δp=10 Pa, these data were conveted into Q_0 for Δp=10 Pa assuming 1/n=0.6.

a) Air-tightness of Japanese houses

Detached houses are plotted in Rank 4 to Rank 6, except for the air-tight houses in Hohhaido, which is the most northern portion of Japan. Almost all of these houses were constructed recently. The air-tightness of older houses constructed several decades ago are assumed to be plotted in the position beyond Rank 6. Multi-family houses are plotted in Rank 2 to 4 except for two houses. Apartments equipped with acoustic insulated windows in housing estate A are so tight as to take the position of Rank 2. One of apartments plotted in Rank 5 was constructed in 1956. The other

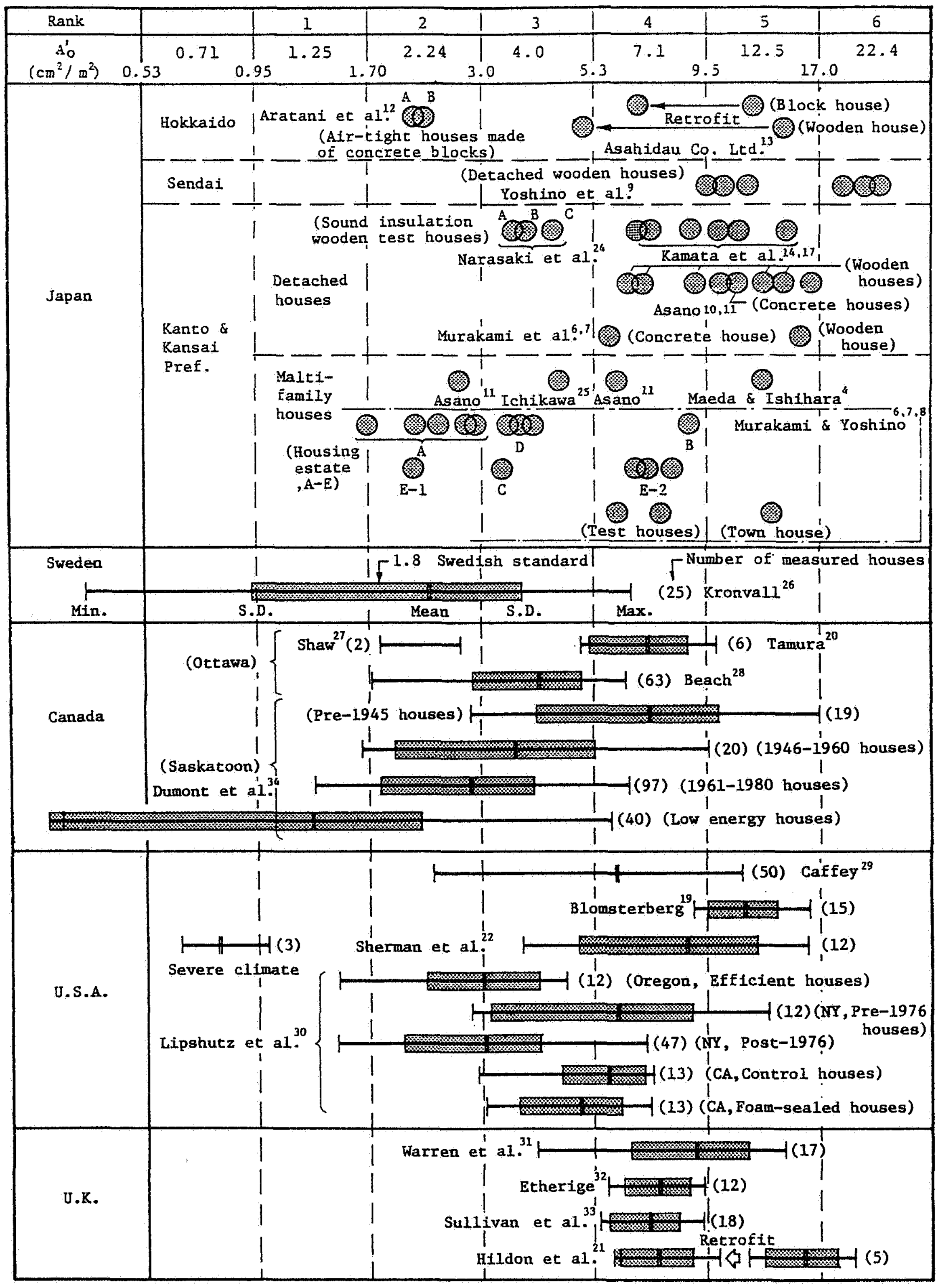

Fig. 7 International comparison of air-tightness of houses

is a terrace house built with concrete panels.

b) Sweden

70 % of Swedish houses, which are between a mean value plus a standard deviation(S.D.) and a mean value minus S.D., occupy Rank 1 to Rank 2. Swedish houses are more air-tight than those of other countries, which is due to Swedish's severe climate. The Swedish standard of air-tightness specified as the air change rate for Δp=50 Pa takes the position of Rank 2, close to Rank 1.

c) Canada

The houses in Ottawa, Canada occupy Rank 2 to Rank 4. One of houses measured by Shaw was reported to be considerably upgraded. On the other hand, it can be seen that the houses in Saskatoon have become tighter and tighter since 1945 and the houses constructed recently(1961-1980) take Rank 2 to 3. Especially, low energy houses are significantly air-tight.

d) U.S.A.

Houses in the United States are widely distributed from Rank 2 to Rank 5, except for three houses located in a severe climate region. The upgraded houses seem to be in Rank 2 to Rank 3.

e) U.K.

Houses in the U.K. are plotted from Rank 4 to Rank 5, which is nearly equal to the detached houses in Japan. It can be seen by Hildon's measurement of houses before and after retrofitting, that the air-tightness of houses are upgraded from Rank 5 to Rank 4 as a result of retrofitting. A similar change in level through retrofitting is seen in the examples of houses in Hokkaido.

As a result, Fig.7 shows not only the present levels of air-tightness of various houses in different countries, but also gives important suggestion as to the target of air-tightness in Japanese houses.

4. FIELD TEST OF THE RELATIONSHIP BETWEEN THE PERFORMANCE OF VENTILATION SYSTEMS AND THE AIR-TIGHTNESS OF A HOUSE

4.1 Introduction

It is expected that the performance of a ventilation system depends on the air-tightness of a house. In order to clarify the relationship between the performance of ventilation systems and the air-tightness of a house, the following points were investigated in three apartments which have different levels of air-tightness.

i) Relationship between the decrease in internal pressure and the extracted air flow rate when the kitchen fan was operated.

ii) Air flow pattern in the most air-tight house when the kitchen fan and the toilet fan are operated simultaneously.

iii) The relationship between internal pressure and extracted flow rate when a temporary duct for the intake of outdoor air is installed for the purpose of the experiment, and the flow rate of air passing through such a supply duct.

4.2 Description of houses and measurement techniques

(1) Houses used for the experiment

The experiment was performed in Houses #12, #19 and #22, the effective leakage areas of which are shown in Table 2. House #12 is seen to be significantly more air-tight than the others.

(2) Ventilation systems

Fig.8 shows the ventilation systems of House #12 and #22. House #19 has the same system as House #22, except that the extract duct system is divided into two series, one for kitchen and one for bathroom, and the capacity of the kitchen fan is a little smaller (300 m^3/h at Δp=100 Pa). The ventilation flow rate required for a kitchen in Japan is much greater than that of other countries, because so much smoke, vapour and combustion gas are generated by boiling, broiling and frying using a gas range.

(3) Measurement technique

The extract flow rate was measured inside the provisional duct attached to the hood using a thermister anemometer. The air flow pattern when the kitchen fan and the toilet fan are operated simultaneously was estimated by the measurement of the pressure difference scross the door dividing the two rooms by the observation of tobacco smoke.

4.3 Decrease in internal pressure and the extracted air flow rate with the kitchen fan operated

Table 3 shows the decrease in internal pressure and the extracted volumetric flow rate when the kitchen fan was operated. Without a supply duct, it is evident that House #12 which is air-tight, shows significant decrease in internal pressure,-125 Pa(-12.8 mmAq) from outdoor pressure for the extracted flow rate of 360 m^3/h when the fan is operating at high speed, and has an internal pressure of -105 Pa(-10.7 mmAq) for 310 m^3/h, even when the fan is on low.

When the toilet fan was operated at the same time, air flow across internal doors was observed(Fig.9). It should be noted that the air in the toilet and the bathroom was reversely pulled into the

Table 3 Air flow rate and decrease in internal pressure under differet conditions

		Supply duct	Inlet of kitchen	Fan speed	Ratio of supply air	Internal pressure Pa (mmAq)	Air flow rate m^3/h (0, 200, 400, 600)
House #12	1.1	-	Closed	High	-	-125 (-12.8)	
	1.2*	-	Open	Low	-	-105 (-10.7)	
	1.3	125 mm	Sealed	High	48 %	-62 (-6.3)	
	1.4	150	Sealed	High	56 %	-46 (-4.7)	
House #19	2.1	-	Open	High	-	-27 (-2.8)	
	2.2	125	Sealed	High	36 %	-16 (-1.6)	
	2.3	150	Sealed	High	47 %	-13 (-1.3)	
House #22	3.1	-	Closed	High	-	-5.4(-0.55)	
	3.2	125	Sealed	High	24 %	-3.4(-0.35)	
	3.3	150	Sealed	High	26 %	-2.9(-0.30)	

* Ventilation inlet provided in window was open.

o Through supply duct
● Through extract duct

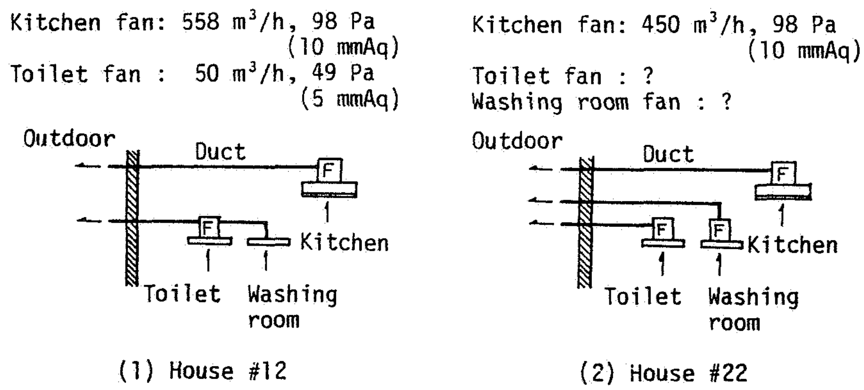

Fig. 8 Extract duct systems of test apartments

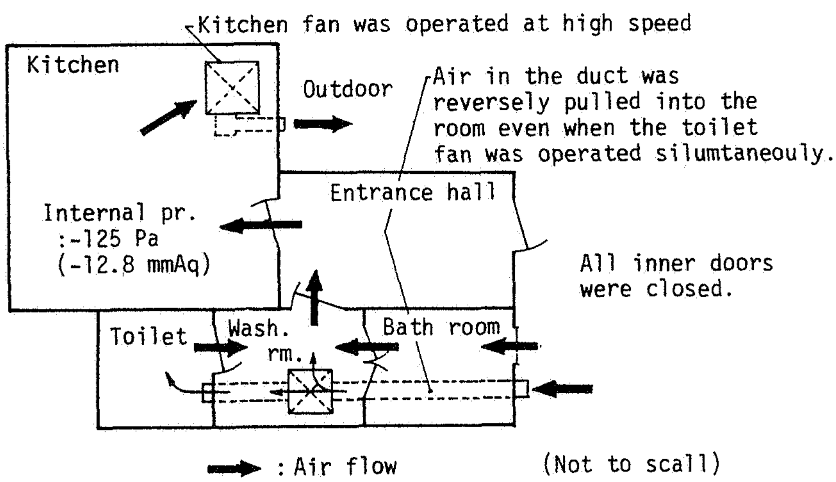

Fig. 9 Air flow pattern when the kitchen fan and the toilet fan was operated simultaneously

kitchen by way of the entrance hall due to the high pressure difference across internal doors.

The decreases in the internal pressure of House #19 and #22 were, -27 Pa(-2.9 mmAq) and -5.4 Pa(-0.55 mmAq), respectively. Reversal flow was not found in houses other than House #12. It is important to note the significant decrease in internal pressure and the reversal flow in an air-tight house.

4.4 Influence of the diameter of the supply duct on the indoor pressure and the extracted air flow rate

Table 3 also shows the decrease in internal pressure, the extracted flow rate through the fan, the flow rate of air passing through the supply duct and the ratio of the supplied flow rate to the extracted flow rate when the kitchen is installed with the temporary air supply duct for the purpose of the experiment. That duct has a diameter of 125 mm and a length of 3.6 m or a diameter of 150 mm and a length of 4 m.

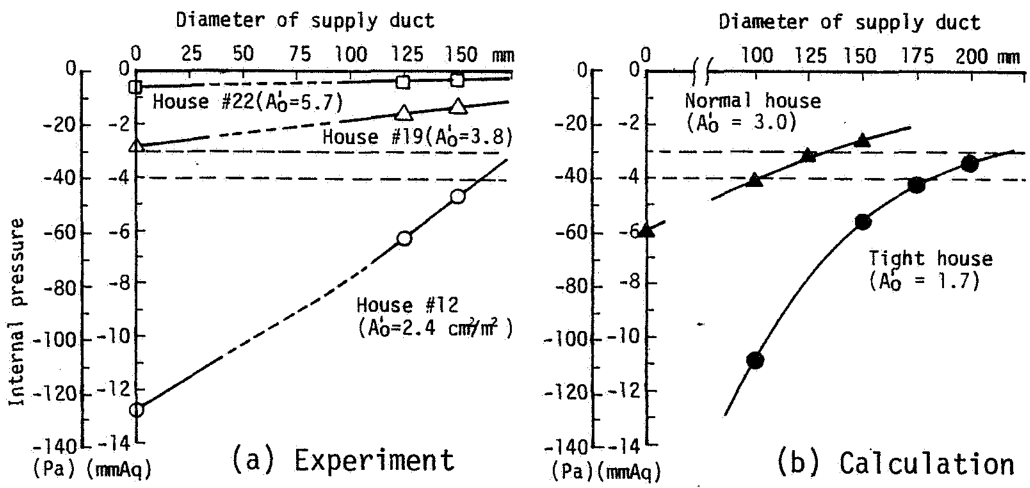

Fig.10 Change of internal pressure due to different diameter of ducts

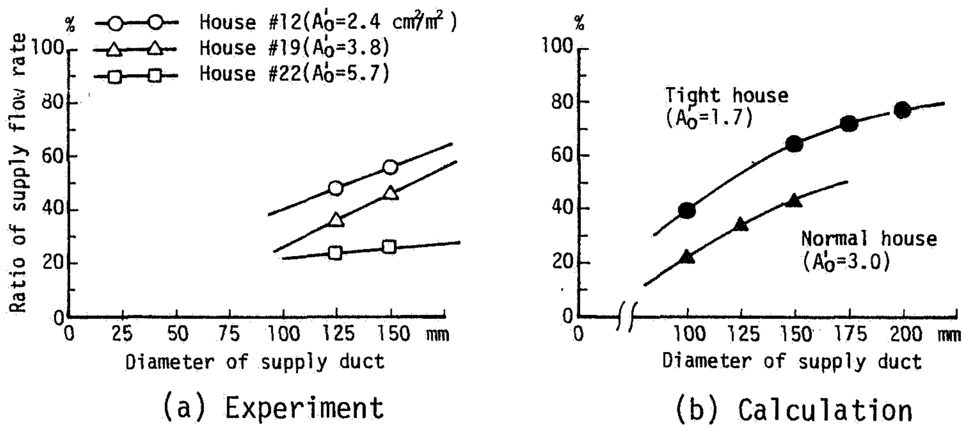

Fig.11 Ratio of air flow rate through the supply duct to that through the extract duct

Fig.10(a) shows the relationship between the diameter of the duct and a decrease in internal pressure. The wider the diameter of the duct, the more the internal pressure rises and approaches zero in two houses. But, House #12, which is tight, still has a low internal pressure(-49 Pa) when the diameter is 150 mm.

On the other hand, internal pressure was calculated[35] using the network method for the two model houses, which had 3 bedrooms and a floor area of 73.7 m^2. The house with an A_0 of 1.7 cm^2/m^2 is hereafter referred to as "Tight house", while the house with an A_0 of 3.0 cm^2/m^2 is called, "Normal house". The calculation results shown in Fig.10(b) indicate a relationship between the internal pressure and the diameter of the supply duct similar to the results obtained by measurement.

If the decrease in internal pressure is to be controlled above -29 Pa(-3.0 mmAq), it is necessary to select a supply duct with a diameter about 125 mm and 200 mm for Normal house and Tight house respectively, to prevent the reversal flow of air when the kitchen and toilet fan were operated simultaneously as well as the problems which accompany opening a door at a high pressure difference. Also, in order to control the decrease in internal pressure above -39 Pa (-4.0 mmAq), it is prefarable to select a duct with a diameter of 100 to 125 mm and 175 to 200 mm, for Normal house and Tight house.

Fig.11 shows the ratio of the air flow rate through the supply duct to the extracted flow rate, relative to the different diameters of the supply ducts. If 175 mm is selected as the diameter of the supply duct in order to control the internal pressure above -39 Pa (-4.0 mmAq), the ratio of the intaking air flow to the extracted flow rate is 70 % for Tight house. For Normal house, if the diameter is 100 mm, the ratio is only 20 %. In the latter case, it can be said that almost all of the air taken into the kitchen passes through the crackage and background leakage other than the supply duct.

4.5 Important points for designing the ventilation system of an air-tight house

a) It is important to pay attention to the capacity of a fan and the diameter of the supply duct or ventilation inlets in a tight house. In House #12, which was built with acoustic insulated windows, when the kitchen fan was operated simultaneously with the toilet fan, the air from the toilet and bathroom was pulled into the kitchen because the internal pressure in the kitchen significantly.

b) In order to control the decrease in internal pressure above -39 Pa(-4.0 mmAq) to prevent reversal flow, the diameter of the supply duct should be 100 to 125 mm for Normal house with an A_0 =3.0 cm^2/m^2(between Rank 2 and 3), and 175 to 200 mm for Tight house with an A_0=1.7 cm^2/m^2(between Rank 1 and 2).

5. CONCLUSIONS

1) The air-tightness of various types of 25 residential units was measured by the fan pressurization technique. When the pressure difference across the shelter was $\Delta p=10$ Pa, the volumetric flow rate per unit floor area of air pushed into the shelter was 8 to 33 m^3/hm^2 for the detached houses, 2.5 to 20 m^3/hm^2 for the multi-family houses and 11 to 45 m^3/hm^2 for one to two rooms.

2) It was found by measuring the air-tightness of building elements that there were many invisible leakages, that is background leakages other than the crackages of windows and doors, ventilation inlet leaks and leaks of openings for pipes. Such background leakage areas vary greatly depending on the quality of construction. For example, in one of the two houses built with concrete panels, the bedroom had no background leakage, while the bedroom of the other house had an air flow rate of 200 m^3/h through the background leakage for $\Delta p=10$ Pa at pressurization. On the other hand, between the three types of apartments, the background leakage areas varied from 28 to 186 cm^2.

3) Installed windows often have air-tightness far inferior to the performance to be originally expected. One of the windows measured this time had a Q_0 six times that of the catalog data.

4) The air-tightness of a house was specified as the effective leakage area for $\Delta p=10$ Pa per unit floor area, or specific leakage area. By plotting various types of houses along the scale of such specific leakage area and comparing the houses of different countries, important information was obtained concerning target of air-tightness in Japanese houses.

5) The internal pressure was measured when operating the kitchen fan in three apartments which had different air-tightness. In the air-tight house(A_0 of 2.4 cm^2/m^2) equipped with acoustic insulated windows, the internal pressure was -125 Pa(-12.8 mmAq) for $Q=360$ m^3/h. When the toilet fan and kitchen fan were operated at the same time, the air in the toilet was reversely pulled into the kitchen. Both experiment and simulation analysis clarified the fact that the diameter of the supply duct should be 175 to 200 mm for air-tight houses of Rank 2 to 3, so as to control the decrease in internal pressure above -39 Pa(-4.0 mmAq) in order to prevent reversal flow and trouble with opening doors.

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AIR INFILTRATION REDUCTION IN EXISTING BUILDINGS

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PAPER 16

COMPONENT LEAKAGE AREAS IN RESIDENTIAL BUILDINGS

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SYNOPSIS

To predict air infiltration in single-zone, residential buildings, some air infiltration models rely on measured values of the effective leakage area and on its distribution within the building envelope. The easiest method of measuring air leakage is a blower door, but, where such a device is not available, leakage areas can be estimated by adding leakage areas of all envelope components. In this paper we first review the published data on component air leakage and, from them, compile a set of component leakage figures for use in estimating leakage areas and their distribution in buildings. These calculations of leakage areas based on component leakages are compared with measurements of leakage areas in 36 houses in different locations in the United States. The model appears to predict leakage area accurately for the average of the 36 houses, while for individual houses the standard deviation is about 20%. In addition to describing the methods used to calculate building leakage areas based on component information, we discuss the assumptions and methods to convert other types of component leakage data to component leakage areas. Where several independent data exist for the same components (e.g., windows), we discuss the quantitative differences in terms of possible differences in construction practices. In addition to understanding the relative importance of each component, the methods and data presented can be used to estimate building leakage areas based simply on drawings.

LIST OF SYMBOLS

Q	total air infiltration rate or air flow through blower door [m^3/s]
Q_s	stack-driven infiltration [m^3/s]
Q_w	wind-driven infiltration [m^3/s]
f_s, f_w	structural infiltration factors
ΔT	indoor-outdoor temperature difference [^oC]
v	wind speed from a weather tower [m/s]
C'	shielding class coefficient
α, γ	coefficients describing terrain class near the building
α', γ'	coefficients describing terrain class near the weather tower
H, H'	heights of the building and the weather tower, respectively
ΔP	pressure difference across envelope [Pa]
Q_P	air flow rate measured at pressure difference ΔP [m^3/s]
n,K	flow exponent and proportionality constant found from regression of measured leakage data
ΔPr	reference pressure difference [Pa]
Q_{Pr}	flow through the building or building component at the pressure difference ΔPr [m^3/s]
ρ	density of air [kg/m^3]

L	effective leakage area of building at ΔPr [cm^2]
L_c	ceiling leakage area [m^2]
L_f	floor leakage area [m^2]
L_i	leakage area per unit dimension of the i-th component [cm^2/m^2 or cm^2/m or cm^2 per component]
D_i	dimension of the i-th component [m^2 or m or number of components]
i	index denoting all building components
i_f	index denoting the floor components
i_c	index denoting the ceiling components
ΔL	uncertainty of the overall building leakage area [cm^2]
ΔL_i	uncertainty of the i-th component leakage area per unit component dimension [cm^2/m^2 or cm^2/m or cm^2/each]
L_C	calculated leakage area [cm^2]
L_M	measured leakage area [cm^2]
R^2	correlation coefficient squared

1. INTRODUCTION

Several air infiltration models have been developed to predict air infiltration in residential buildings. Some of these models rely on measured values of the effective leakage area and its distribution within the building envelope. The effective leakage area is a quantity that characterizes the air leakage of a structure. In 1980, Sherman and Grimsrud introduced the "LBL infiltration model"[1] in which the leakage area is combined with local weather data to predict average seasonal air exchange rates. The model predicts the air exchange through the building envelope on the basis of a few measurable parameters:

- the leakage area of the structure and its distribution
- the geometry of the structure
- the inside-outside temperature difference
- the wind speed
- the terrain class of the structure location
- the shielding class of the structure

For purposes of calculating air infiltration in a building using the LBL model, the single most important parameter is its leakage area, defined as the equivalent area of an orifice with a unit discharge coefficient that would allow the same volume of air flow as the actual building, assuming it is exposed to the same pressure difference. The easiest method of measuring the leakage area is by using a blower door.[2,3] An alternate method, called AC-Pressurization, is being developed by our group at Lawrence Berkeley Laboratory.[4]

Where a blower door is not available, leakage areas can, in principle, be estimated by adding component leakage areas of all the envelope components. There are two drawbacks to this method. First, finding all air leakage sites in the building envelope is difficult without a direct inspection assisted by specialized instrumentation (e.g., building pressurization with smoke tracers or thermographic equipment, or high-frequency acoustic methods). The second difficulty is the lack of data on air leakage through such leakage sites.

In this paper we addressed these drawbacks as follows. First, we only considered a fixed set of leakage sites that have been found by direct measurement to be significant. The frequency of occurrence or physical quantity of these leakage sites (i.e., number of pipe penetrations or overall window area) were determined solely by inspection of architectural drawings or sketches, not by information from direct visual inspection during a field visit, although such information is available for some of the houses used to validate the model and would have helped improve the model accuracy. Second, we compiled leakage areas measured for such leakage sites from the published literature. For some building components, other investigators have measured component leakage areas by methods similar to blower door pressurization.[5,6] In general, however, component leakage tests, although used for many years, have been used for slightly different purposes: consequently, the figures published in the literature reported component leakage in different formats, as best suited to their separate purposes:

- air changes per hour
- air flow in m^3/s or cfm
- leakage areas or effective leakage areas in cm^2 or square inches.

Regardless of the format, leakage can be expressed per component, per unit surface area, or per unit length of crack, and it can be quoted at a fixed pressure difference (usually 4 Pa, 50 Pa or 75 Pa) or over a given range of pressures.

The variety of reporting formats and the lack of coordination among different measurements have been the main obstacles to using such measured component leakages as a basis for deriving the leakage area and the air infiltration rate of a building. Accordingly, part of our emphasis is on the standardization of the component leakage areas reported by others into leakage areas per unit length, per unit area, or per unit component (e.g., leakage area per fireplace). The building leakage areas estimated from the component leakage areas may be used as input to the LBL infiltration model to predict the infiltration in the building.

From the methods and values reported in this paper, designers and architects can estimate component and building leakage areas based simply on drawings and their knowledge or decisions about such important details as whether the structure has weatherstripping around windows, or dampers in ventilation ducts and fireplaces. The better the knowledge about construction details, the more accurate the resulting estimate of building leakage area. On the other hand, no amount of sleuthing will be better than direct measurement by pressurization techniques. That is, this paper should not be construed as an invitation to replace blower doors with mindless crack counting, but it should help those who, for institutional or practical reasons, are not in a position to make actual leakage area measurements.

2. OVERVIEW OF THE LBL MODEL

The LBL-model[7] is a single-zone calculation method to predict the weather-induced infiltration of a residential or small commercial building. The model also predicts the impact of retrofits or other changes in the building envelope on the basis of performance changes effected in a few measurable parameters:

1) The leakage area(s) of the structure and its distribution. This parameter describes the tightness of the structure (obtained by pressurization and depressurization). Most retrofits will affect the leakage area or the leakage distribution.

2) The geometry of the structure. The height and other geometric quantities are usually known or can be directly measured.

3) The inside-outside temperature difference. The temperature difference controls the infiltration caused by thermal buoyancy commonly called stack effect. It is also necessary for calculating the heating and cooling loads due to infiltration.

4) The wind speed. The wind speed is required to calculate the wind-induced infiltration, usually called "wind effect."

5) The terrain class of the structure. Standard wind-engineering practice has established five "classes" for characterizing the terrain surrounding a structure: they range from open terrain, as on a prairie, to the completely obstructed terrain typical of a large city.

6) The shielding class of the structure. Similar to terrain class is the concept of shielding class, which, however, applies only to the structure's immediate vicinity (within two house heights). For any particular calculation, the shielding class, also in five categories, is assigned on the basis of the density of surrounding buildings and obstructions, such as trees, fences and sheds.

Of these parameters, the distribution of leakage area is the most difficult to measure directly. To measure ceiling leakage area, the building should be pressurized and depressurized with walls and floors well sealed. Conversely, walls and ceiling should be sealed to measure floor leakage area. In practice, ceiling and floor leakage areas are estimated from leakage areas of light fixtures, floor penetrations, and similar components in ceiling and floor. The effect of the apparent inconsistency of this method is minimized when one considers the comparatively weak sensitivity (0 - 15%) of the model to the leakage distribution for average houses. Still, one of the purposes of this paper is to put the estimation of the leakage area distribution on a more scientific basis.

The principal equations of the LBL infiltration model are summarized below. A cardinal assumption of the model is the addition of stack and wind effects in quadrature:

$$Q = \sqrt{Q_s^2 + Q_w^2} \tag{1}$$

Both stack- and wind-driven infiltration terms have similar forms:

$$Q_s = L\, f_s \sqrt{\Delta T} \tag{2.1}$$
$$Q_w = L\, f_w\, v \tag{2.2}$$

The structural factors, f_s and f_w are:

$$f_s = \frac{(1 + R/2)}{3} \left[1 - \frac{X^2}{(2-R)^2} \right]^{3/2} \sqrt{\frac{gH}{T}} \tag{3.1}$$

$$f_w = C' \,(1 - R)^{1/3} \left[\frac{\alpha (H/10)^{\gamma}}{\alpha' (H'/10)^{\gamma'}} \right] \tag{3.2}$$

The building leakage area distribution parameters, R and X, are:

$$R = \frac{L_c + L_f}{L} \quad \text{and} \quad X = \left| \frac{L_c - L_f}{L} \right| \tag{4}$$

Knowing the terrain class and the shielding class of the structure allows the use of off-site weather data for calculating wind-induced pressures on the building surfaces. Thus, even though on-site weather data collection greatly improves the results obtainable in a research setting, it is not necessary. The only requirement when using off-site weather data is that the measured wind data is for the "same wind", i.e., that there be no mountains or other major disturbances in terrain between the site and the wind tower.

Drawings of a building are generally sufficient for determining the building height, H. For the leakage area and the leakage area distributions, R and X, direct measurements should be used or, alternatively, component leakage areas in conjunction with drawing details. In other words, air infiltration can be calculated for a building as early as in the planning stage. Moreover, the consequences of different design details can be evaluated immediately. For existing buildings, direct information from an on-site visit would complement the information gathered from any drawings available.

3. CALCULATION OF LEAKAGE AREAS

The leakage area values presented in this paper conform to the definition used in the LBL model:

$$L = 10{,}000\ Q_{Pr} \sqrt{\frac{\rho}{2\ \Delta Pr}} \qquad (5)$$

In accordance with the LBL infiltration model, we use a reference pressure difference of 4 Pa. The component leakage areas presented in this paper are given in cm^2 per unit, where the "unit" could be:

- linear meters of house perimeter
- square meters of window area
- number of penetrations through the envelope
- number of components of one type (e.g., fireplace).

The component leakage areas per unit are found in the tables in Appendix A. To calculate the total leakage area of a building, we multiply the overall dimensions or the number of occurrences of each building component by the appropriate table entry; by adding the resulting products we obtain the building leakage area. If we do the sum separately for ceiling or floor, using the entry for leakage location -- "Walls," "Ceiling," or "Floor" -- at the bottom of each table, we can estimate ceiling and floor leakage areas to be used in calculating the parameters R and X. That is

$$L = \sum_{i} D_i\ L_i \qquad (6.1)$$

$$L_f = \sum_{i_f} D_i\ L_i \qquad\qquad L_c = \sum_{i_c} D_i\ L_i \qquad (6.2)$$

Note that the component "dimension," D_i, refers to all components of the i-th kind. For example, D_i may refer to the overall window area, to the overall length of floor joint, or to the overall number of plumbing penetrations.

The amount of care used in determining the size and number of leakage sites directly affects the accuracy of the estimates obtained by this method. For instance, based on reference to drawings alone, a window frame would likely be considered "average" and assigned an average leakage-area-per-unit-surface area. An on-site inspection, however, may reveal that the cracks around the frame have been carefully caulked, a finding that would be reflected in a lower value in the component leakage table. Finally, a direct test with a smoke-stick could distinguish between "well caulked" and "average caulked." An example of an actual leakage area calculation is shown in Table 1. The calculated leakage area is 810 cm^2 with an uncertainty of ± 128 cm^2. The measured leakage area is 770 cm^2. Of course, in general, we would not expect such good agreement.

TABLE 1
Example of Calculation of Building Leakage Area Based on Component Leakage Areas and Comparison to the Measured Leakage Area.

Component	Description	D_i	L_i	ΔL_i	$D_i L_i$	$(D_i \Delta L_i)^2$
Sills	Uncaulked	43.2 m	4.0 cm^2/m	2.0	173	7,482
Elec. outlets		20	0.5 cm^2 ea	0.5	10	100
Windows Framing	Sliding	13.1 m^2	4.0 cm^2/m^2 1.7 cm^2/m^2	2.0	75	676
Exterior doors Framing	Single	5.7 m^2	7.7 cm^2/m^2 1.7 cm^2/m^2	7.0	54	1,592
Fireplace	Without damper	1	350.0 cm^2 ea	30.0	350	900
Penetrations	Pipes	7	6.0 cm^2 ea	3.0	42	441
Heating ducts	Ducts untaped, in basement	1	144.0 cm^2 ea	72.0	144	5,184
						16,375
Calculated Building Leakage Area, L_C (cm^2):					810	± 128
Measured Building Leakage Area, L_M (cm^2):					770	

Note: Refer to symbol list for explanation of column headings

3.1 Estimation of Uncertainty

In general, the leakage of any component depends on a number of factors, such as quality of workmanship or type of fireplace damper. Other variables have to do with differences in the way the literature reports leakage area values for the same component. Whenever such differences could not be correlated with observable features, or when, in our experience, the leakage area of a particular component was especially susceptible to construction quality, we entered a range of leakage areas to reflect the uncertainty. In Appendix A, we use "Max" to describe the leakiest and "Min" to describe the tightest components reported in the literature. Harrje and Born[9] indicate their component leakage areas in a similar but graphical form, but do not include the discharge coefficient of each component in their definition of leakage area.

An overall building leakage area derived from individual component leakage areas with individual uncertainties must, of course, have a similar uncertainty associated with it. We suggest that the uncertainty of the overall building leakage area be determined by following the rules for error propagation used in analyzing measurements;[10] that is, by assuming the error in each individual component leakage area to be independent of that of any other component in magnitude and in sign. Then, the uncertainty in overall building leakage area can be estimated from the square root of the sum of squares of individual uncertainties:

$$\triangle L = \sum_i (D_i \triangle L_i)^2 \tag{7}$$

Calculating the leakage area and its uncertainty from drawings or sketches can be an aid in deciding whether more time-consuming measurements or surveys are necessary or warranted. Suppose that the calculation in Table 1 had been done on an actual house before the survey. It would then have been known that concentrating on a careful inspection of the sill, the doors, and the fireplace would reduce the uncertainty of the total leakage area. The calculation also shows that an extensive survey to ascertain the quality of the sealing of electric outlets is not warranted: decreasing the uncertainty of the leakage area of each electrical outlet from 0.5 to 0.2 would decrease the uncertainty of the total leakage by less than 0.3%.

4. REVIEW OF EXISTING DATA FOR COMPONENT LEAKAGES

A review of the component leakage data found in the literature listed in Appendix A,[11-23] and shown in Table 2 reveals that:

- most of the data used pertain to residential houses in North America only;
- most data are for windows and doors of various types;
- there are some data for leakages around pipes and wires;
- there are some data for fireplaces and heating systems;
- there are no data for leakages of windows and doors where weatherstripping was installed several years prior to test;
- there are very few data for leakage of sills and wall-ceiling joints, and those available are not detailed;
- there are no data for leakages through walls, floors, and ceilings except for penetrations;
- the Scandinavian references contain results from laboratory tests only, but all test samples represent current Scandinavian building technology.

TABLE 2
Synopsis of Measured Component Leakage Areas Reported in Literature.

Component	Ref. 11*	Ref. 12*	Ref. 13*	Ref. 14*	Ref. 15*	Ref. 16*	Ref. 17*	Ref. 18*	Ref. 19*	Ref. 20*	Ref. 21*	Ref. 22*	Ref. 23*
Sill (wall foundation)		Caulked and not caulked	3 types		6 types				2 types			8 x 2 types	
Ceiling/roof									1, not described				21 types w/vapor barrier
Wall/ceiling joints		Internal walls											
Floor													
Windows		18 types			Older types	5 types of newer windows	2 calibrated plastic	1 with and w/out storm	2 types				
Doors		15 types			Swinging door								
Penetrations in walls and ceilings	Electrical outlets	Electrical outlets, pipes, ducts	Electrical outlets	17 types							Electrical installations		
Heating systems	Ductwork	9 types											
Exhaust fans	2 types	9 types											
Fireplaces	With and without insert	8 types											
Natural ventilation										21 types			
TEST	Field measurement		Lab test	Lab test	Standard	Field measurement of 192 windows	Lab test			Lab test		Lab test	
DATA	Leakage area at 4 Pa	Leakage area at 50 Pa	Curve airflow/ pressure	Curves	Airflow at 4 diff. pressures	Airflow at 75 Pa	cfm vs. in. H_2O curves	Leakage area	Airflow at 75 Pa	Curves m^3/h vs. 0-200 Pa		Curves m^3/h 0-150 Pa	Curves m^3/h 0-150 Pa

*Column Headings Refer to References in Paper.

We used the data from the Scandinavian references[13-14,20-23] to determine the lower limits of the uncertainty range for the leakage areas of some components.

4.1 Transformation of air leakage data into effective leakage area

Whenever the data in the literature were not given in units of effective leakage area at $\Delta Pr = 4$ Pa, one of the two transformation formulae shown below was used.

Pressure curve: If the leakage results were reported as a series of flow rates through the component at several different reference pressures, the data was fitted to the following empirical form:

$$Q = K \Delta P^{n} \tag{8}$$

The equation was then evaluated at $\Delta P = 4$ Pa to obtain the air flow needed in Eq. (5) determining effective leakage area.

Fixed pressure data: Where the air flow was given at a fixed difference pressure, usually 50 Pa or 75 Pa, the leakage area was calculated by assuming a value for the flow coefficient n, usually

$$n = 0.65, \tag{9}$$

since this value appears to be a good estimate for many houses.[24] The equation used to calculate the leakage area then becomes:

$$L = 10{,}000\ Q_P \left[\frac{\Delta Pr}{\Delta P} \right]^{n} \sqrt{\frac{\rho}{2\Delta Pr}} \tag{10}$$

5. COMPARISON OF CALCULATED AND MEASURED BUILDING LEAKAGE AREAS

To test the method outlined above, we calculated effective leakage areas from component leakage information for a sample of 36 houses from various areas of the United States for which we had both detailed drawings and measured values of overall effective leakage area.[25-28] These were all single-family residential houses, some of which have leakage area measurements available for before and after certain air-tightening retrofits had been carried out. The locations were: Rochester (New York), Midway (Washington), Eugene (Oregon) and Davis and Walnut Creek (California).

In addition to drawings or sketches of the houses, ranging from simple sketches done by house doctors to detailed architectural drawings, we relied upon notes about window types, weatherstripping, etc. However, we only used information that was or would have been available without an on-site inspection. The calculation presented in Table 1 was performed on each of the 36 houses.

5.1 Comparison on Full Set of Houses

In Fig. 1 we show the comparison of calculated and measured leakage areas for the 36 houses in our sample. Each point represents one comparison, with the measured value as the abscissa and the calculated value as the ordinate. The uncertainty calculated for each leakage area is shown as a vertical bar and is in the range of ±10% to ±20%. For a few of the tighter houses, the uncertainty was as high as ±40%. The error in the measurement of leakage area is estimated to be between ±10% and ±15%. The solid diagonal line represents perfect correspondence between calculated and measured values, while the dotted lines show the limits of ±20% discrepancy with respect to measured leakage areas.

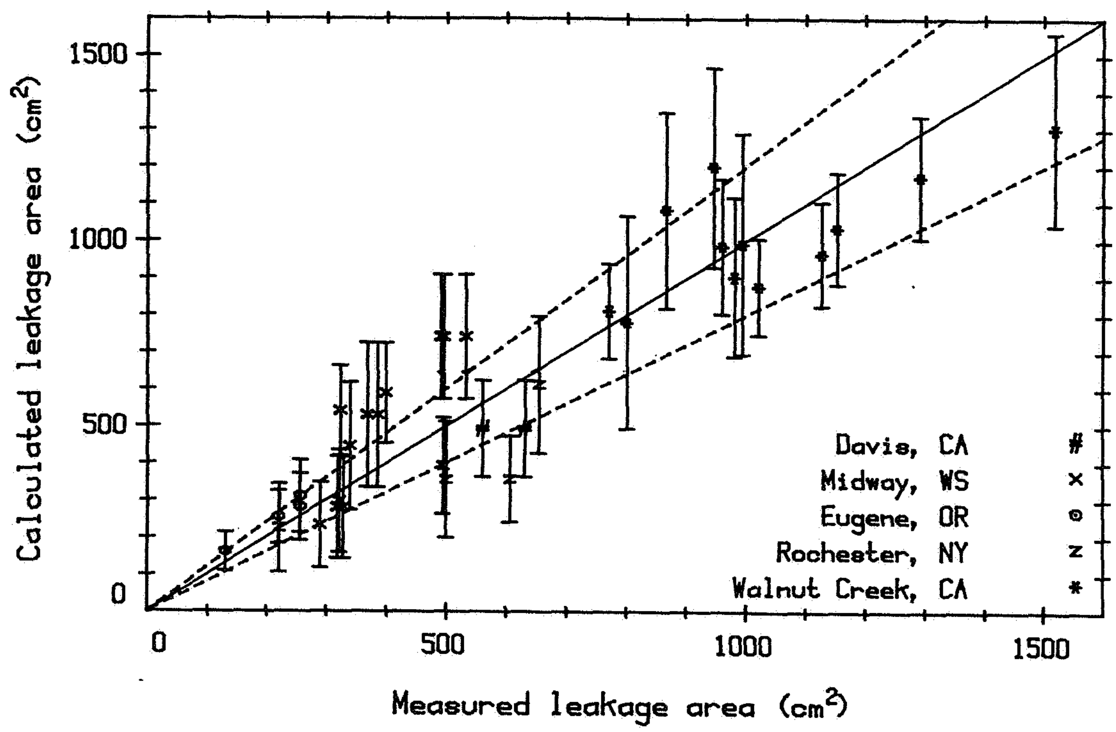

Fig. 1: Comparison of measured and calculated leakage areas for 36 houses; vertical bars represent uncertainty of calculation; solid diagonal line indicates perfect agreement; dashed lines indicate ±20% discrepancy.

A simple linear regression of the points in Fig. 1 yields a best-fit line of:

$$L_C = \underset{(0.06)}{0.84}\, L_M + \underset{(46.3)}{111.5} \qquad (R^2 = 0.84) \tag{11}$$

The figures in parentheses indicate the standard deviation of the estimated regression coefficients. The R-squared value of 0.84 indicates that 84% of the variation in calculated leakage area is explained by the measured leakage area, with only 16% of the variation due to lack of fit of the model.

The apparent correlation between calculated and measured leakage areas is encouraging. In most cases, calculated values fall within the ±20% range, with the greatest outliers at ±40%. For this particular sample, it appears that the calculations overpredict for tight houses and underpredict for very leaky houses. A comparison of the drawings of tight and leaky houses might reveal systematic differences in building construction details. For example, most of the tight houses had continuous vapor barriers, while the leakier ones did not.

5.2 Continuous Vapor Barrier

One component of great importance to the overall leakage area is a continuous polyethylene vapor barrier. Although its effect on the overall tightness of a building is undisputed, we could not find quantitative results in the literature, except for ceiling and wall joints (Table A-2), and ducts through walls or ceiling (Table A-8). Moreover, because it acts in series to other envelope components, a vapor barrier can not be characterized as an additive leakage area.

As an interim solution, we propose to use the "Min" values in the tables in Appendix A for window and door frames, sills and wall joints, electric outlets and light fixtures, and pipes and ducts through the envelope. The application of this rule to the tight houses for which our method overpredicts leakage area would improve the correspondence between prediction and measurement. Because of the arbitrary nature of such a "rule," however, we did not use those results and thus, as an interim solution, ignored the effect of a continuous vapor barrier. In any case, any premature conclusions with regards to continuous vapor barriers or to the calculation method presented here should be tempered by the current paucity of component leakage data and by the fact that the tightest and the leakiest sets of houses in our comparison are each located on a single site and are each reported in a single reference.

5.3 Comparison of "Unique" vs. "Replicated" Houses

Some of the houses in the sample were replicated from the same set of drawings and some of the houses were evaluated both before and after retrofits. In the first case, of course, the calculations will predict the same leakage areas for all houses, and in the second case the calculated leakage areas, although different, will be strongly interdependent. If we eliminate the repetitions, there are only 22 physically distinct houses in our data set. Fig. 2 shows the comparison of calculated and measured leakage areas for these 22 "unique" cases.

In these cases, a linear regression yields:

$$L_C = \underset{(0.07)}{0.89}L_M + \underset{(50.5)}{49.5} \qquad (R^2 = 0.90) \tag{12}$$

with the same nomenclature and conventions as in Eq. (11).

Based on the comparison shown in Figs. 1 and 2, it appears that the uncertainties of 20% to 40% calculated with the method described earlier and quantified by Eq. (7) are too conservative. If the vertical error bars are to symbolize standard errors and if the error distribution for each prediction is assumed to be normal, then we would expect only about two-thirds of the vertical error bars to intersect the diagonal line. In fact, 28 out of 36 do so for the full sample of 36 houses (Fig. 1) and 19 out of 22 do so for the subset of 22 "unique" houses (Fig. 2). A casual inspection of the two figures suggests that vertical error bars in the range of 20% would better satisfy the criteria for standard deviations.

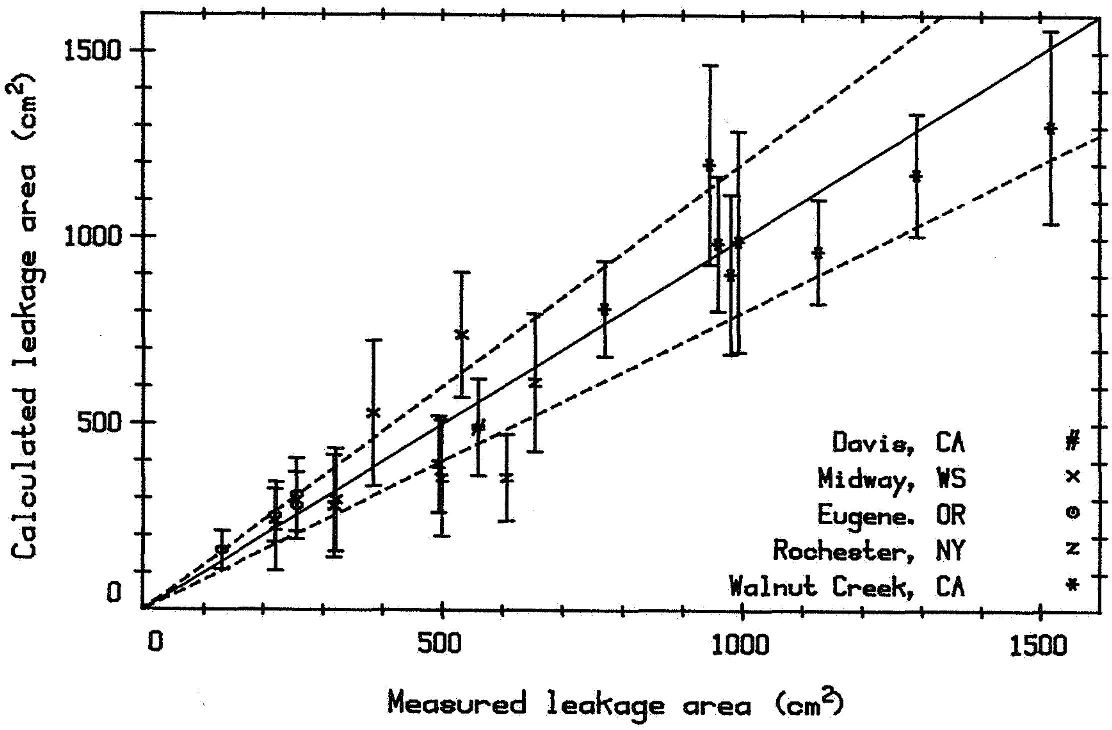

Fig. 2: Comparison of measured and calculated leakage areas for 22 "unique" houses; vertical bars represent uncertainty of calculation; solid diagonal line indicates perfect agreement; dashed lines indicate $\pm$20% discrepancy.

For each of the 22 unique calculations, we computed the ratio of calculated to measured leakage areas -- a ratio of 1.0 indicating perfect correspondence, a ratio of 1.2 translating to 20% overprediction, and so on. Fig. 3 shows a histogram of the 22 ratios calculated in this manner. The average is 1.005 with a standard deviation of 0.20, suggesting that the calculation method generally produces accurate predictions. Thus, based on this limited data set, and assuming that the error distribution is normal, the leakage area of a house, calculated on the basis of its drawings alone, falls within 80% and 120% of the actual value with a probability of 68%. If the limits are relaxed to 60% to 140% of actual value, the probability increases to 95.5%.

The standard deviation of 20% should be compared with two related quantities: the error of 10% to 15% inherent in leakage area measurements, and the uncertainty of about 20% resulting from the uncertainty in component leakage areas. If we make the hypothesis that these results would hold over a significantly larger set of houses, we would conclude that the simple method for calculating leakage area, as described in this paper, is of a quality comparable to that of our data. In other words, few refinements to the method are warranted until the large uncertainty is reduced that presently exists in the values reported for component leakage areas.

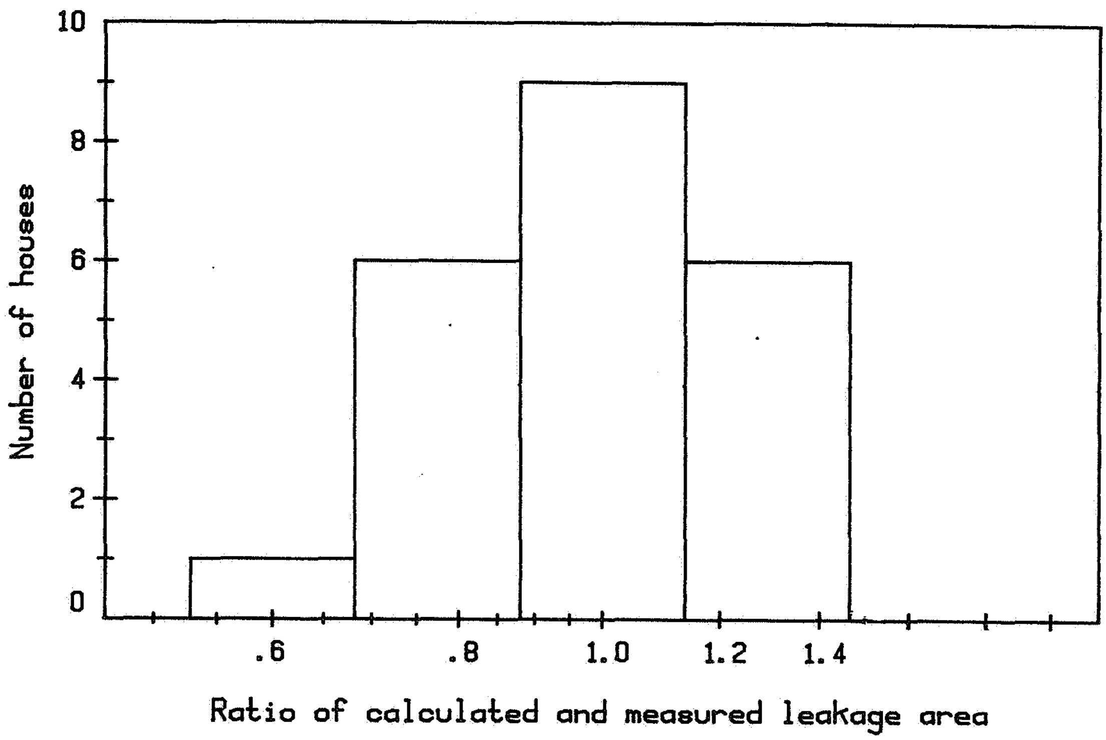

Fig. 3: Histogram of ratios of calculated to measured leakage areas for 22 "unique" houses.

On a different level, the small predictive bias of our model based solely on architectural drawings may appear to be contradictory to the findings widely reported in the literature and consistent with our experience that only on-site inspection can accurately reveal location and size of air leaks in buildings. In reality, the sizeable standard deviation of the predictions indicates the existence of inaccuracies of the model. The small bias implies only that the errors committed in omitting leakage sites or in assigning improper leakage areas are uncorrelated and, thus, tend to cancel each other. Nevertheless, it is important to recognize that this model, as any deterministic method, is inherently best suited for design calculations on new buildings and for predictions of energy savings in sets of existing buildings. When predicting the savings from retrofitting an individual building on the basis of drawings alone the model, obviously, can only be as good as its assumptions, namely, the identification and the sizing of all leakage sites.

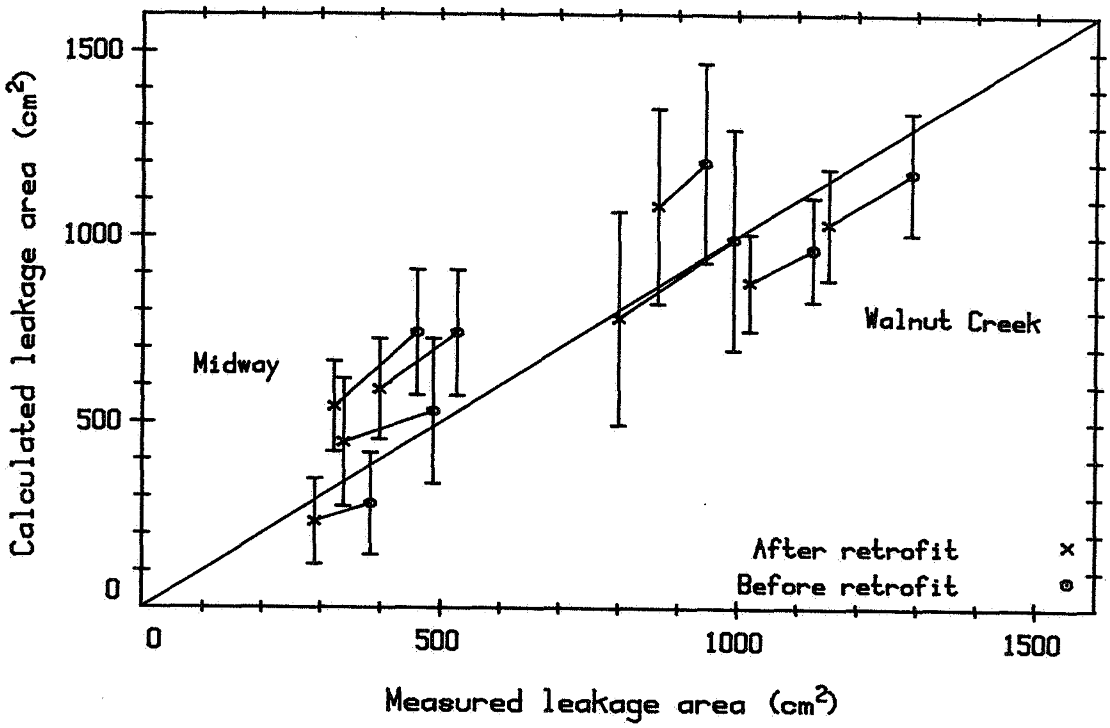

Fig. 4: Comparison of measured and calculated leakage areas of 8 houses before and after air-tightening retrofits; the solid line indicates perfect agreement.

5.4 Comparison of Air-Tightening Retrofits

Figure 4 shows the results of calculations on the eight houses in which leakage area had been measured before and after air-tightening retrofits were carried out. Four houses are located in Midway and four in Walnut Creek. The calculations on these eight houses are based on sketches and notes done by house doctors since no detailed architectural drawings were available. Each house is represented by a line connecting the two points indicating the leakage areas before and after retrofit. A connecting line parallel to the solid diagonal indicates perfect agreement between calculation and measurement of the change in leakage area. This comparison is possibly the most encouraging thus far. It shows that for six of the eight houses, the change in leakage achieved by retrofit was calculated to much greater accuracy than the absolute leakage areas either before or after retrofit. In light of our earlier discussion on the relative benefits of on-site visits and calculations based on drawings, one might conclude that our knowledge of the values of individual component leakage areas (at least those affected by the retrofits in these eight houses) is better than our awareness of the existence of all leakage sites in the shell.

5.5 Comparison of Calculations with Measured System Leakage Areas

Several previous studies have reported measurements of component leakage areas aggregated by groups of components (e.g., all electric outlets and recessed light fixtures) and by large discrete components (e.g., fireplaces). In the pie charts in Figs. 5a and 5b we aggregate in a similar manner the component leakage areas of a subset of houses formed by the "unique" houses, including both the before and after configurations of the eight retrofitted houses. Partly because of the reporting format of the previous studies, we considered the 19 houses with fireplaces separately from the 11 houses without. The percentages in each sector -- windows, for example -- were obtained by dividing the average window leakage area of all houses by the average total leakage area.

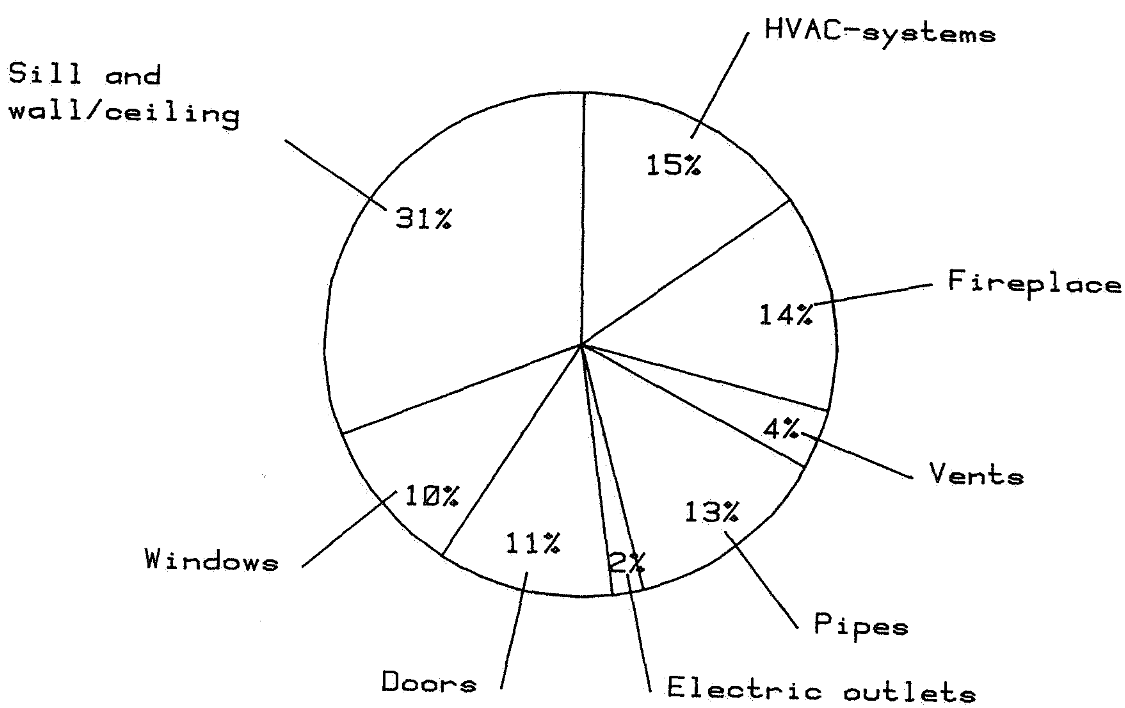

Fig. 5a: Distribution of leakage areas by major component systems for 19 houses with fireplace.

Our calculation of 14% as the contribution of a fireplace to total leakage area (see Fig. 5a) compares favorably with the 16%

measured in a previous study by Dickerhoff et al.[29] The leakage attributable to forced air heating and cooling ducts was calculated to be 15% and 13%, respectively. Caffey found duct leakage to be 14% of the total,[30] while the study by Dickerhoff et al. found 13%; similar measurements by Lipschutz et al. reported 15% and 21%, respectively.[31-33]

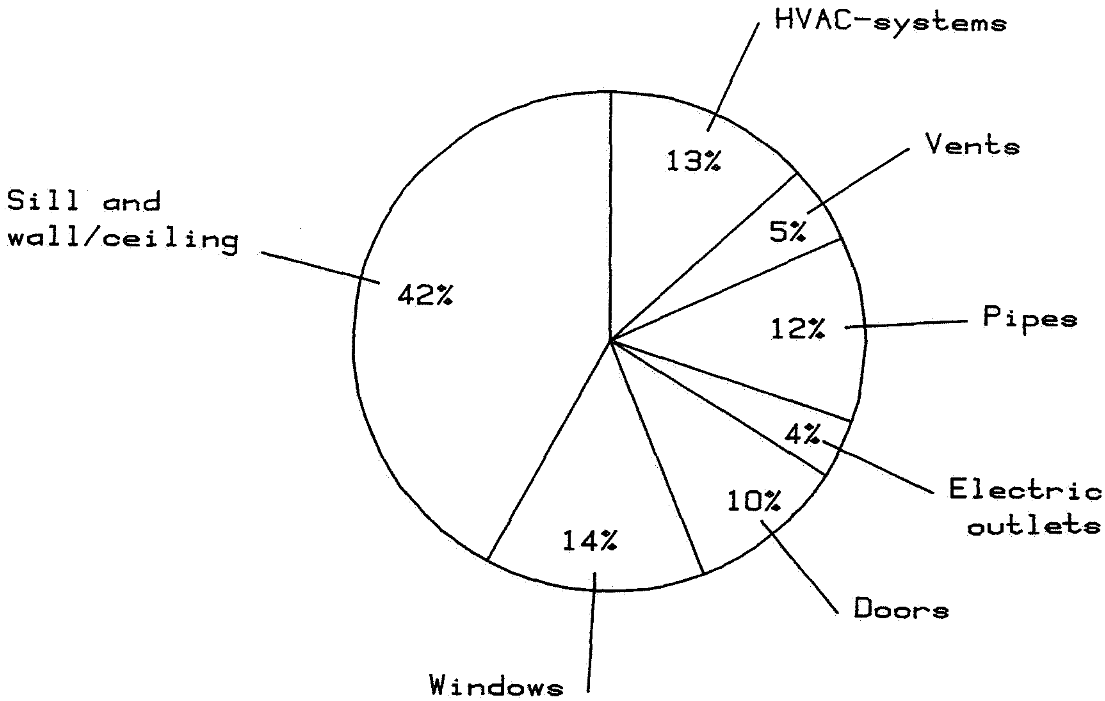

Fig. 5b: Distribution of leakage areas by major component systems for 11 houses without fireplace.

The leakage associated with kitchen fans, bathroom fans, and clothes dryers is indicated by the sectors marked "Vents." Here, we found average values of 4% and 5% for houses with and without fireplaces, respectively, while Dickerhoff et al. measured 3% to 6%.[34]

Our calculations show that electric outlets and recessed light fixtures contribute 2% and 4%, respectively. Values reported in the literature display dramatic variations for this component. While Dickerhoff et al. determined this contribution to be 1%,[35] Caffey reported 25%.[36] Swedish laboratory tests measured leakage areas for electric outlets to be between 0.00 cm^2 and 0.33 cm^2 each, depending on how well they were sealed.[37] No recessed light fixtures were tested. In our calculations, we used 0.5 cm^2 per outlet and 10 cm^2 for each recessed light fixture. While they did not address recessed light fixtures, the Swedish tests thus appear to confirm the range found by Dickerhoff et al. and by our calculations.

6. CONCLUSIONS

Leakage areas predicted for 36 building plans using component leakage areas appear to be in good agreement with direct measurements using a blower door. Care was taken to use only architectural drawings of the buildings and to ignore additional information from prior on-site visits. The weakness of this comparison, of course, is that we had prior knowledge of the buildings and their measured leakage areas. Although we strived to prevent such knowledge from biasing our judgments when interpreting the building plans, our results might have been stronger if the leakage areas had been calculated before any on-site visit had been made.

With these caveats in mind, we still feel that calculating building leakage areas from component information provided by architectural drawings appears to be a sound alternative to direct measurement by blower door. Although calculations without site visits will never yield the accuracy obtainable by direct measurement, they may prove more cost-effective when planning large numbers of retrofits. For new houses, the availability of an accurate and exhaustive list of component leakage areas may be crucial for evaluating the energy efficiency of a proposed design as a basis for suggesting alternative air tightness strategies or trade-offs when necessary.

To be sure, more than the air tightness of a building is involved in estimating air infiltration, but it is air tightness that so far has been least amenable to desk calculations. With the understanding that the values reported in this paper are far from definitive, and that we may have involuntarily omitted some data on measured values of leakage areas of components, we regard this paper as the first in a series of periodic updates. A format for data collection -- component leakage areas at a reference pressure of 4 Pa -- is suggested, but not mandatory for inclusion in this data base. For purposes of transforming other reporting formats to leakage areas we have included appropriate conversion formulae.

New information on component leakage areas does not emanate solely from direct measurements on a component-by-component basis. As in the studies reviewed in this paper, selective systems of components can also be measured. A sufficient number of such aggregate data could be transformed into component leakage areas through multiple linear regression. Indeed, a similar analysis of a large number of measured whole-building leakage areas could yield accurate estimates of component leakage areas, provided that the architectural details of the buildings relevant to air leakage are reported in a consistent format, one of which is suggested in our paper. Of course, it is probable that such a format, even if agreed upon by all air infiltration researchers today, would evolve as new measurements were reported. More window types would likely be added, with more consideration given to international differences in component details. Similarly, fireplaces may be generalized to wood-burning appliances but characterized by a much greater variety of design than the present four entries -- with and without fireplace insert, with and without damper.

Aside from allowing air tightness and air infiltration to be calculated on the basis of drawings alone, the reporting of component leakage areas in a consistent format would be of great assistance in analyzing international differences in building practices. For example, are all Scandinavian houses built tighter than all United States houses, or is this difference less pronounced in new houses? If there are large differences, how do they break down by component or how do they relate to building style? These and similar questions could be addressed more rationally if more component leakage areas were known and reported in a format allowing comparison.

ACKNOWLEDGEMENTS

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36. Caffey, op.cit.

37. Levin, op.cit.

APPENDIX A
COMPONENT LEAKAGE AREAS

TABLE A-1
SILL FOUNDATION - WALL

Component	Best Estimate	Max	Min	Unit
SILL, caulked per m of perimeter	0.8	1.2	0.4	cm^2/m *
SILL, not caulked per m of perimeter	4	4	1	cm^2/m *

Leakage location: "Walls" if sill is open to outdoors or if slab-on-grade construction;
"Floor" if sill open to crawlspace or basement.

TABLE A-2
JOINTS BETWEEN CEILING AND WALLS

Component	Best Estimate	Max	Min	Unit
JOINTS per m of wall Only if not taped or plastered and no vapor barrier.	1.5	2.5	0.5	cm^2/m *

Leakage location: "Ceiling"

Note: * indicates that Max and Min are not found in the literature. The given values of Max and Min are our estimates.

TABLE A-3
WINDOWS

Component	Best Estimate	Max	Min	Unit
CASEMENT Weather stripped per m^2 window area	0.8	1.2	0.4	cm^2/m^2
Same, not weatherstr.	1.6	2.4	0.8	cm^2/m^2.
AWNING Weather stripped per m^2 window	0.8	1.2	0.4	cm^2/m^2
Same, not weatherstr.	1.6	2.4	0.8	cm^2/m^2
SINGLE HUNG Weather stripped per m^2 window	2.2	2.9	1.8	cm^2/m^2
Same, not weatherstr.	4.4	5.8	3.6	cm^2/m^2
DOUBLE HUNG Weather stripped per m^2 window	3.0	4.4	1.6	cm^2/m^2
Same, not weatherstr.	6.0	8.8	3.2	cm^2/m^2
SINGLE SLIDER Weather stripped per m^2 window	1.8	2.7	0.9	cm^2/m^2
Same, not weatherstr.	3.6	5.4	1.8	cm^2/m^2
DOUBLE SLIDER Weather stripped per m^2 window	2.6	3.8	1.4	cm^2/m^2
Same, not weatherstr.	5.2	7.6	2.8	cm^2/m^2
Leakage location: "Walls"				

TABLE A-4
DOORS

Component	Best Estimate	Max	Min	Unit
SINGLE DOOR Weather stripped Per m^2 door	8	15	3	cm^2/m^2
Same, not weatherstr.	11	17	6	cm^2/m^2
DOUBLE DOOR Weather stripped Per m^2 door	8	15	3	cm^2/m^2
Same, not weatherstr.	11	22	7	cm^2/m^2
ACCESS TO ATTIC OR CRAWL-SPACE Weather stripped Per access	18	18	8	cm^2 each *
Same, not weatherstr.	30	30	10	cm^2 each *

Leakage location: "Walls"

TABLE A-5
WALL - WINDOW FRAME

Component	Best Estimate	Max	Min	Unit
WOOD FRAME WALL With caulking. Per m^2 window	0.3	0.5	0.3	cm^2/m^2
Same, no caulking	1.7	2.7	1.5	cm^2/m^2
MASONRY WALL With caulking Per m^2 window	1.3	2.1	1.1	cm^2/m^2
Same, no caulking	6.5	10.3	5.7	cm^2/m^2
Leakage location: "Walls"				

TABLE A-6
WALL - DOOR FRAME

Component	Best Estimate	Max	Min	Unit
WOOD WALL With caulking Per m^2 door	0.3	0.3	0.1	cm^2/m^2
Same, no caulking	1.7	1.7	0.6	cm^2/m^2
MASONRY WALL With caulking Per m^2 door	1.0	1.0	0.3	cm^2/m^2
Same, no caulking	5	5	1.7	cm^2/m^2
Leakage location: "Walls"				

TABLE A-7
DOMESTIC HOT WATER SYSTEMS

Component	Best Estimate	Max	Min	Unit
GAS WATER HEATER (only if in conditioned space)	20	25	15	cm^2 each *
Leakage location: "Ceiling" (see note at end of appendix).				

TABLE A-8
ELECTRIC OUTLETS AND LIGHT FIXTURES

Component	Best Estimate	Max	Min	Unit
ELECTRIC OUTLETS AND SWITCHES Gasketed	0	0	0	each
Same, not gasketed	0.5	1.0	0	cm^2 each *
RECESSED LIGHT FIXTURES	10	20	10	cm^2 each *

Leakage location: "Walls" for outlets or fixtures in walls;
"Ceiling" for fixtures in ceiling.

TABLE A-9
PIPE AND DUCT PENETRATIONS THROUGH ENVELOPE

Component	Best Estimate	Max	Min	Unit
PIPE PENETRATIONS Caulked or sealed	1	2	0	cm^2 each *
Same, not caulked	6	10	2	cm^2 each *
DUCT PENETRATIONS Sealed or with contin. vapor barrier	1.6	1.6	0	cm^2 each *
Same, unsealed and without vapor barrier	24	24	14	cm^2 each *

Leakage location: "Walls" for penetrations of outside wall surfaces;
"Ceiling" for penetrations of the ceiling;
"Floor" for penetrations going from the living space to crawlspace or basement.

TABLE A-10
FIREPLACE

Component	Best Estimate	Max	Min	Unit
FIREPLACE W/O INSERT Damper closed	69	84	54	cm^2 each
Same, damper open	350	380	320	cm^2 each
FIREPLACE WITH INSERT Damper closed	36	46	26	cm^2 each
FIREPLACE WITH INSERT Damper open or absent	65	90	40	cm^2 each

Leakage location: "Ceiling" (see note at end of appendix).

TABLE A-11
EXHAUST FANS

Component	Best Estimate	Max	Min	Unit
KITCHEN FAN Damper closed	5	7	3	cm^2 each
Same, damper open	39	42	36	cm^2 each
BATHROOM FAN Damper closed	11	12	10	cm^2 each
Same, damper open	20	22	18	cm^2 each
DRYER VENT Damper closed	3	6	0	cm^2 each *

Leakage location: "Walls" for wall fans;
"Ceiling" for ceiling fans (see note at end of Appendix.

TABLE A-12
HEATING DUCTS AND FURNACE

Component	Best Estimate	Max	Min	Unit
FORCED AIR SYSTEMS				
DUCTWORK (only if in unconditioned space)				
Duct joints taped or caulked	72	72	32	cm^2 per house
Duct joints not taped or caulked	144	144	72	cm^2 per house
FURNACE (only if in conditioned space)				
Sealed combustion furnace	0	0	0	each
Retention head burner furnace	30	40	20	cm^2 each *
Retention head plus stack damper	24	30	18	cm^2 each *
Furnace with stack damper	30	40	20	cm^2 each *

Leakage location: "Floor" for ducts in basement or crawlspace;
"Ceiling" for ducts in attic;
"Ceiling" for furnace (see note at end of Appendix.

TABLE A-13
AIR CONDITIONER

Component	Best Estimate	Max	Min	Unit
AIR CONDITIONER Wall or window unit	24	36	0	cm^2 each *

Leakage location: "Walls"

Note on ceiling leakage areas:

In this paper we assign to "Ceiling Leakage" the leakage area of all ducts, fans, stacks, chimneys, and exhaust vents that pierce the ceiling regardless of whether they also cross the roof. Strictly speaking, only leakage paths from the living space to the attic are part of the ceiling leakage area. Air flows from the living space through the roof directly to the outdoors should be calculated separately and added in quadrature to natural infiltration. See, for example, M.H. Sherman and D.T. Grimsrud, "A Comparison of Alternate Ventilation Strategies" in Proc. 3d AIC Conference on Energy Efficient Domestic Ventilation Systems for Achieving Acceptable Indoor Air Quality (The Air Infiltration Centre, Old Bracknell Lane West, Bracknell, Berkshire, RG12 4AH, England, 1982).

When using a blower door to measure leakage area, one should therefore seal all stacks, chimneys and vents in direct communication with the outdoors and calculate the airflow through those openings separately. As in the measurements reported in this paper, this procedure is not always followed in practice. In such cases the ceiling leakage area refers to all air flows, including those through the roof which are then implicitely lumped with natural air infiltration. The error in the resulting air infiltration calculation is usually small, except for houses with large chimneys without dampers.